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Yangquan Mine CMM-to-Power Project: Technical and Economic Evaluation

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ABSTRACT

Evaluation of coal mine methane (CMM) production and utilization options at the Yangquan coal mine in Shanxi Province indicates that a CMM-to-power facility is technically and economically feasible. The Yangquan mine complex, one of China's largest anthracite production centers, currently captures 320,000 m^3/day of CMM (@100% CH_4 equivalent) using superjacent gallery and cross-measure borehole drainage techniques. One-third of this methane is used locally via an extensive low-pressure pipeline and storage system. However, most of the captured methane (200,000 m^3/day) is considered excess supply and vented to the atmosphere. Our analysis shows that the most feasible design would be an array of small (1-MW) reciprocating engines. Current gas supply is sufficient for a 30- to 40-MW power facility, increasing to as much as 50-MW by 2005. The power facility could also accrue significant GHG credits of over 1 million t/year of CO_2-equivalent. To improve gas recovery and reliability, recommended improvements to the gas recovery system include: implementation of directional drilling equipment for drainage and karst exploration in advance of mining and gob gas recovery, underground gas collection upgrades including fused HDPE pipelines, and enhanced monitoring and control systems. If successful, the Yangquan power project could serve as a demonstration for expanding CMM utilization throughout mining areas in China.

INTRODUCTION

The 1,105-km^2 Yangquan mining area is located in east-central Shanxi Province, about 325 km southwest of Beijing and 80 km east of Taiyuan, the provincial capital. Yangquan is an industrialized city with a metropolitan population of approximately half a million. The Yangquan mining area is one of China's principal anthracite production centers. Yangquan Coal Group, Ltd. (YCG) produces about 16 million metric tons/year from a complex of six coal mines. The area contains extensive coal mine methane (CMM) and coalbed methane (CBM) resources.

Methane emissions from coal mining operations at Yangquan were an estimated 400 million m^3 (calculated on 100% CH_4 basis unless otherwise noted) during 1999, of which 119 million m^3 was drained by YCG's underground degasification systems. Methane is captured using a variety of in-mine methods, principally superjacent galleries developed in the roof above the coal seam, and cross-measure gob boreholes. Some 120,000 m^3/day of captured methane is utilized by the city town gas system, but this demand sector is considered mature. An additional 200,000 m^3/day of methane is currently vented to the atmosphere.

An earlier pre-feasibility study by the Ministry of Coal Industry's Handan Design Institute had indicated good potential for a commercial CMM utilization project at Yangquan (Ministry of Coal Industry, 1998). The purpose of our study, conducted for the Asian Development Bank, was to evaluate in detail the commercial feasibility for more effectively producing and utilizing CMM and CBM supplies at Yangquan (ICF Consulting et al., 2000). This paper focuses on the geologic and mining engineering aspects of our evaluation.

GEOLOGIC SETTING

The Yangquan area is located at the northeastern corner of the Qinshui Basin, which is one of China's major coal and coalbed methane basins (**Figure 1**). Extensive coal deposits occur in the Carboniferous Taiyuan and Permian Shanxi Formations, the primary CMM and CBM exploration targets in northern China. The Taiyuan Fm averages 120 m thick at Yangquan and includes commercially important seams 9 and 15. The Shanxi Fm is about 56 m thick and contains seam 3. Coal seams also occur in the Permian Lower Shihezi Fm but are relatively thin and discontinuous.

Coal rank is high at Yangquan, mostly anthracite with vitrinite reflectances (R_o) of 2.28% to 2.50%. Rank is much higher than the rank of productive CBM basins in the U.S., which range from a minimum 0.3% R_o at the Powder River Basin to a maximum of 1.5% R_o in the shallow fields of the Piceance Basin. Yangquan's high rank is considered by Chinese geologists to be primarily the result of elevated temperature. Coal cleating and permeability, while still not favorable, are better than in the anthracites of the eastern U.S., which formed in response to both elevated temperature and great pressure (Murray, 1997). Although extreme rank is not favorable for CBM development, it is less of a liability for CMM projects, because the mining process itself may ensure adequate methane deliverability.

Compared with many other coal basins in eastern China, Yangquan is characterized by favorably simple structural geology. Regional dip is generally 5-10° southwest into the basin, interrupted by mostly northeast-trending minor folds. Faulting is much less frequent than in coal basins further east in China. A few large normal faults strike NNE and exceed 40 m of throw. Most faults are smaller and not considered major barriers to gas and water flow.

