GEOLOGICA BELGICA (2004) 7/3-4: 207-213

NUMERICAL MODELLING AND PREDICTION OF ABANDONED MINE METHANE RECOVERY: FIELD APPLICATION AT THE SAAR COALFIELD, GERMANY

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(10 figures)

ABSTRACT. In a recently completed EC- Thermie research project, jointly carried out by Imperial College and Deutsche Steinkohle Aktiengesellschaft (DSK), an in house gas-water two-phase CBM simulator developed at Imperial College London was modified to simulate abandoned mine methane recovery in the Saar Coalfield. Historical data on mining and methane emissions, as well as the long-term methane production data monitored from the Hangard shaft was used to validate the model developed. A satisfactory match to the historical and current field data was achieved, and predictions for future production opportunities were made.

Keywords: Abandoned mine methane abandoned mine reservoir characterisation, history matching.

1. Introduction

In abandoned mines, especially those which operated longwall mining, the super and subjacent coal seams can be destressed and fractured at a significant distance away from the worked seam. Therefore, the coal bearing strata surrounding an abandoned coal mine can be modelled as a highly fractured, naturally stimulated reservoir with substantial part of the original gas resource available for subsequent extraction and utilisation. This very favourable characteristic presents abandoned coal mine reservoirs as a very attractive prospect for unconventional natural gas production. This is especially true within the European context as many coal basins in Europe are populated with abandoned mines.

DSK has been involved in extracting and utilising methane from abandoned mines in the Saar Basin of Germany for many decades. Until 2002 the company produced mine gas from 13 shafts with methane concentrations varying from 30 to 90%. In 2003 the gas

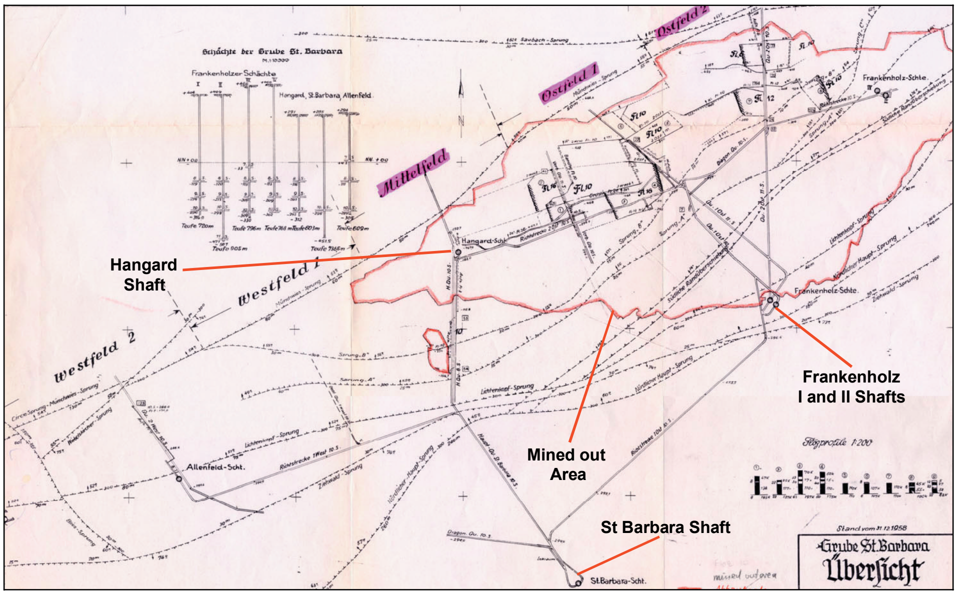

Figure 1. Plan view of the Frankenholz – St. Barbara mine complex: the infrastructure and the mined out section of the coal seams, the location of Frankenholz, St. Barbara and Hangard shafts.

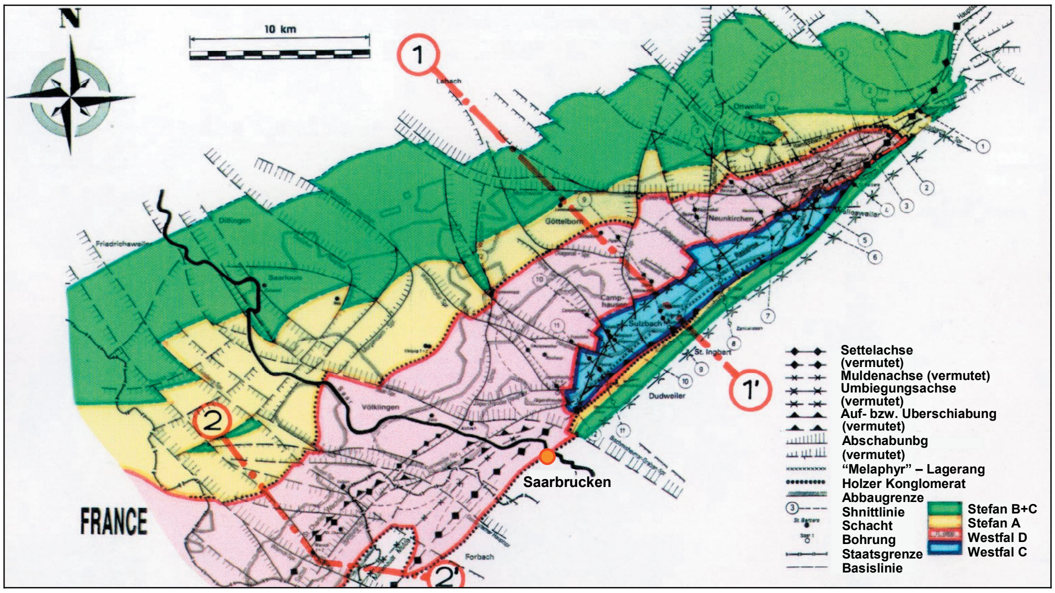

Figure 2. General geology of the Saar Coalfield.

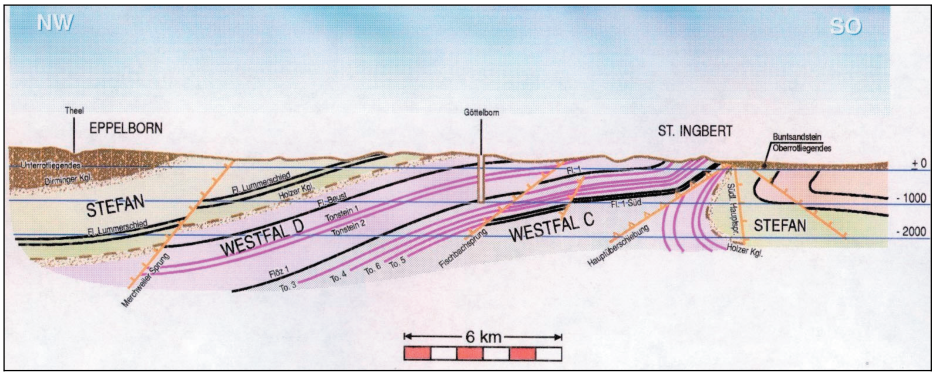

Figure 3a. Geological sections along the Saar Coalfield. Section 1-1 (Figure 2).

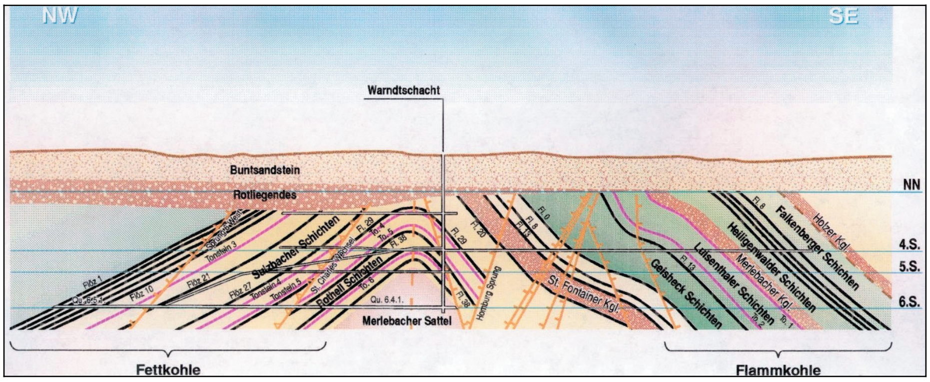

Figure 3b. Geological sections along the Saar Coalfield. Section 2-2 (Figure 2).