Thick Ordovician carbonates directly underlie the coals at Yangquan and directly impact CMM/CBM recovery. As these carbonates underwent chemical dissolution during post-Mesozoic uplift, cylindrical-shaped karstic collapse columns formed and seriously disrupted the continuity of the overlying coal seams. These karsts can be quite large (up to 200 m diameter). Some extend up to the surface, where they cause noticeable ground subsidence. Typically, only 60% of large karsts (>200 m in diameter) but no small karsts (<100 m in diameter) are detected in advance of mining at Yangquan. Unanticipated karsts disrupt mining operations and require changes to mine plans and in some cases, repositioning of longwall mining equipment, a process that can take days or weeks and may be quite costly in terms of lost coal production.

COAL MINING AND DEGASIFICATION

Coal mining takes place at six coal mines at Yangquan (No.'s 1, 2, 3, Xinjing,, 4, and 5; **Figure 2**). YCG uses the longwall system of mining, operating in retreat. The mines are equipped with multiple longwall faces that operate on various vertical levels. Dual drum shearers, manufactured in China, are used to extract the 2-3 m thick coal seams. Longwall mining with subsequent caving of overlying undercut coal is used to exploit the thicker Seam 15 (over 6 m thick in places). The main entryways are driven into rock above and below the mined coal seam for stability reasons. Typical longwall panels range from 500 to over 1,000 m long, with a face length of 150-180 m. Longwall production rates average 1,100 t/day when mining Seams 3 through 12, and 1,800 t/day when mining Seam 15.

YCG's mines produce significant volumes of gob gas during longwall mining. Gob gas emissions vary with the rate of mining, the coal seam mined, the geologic characteristics of the overlying and underlying strata, the amount of overlying mining activity, and the depth of overburden. YCG applies the cross-measure borehole technique to all longwalls in all coal seams except Seam 15 when gob gas drainage is necessary.

Superjacent drainage galleries are used exclusively for longwalls that exploit Seam 15. These are tunnels (typically 2 x 2 m) driven along the longitudinal axis of each panel in overlying rock, generally about 60 m above the targeted coal seam. With the superjacent gallery system, YCG recovers on average 80% of all gob gas emissions generated during longwall mining of a panel. While highly effective, superjacent galleries are also very costly.

The volume of methane vented and drained varies widely by mine at Yangquan (**Figure 3**). For example, Mines 1, 2 and 3 have large emissions of 125,000 to 190,000 m^3/day, but relatively poor recovery from cross-measure borehole degasification systems. The more recently developed Mine 5 and Xinjing Mine have fewer mine workings exposed to sources of emissions, and thus achieve higher methane drainage efficiencies of more than 40% of total methane liberated (**Figure 4**). Specific emissions also vary widely, from about 11 m^3/t of coal mined at Mine 4 to over 47 m^3/t of coal mined at Mine 5, reflecting geologic and mine operational differences.

CMM methane concentration is moderate at Yangquan, generally 30-50% by volume. But methane concentrations vary widely, on short- and long-term bases, as much as 50% over a 1-year period (**Figure 5**). These fluctuations in methane flow and concentration can be dampened somewhat through use of surface storage tanks, but still have a large impact on utilization options.

To help maximize gas recovery and improve gas quality and stability, we identified the following areas where degasification operations could be upgraded at Yangquan as part of a CMM utilization project:

- Improved detection of karsts to maintain mining continuity and gas production. Disruptions in coal production caused by intercepting unforeseen geologic anomalies (e.g., karsts) cause large variations in recovered gas flow and methane concentration at Yangquan. In-mine horizontal borehole drilling technology equipped with directional drilling capability could be employed to detect karsts, while also helping to degasify the coal seams in advance of mining. Karsts may also be detected by the latest commercial satellite imagery, such as IKONOS-1, which is capable of 1- to 3-m resolution.

- Directionally drilled horizontal gob boreholes could be used in place of more costly superjacent galleries, saving an estimated $24,000 per longwall panel.

- Improved surface and subsurface gas pipeline collection and monitoring systems could help maintain methane flow rates and concentration levels in produced CMM. For example, seamless fused HDPE pipe is less prone to leakage than flanged steel pipe.

- Improved cross-measure borehole systems (drilled with properly sealed stand-pipes and installed with monitoring systems) could boost gas recovery and reduce air contamination.

COAL MINE METHANE (CMM) PRODUCTION AND RESERVES

Coal mine methane production at Yangquan is closely linked to coal production. CMM production was forecasted using an empirical relationship between coal mining and gob gas production for each individual mine. Unlike earlier years when China's coal output was bureaucratically controlled, in today's Chinese economy the future production of coal is market driven and thus uncertain. Individual coal mining groups (such as YCG) no longer have bureaucratically assigned output targets, but instead produce and sell coal as the market allows.