production activities have been transferred to a regional energy producer. One of the high purity producers is the Hangard shaft, which is situated in the old Frankenholz – St. Barbara mine complex. Figure 1 illustrates a plan view of the mine infrastructure and the mined out section of the coal seams, together with the location of Frankenholz, St. Barbara and Hangard shafts.

Aiming to achieve a better understanding of methane recovery from abandoned coal mines, a reservoir characterisation study was recently carried out at the

Frankenholz – St. Barbara mine complex. An attempt was made to history-match the past and current methane production data from the Hangard shaft, with a view to forecasting the medium to long-term production at this shaft. This paper presents the main results of this study.

Geology and mining history

The coal seams of the Saarland region are of Upper Carboniferous age (formed 350-285 Million years ago). Stratigraphically it is divided in two groups, the older Saarbrücker Group of Westphalian age and the younger Ottweiler group of Stephanian age, Figure 2. In terms of their calorific values, the Westphalian sequence consists of "Fat Coals" with high methane gas contents, whereas the upper sequence is of the "Flame Coal" variety, with comparatively lower gas content.

The lower boundary of the coal bearing formations is formed by an over-thrust with a general SW-NE direction and a mean dip of around 70º near the surface that flattens out with depth, Figure 3a. The coal sequences appear highly fractured with a system of sub-parallel overthrusts that follow the same SW-NE direction and nearly vertical faults perpendicular to this system. In some places, including the Hangard area, the same stress system is expressed with folding near the overthrust creating a dome shaped structure, Figure 3b.

At Frankenholz Colliery, mining activity within each seam was generally confined in an area delineated by the three major faults (Figure 5). First coal was produced in 1881 from a 90 cm thick seam at 184 metres depth. Production has continued for a long period of time. Frankenholz was known to be a gassy mine with a number of methane explosions claiming many lives. The first explosion occurred in 1884. In 1941, the mine was closed down due to a large explosion which resulted in 41 deaths. In 1946, Frankenholz Colliery was re-opened and later joined with the St. Barbara mine in 1954. Both mines were closed in 1959. Between 1947-59 the total production was 4.7 Million tonnes and between 1954-59 the two mines maintained a joint production rate of 45,000 tonnes/year. In total, from 1833 to 1959, the two collieries mined a total coal surface area of 4.5 km^2.

2. Abandoned mine reservoir model development at the Frankenholz – St. Barbara Collieries

There are up to 32 seams of varying thickness between 0.3 – 3 m in the Frankenholz – St. Barbara mining complex, dipping in Northwest direction. It has been estimated that between levels 1 and 11 (-470 m), the total thickness of coal is 40 metres in 430 metres of coal measures strata. Mining in each seam progressed down dip, sweeping from East to West. The seam configuration and mined out areas are illustrated in Figure 4. The figure shows that Seam 10 (Flötz 10) is one of several seams that have been extensively mined.

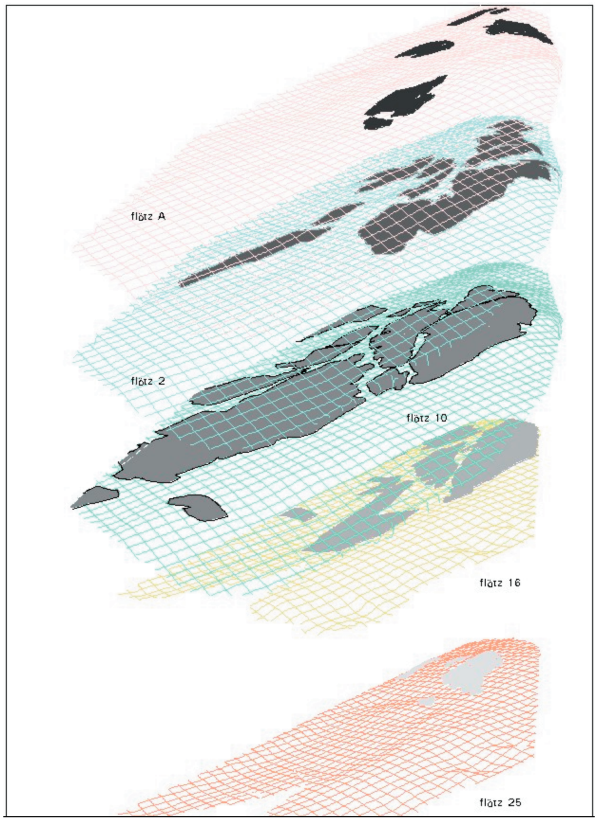

Figure 4. Seam configuration (meshed surface) and mined out sections (dark solid areas) within the Frankenholz – St. Barbara mining complex.

The initial seam gas contents for the Saar Basin are expected to vary from 7 m^3/t to 12 m^3/t. The lower end of this range was estimated by Juch [1996], who excluded seams with less than 20 cm thickness from his calculations, and assumed that there is a decrease in coal thickness towards the Northwest. On the other hand, a gas content of 12 m^3/t was suggested by Demuth and Muller [in Juch, 1996]. They included all the coal present in their stratigraphic sections and assumed that the coal thickness would be the same towards the Northwest of the basin, which is an area not very well studied [Juch, 1996].

2.1. Areal Model

As a first step in abandoned mine reservoir modelling, it was decided to form a lumped areal model to represent the multiple seams in the area of interest. The model has a uniform thickness of 40 m, representing the net thickness of all the seams between levels 1 and 11 (-470 m). The areal model domain was chosen with reference to the three major faults surrounding the mined-out area in the Frankenholz – St. Barbara complex (Figure 5). Based on field observations by DSK, it was assumed that these faults form a barrier to gas flow in the region. Figure

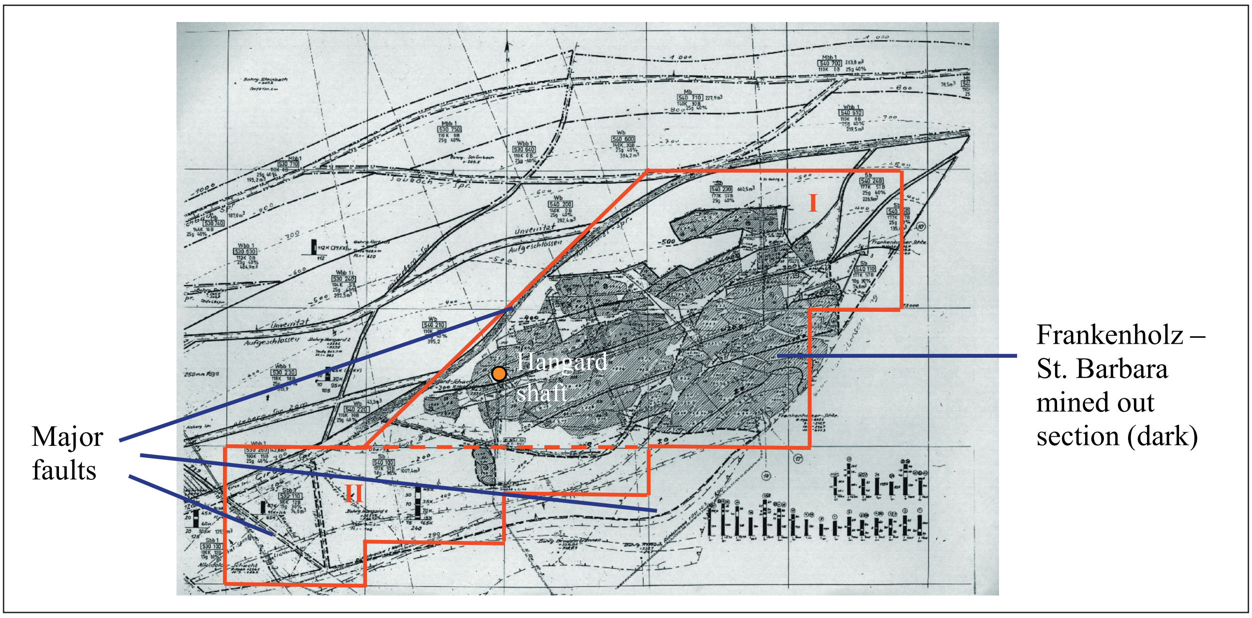

Figure 5. The model domain superimposed on mined-out Seam 10 (Flötz 10) footprint.

5 illustrates the model domain superimposed upon the mined-out footprint of Seam 10.

In this study, the model domain is characterised by two regions: the Northeast region (I) where extensive mining has taken place, and the Southwest region (II), which has hardly been mined or affected by mining. The model domain covers a total area of approximately 7.1 million m^2, with the mined region (I) and unminded region (II) occupying an area of 5.1 million m^2 and 2 million m^2 respectively, yielding a net coal volume of 7.1 x 40 = 284 million m^3.

2.2. In Situ Gas Content/Gas-in-Place

In 1980, Düpre and Barth [Hebel, 1999] have carried out a study of the gas contents and methane emissions in the Frankenholz – St. Barbara Collieries. They calculated 2,700 million m^3 of methane *in situ* in virgin conditions. The total mined coal surface area in the region was estimated as 4.5 million m^2. A net coal thickness of 40 m between levels 1 and 11 would yield a total coal volume of 4.5 x 40 = 180 million m^3. Based upon this coal volume and a coal density of 1.3 t/m^3, an average gas content of 2,700/180 = 15 m^3/m^3 (11.5 m^3/t) may be inferred. More recently, during the project reported here, Hebel [1999] estimated that there is approximately 4,000 million m^3 gas *in situ* between levels 1 and 11 in the area defined as regions I and II in the areal model. Based upon this estimation, the average lumped mean gas content within the model domain becomes approximately 4,000/284 = 14.1 m^3/m^3 (10.8 m^3/t). This figure is very close to the average gas content of 10.77 m^3/t previously reported by Kneuper & Müller [1968].

The seams in the unminded region of the model domain are generally shallower than those in the mined area. Consequently a relatively lower initial gas content of 9.7 m^3/t was assigned to the unmined region (II), compared to a gas content of 11.5 m^3/t in the mined region (I). This yields an average gas content of 11.0 m^3/t for the areal model used, which is in good agreement with the values reported by Hebel [1999] and Kneuper & Müller [1968] previously.

2.3. Permeability Characterisation

Permeability characterisation of abandoned coal mines needs to take into account the impact of historic mining activities on the permeability of the seams surrounding the mine workings. Coal extraction and subsequent caving of the roof strata creates a low stress and fractured zone in both the overlying and, to a lesser extent, in the underlying strata with a significantly increased permeability. The result is a highly heterogeneous permeability distribution in the affected zones around the mine workings. In the areal model described, it was decided to assign an enhanced permeability value to the mined-out region to reflect the mining induced changes (fracturing) on seam permeability (Figure 6).

In this study, the laboratory permeability of intact Saar coal samples was determined as being less than 0.1 md. The field permeability of a coal seam is primarily due to the presence of regularly distributed cleat networks and larger-scale fractures. Therefore, it is widely accepted that laboratory measured permeability of relatively small coal samples cannot be used directly for field applications. A better indication of the filed permeability would come from the permeability values measured on lightly fractured coal samples under low confinement, which was determined as 1 md for the Saar coals. The laboratory results have also indicated that the enhanced coal

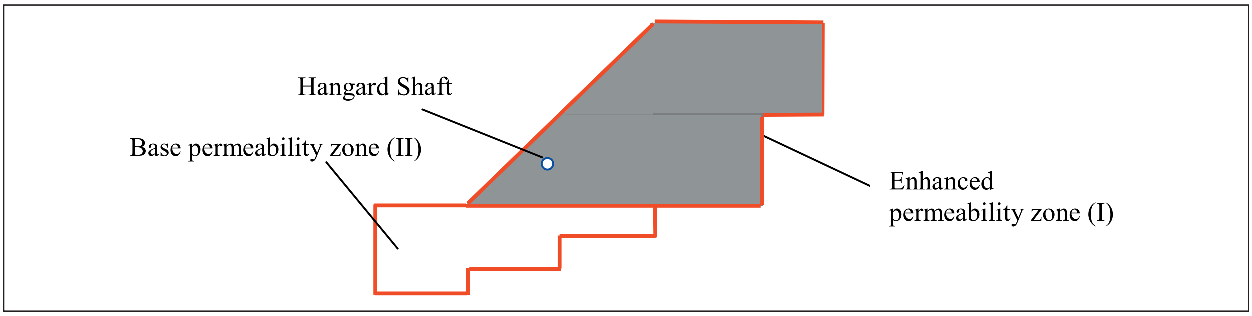

Figure 6. Schematic of different permeability zones used in the areal model.

permeability for fractured and stress relieved coal seams would be at least one order of magnitude higher than the undisturbed seam permeability (base permeability). Using a base permeability value of 1 md for Zone II, the enhanced permeability value for Zone I was evaluated through history matching of the field production data as discussed later in Section 3.

2.4. Residual Gas-in-Place and its Distribution

One of the challenges in abandoned coal mine reservoir characterisation is the determination of the residual gas-in-place and its spatial distribution throughout the region. The residual gas–in-place may be estimated if the original gas contents of the coal seams and the historic methane emission data were available. Fortunately, this was the case for the Frankenholz – St. Barbara Collieries. It has been estimated that by 1960, out of an estimated total methane-in-place of 4,000 million m^3, 2,200 million m^3 had been emitted, leaving approximately 1,800 million m^3 of methane available for extraction [Hebel, 1999].

It is expected that, at the time of mine closure, a gradient of residual gas content would exist in the area. The coals close to the mined out regions would be degassed to a greater degree while coals at some distance from the mine openings would retain most of their original gas contents. In this study, a simple methodology which reflects the former mining activities and related gas emissions was developed to establish a residual gas content and its distribution within the model domain. This involves the introduction of a hypothetical methane extraction period, with the extraction point located at the centre of the mined out region, in order to account for the total loss of methane prior to mine closure. Starting from the original gas contents and pressure distribution, the cumulative gas produced in this period should match exactly the recorded/estimated historic gas emissions plus the residual gas on the mined out coal. The specific volume of sorbed methane left at the end of this hypothetical production period is taken as the residual gas content of the remaining coals in the modelled region. The field data used in the model and the results obtained will be presented in the next section.

3. History matching methane production at Hangard Shaft

Unlike a virgin coalbed methane reservoir, where the seams are usually fully or partially saturated with water, the unflooded parts of an abandoned coal mine contain only the gas phase, which is likely to be a mixture of methane, nitrogen, and carbon dioxide and other minor components. Furthermore, the adsorbed phase is believed to consist of primarily methane, as re-adsorption of nitrogen and carbon dioxide would be minimum given the relatively low free gas pressure in the mine openings. Considering that methane desorption is controlled by the partial pressure of free methane gas in the mine, the in-house coalbed methane simulator (METSIM) was modified to describe the methane flow in abandoned coal mines by working with methane partial pressure only [Durucan *et al*, 1995].

Using the abandoned mine model constructed above, a history matching study was carried out. Figure 7 presents the sorption isotherm used and the actual and modelled suction pressure history applied at the Hangard shaft. In accordance with the previously defined virgin coal seam gas contents of 11.5 and 9.7 m^3/t (Section 2.2), the initial mean methane pressures in the model domain were assigned as 4 and 3 MPa respectively for the mined out and unmined regions I and II (Figure 7a).

The model predictions, with three different enhanced permeability values assigned to the mined-out region, to year 2000 are compared with the recorded annual methane production in Figure 8. The base permeability used was 1 md, taking into account the presence of several small scale fractures in the virgin seams.

Figure 9 illustrates an example of the methane pressure distribution in the abandoned mine generated by the model. In this run, the base and enhanced permeabilities used were 1 md and 40 md respectively. It can be seen from the figure that the mined out region has been preferentially depleted due to the enhanced permeabilities there. It should be noted that the gas pressures in the figure are representative of those in the cleat network of remaining coal, as the pressure in the voids such as older mine workings, galleries would be close to atmospheric pressure.

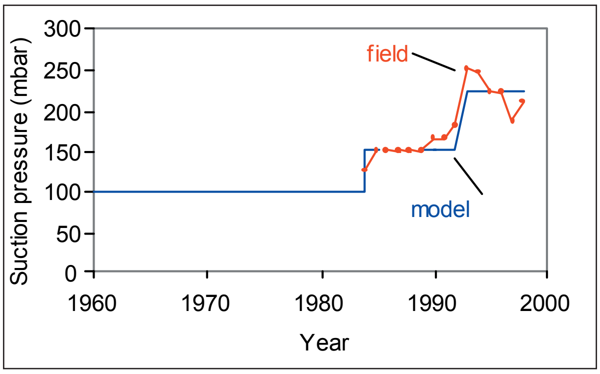

Figure 7.a. Sorption isotherm used in the history matching study.

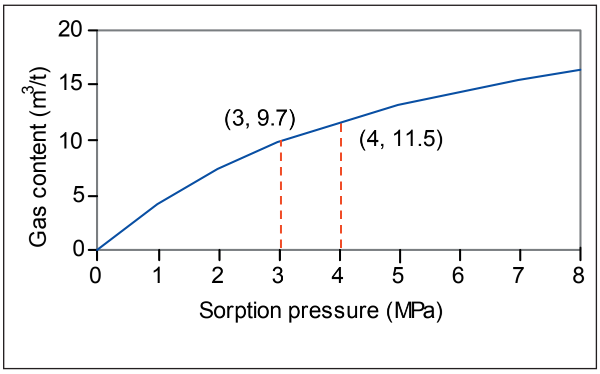

Figure 7.b. Suction pressure used in the history matching study.

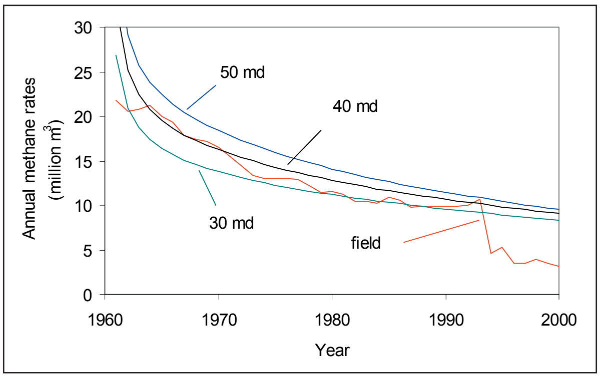

Figure 8. Model predictions compared with recorded methane production at Hangard shaft.

DSK's monitoring records have shown that the water level rose from level 11 (– 470 m) to between levels 9 and 10 (– 244 m) by 1984 and has remained at the same level since. As the mine water level rises, increase in hydrostatic pressure eventually prevents the submerged seams from desorbing and cause a reduction in the methane production. This factor has not been explicitly taken into account in the model.

Since 1994, the methane production at Hangard has been under operational control to meet the variable demands of the market. Figure 10 shows the monthly methane production for years 1999 and 2000. The figure illustrates that the gas rates varied widely from month to month. In order to facilitate a meaningful comparison with the simulation results, an estimation of the likely annual methane production under full capacity extraction was made. In April 1999 and March 2000, 0.643 and 0.722 million m^3 methane were produced respectively, giving rise to a two-year annual mean production value of 8.2 million m^3. The maximum production model predicted an average annual production of 9.0 million m^3 for years 1999 and 2000 using an enhanced permeability of 40 md in the mined out region (Zone I).

The abandoned mine reservoir simulator developed and validated using the Hangard shaft long-term production data enabled the researchers to extend this research into the other regions of the coalfield. High methane partial pressure zones in the region were identified as potential sites for producing high purity methane gas and plans were drawn up accordingly.

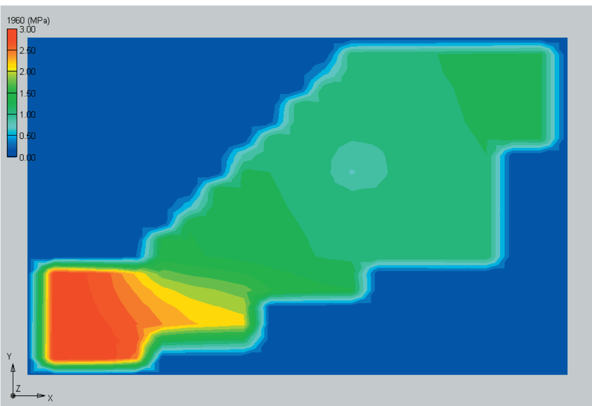

Figure 9.a. Simulated methane (partial) pressure distribution in abandoned Frankenholz – St. Barbara Collieries in 1960.

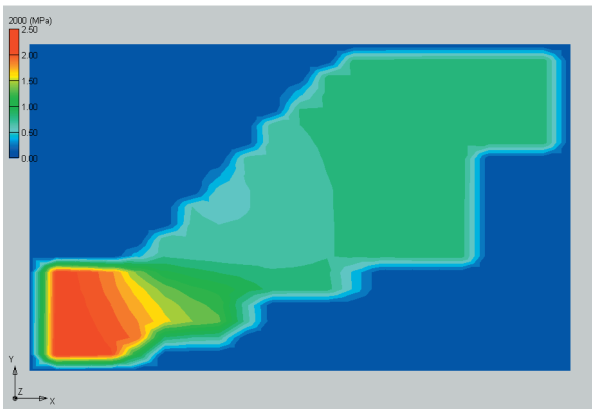

Figure 9.b. Simulated methane (partial) pressure distribution in abandoned Frankenholz – St. Barbara Collieries in 2000.

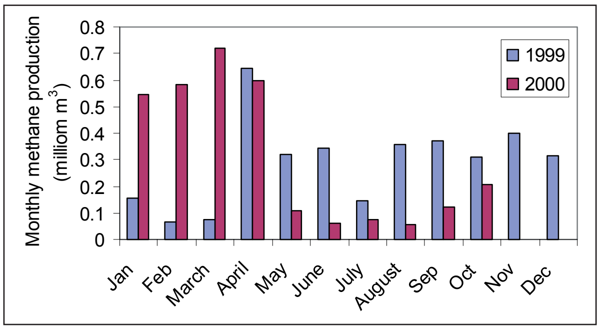

Figure 10. Methane production data from Hangard shaft during 1999-2000 periods.

4. Conclusions

A reservoir characterisation and history matching study of abandoned Frankenholz – St. Barbara mining complex was carried out. A lumped areal model was constructed and used to history match the long-term and recent methane production rates from the Hangard shaft. A methodology was developed to account for the lost gas resulting from former mining activities in the model domain. The history matching results were encouraging and have led to the analysis of other potential production areas in the Saar coalfield.

5. Acknowledgements

This study forms part of a recently completed EC-Thermie funded project, Contract No: OG85/98. The authors wish to thank their industrial partner DSK and their engineering staff, Mr Hans-Juergen Kaltwang, Mr Gerhard Hebel, Mr Robert Cayrol, Mr Jörg Lehmann and Mr Michael Schwan for their help and collaboration during the project. DSK's permission to reproduce some to the figures and data included in this paper is also acknowledged.

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Manuscript received 21.11.2002 and accepted for publication 20.2.2004.