We developed a Base Case scenario, which assumed that total coal production increased gradually by 50% over 1998-1999 levels by the year 2005, but remained flat thereafter (individual mine production is assumed to vary based on actual mining circumstances). In the Base Case scenario, total methane captured increases from 220,000 m^3/day in the base year to 360,000 m^3/day by 2005. Excess methane available for utilization is forecast to increase from 144,000 m^3/day currently to approximately 290,000 m^3/day by 2005 (**Figure 6**).

CMM reserves were computed using volumetrically calculated coal reserves and an empirical CMM-to-coal-mined ratio. For this analysis, detailed GIS mapping and analysis of coal reserves was performed using a database of several hundred corehole logs. **Figure 7** shows our detailed analysis of the Mine No. 5 area, where coal and CMM reserves were mapped in particular detail. The following steps were used to compute CMM reserves:

- A coal thickness isopach map of Seam 15 was prepared and the initial pre-mining volume of coal within the area was calculated (1,562 Mt using 1,600 kg/m^3 coal density).

- Total CMM gas resources (initial, pre-mining levels) were estimated to be 22,664 x 10^6 m^3 (800 Bcf), based on 20-year average 14.51 m^3/t CMM/coal mined ratio.

- Coal and gas resources within mined-out areas, non-YCG areas, and areas disturbed by karsts were removed from consideration.

- YCG has designated 57 Mt of proven developed coal reserves that will be mined at Mine No. 5 during the period 2000-2010. This coal, when mined, is estimated to provide 830 x 10^6 m^3 of proven developed CMM reserves.

- An additional 1,410 Mt of proven but undeveloped coal reserves remain, containing 20,460 x 10^6 m^3 (723 Bcf) of proven, undeveloped CMM reserves.

- Proven CMM reserves of 21,290 x 10^6 m^3 (830 + 20,460) are more than adequate to provide the 722 x 10^6 m^3 of CMM fuel forecasted to be produced over the life of the Mine No. 5 utilization project.

COALBED METHANE (CBM) POTENTIAL

In addition to coal mine methane (CMM) reserves, discussed above, coalbed methane (CBM) resources also exist at Yangquan within virgin coal seams located away from active mining areas. Using volumetric methods, YCG estimated in-place CBM resources down to a depth of 2,000 m to be approximately 645 x 10^9 m^3 (22.8 Tcf; Liu and Bai, 1997). This is a substantial resource that is comparable in size to that existing in several of the commercial U.S. CBM basins, such as the Uinta and Raton Basins. However, Yangquan's CBM resources are poorly characterized, remains largely untested, and thus is far less certain than its CMM potential. Proven CBM reserves have not yet been established.

Coal thickness and depth are favorable at Yangquan for CBM development, but other important reservoir parameters – such as gas content, permeability, and reservoir pressure – have not yet been rigorously measured. Local data, along with data from other parts of the Qinshui Basin, indicate the following reservoir properties:

- High absolute gas contents in the range of 10-20 m^3/t (dry, ash-free basis).

- Extremely high methane sorptive capacity of over 30 m^3/t at 800 m depth, based on sorption isotherms performed by TerraTek Inc. on Yangquan coal samples.

- Undersaturated conditions due to the extremely high sorptive capacity of anthracite (exacerbated by thermal cooling; direct de-gassing is unlikely to have occurred).

- Low permeability (<1 md) probably caused by poor coal cleating and moderately high horizontal tectonic stress.

A further significant geologic challenge facing CBM development at Yangquan are the numerous karsts (limestone dissolution collapse zones). Because none of the productive CBM basins in the U.S. have experienced karsting, it is difficult to evaluate the impact of karsts on CBM development at Yangquan. There is no evidence of degassing or enhanced gas recovery in or surrounding the karsts, either during corehole drilling or mining operations. Nonetheless, we anticipate that these karsts would seriously hinder the layout and effectiveness of CBM developments at Yangquan, because they are likely to interfere with normal dewatering of vertical CBM wells.

CBM production from vertical, fracced wells has not yet been attempted at Yangquan. However, CBM production testing has been initiated at the nearby Shouyang (north-central Qinshui Basin) and Jincheng (southeast Qinshui) areas. Shouyang and Jincheng share generally similar rank and depth settings and may offer insight into the CBM potential at Yangquan (though karsts are much less common at these analog sites). We conclude that CBM potential does exist at Yangquan, but the considerable exploration risks of undersaturation, low permeability, and karst disruption need to be evaluated by a multi-well production pilot before commercial development and utilization can be considered.

GAS UTILIZATION FOR POWER GENERATION

Currently, YCG uses approximately 30% of its recovered CMM to supply town gas for Yangquan City (72,000 households), local employee housing complexes (3,000 households), and for industrial use (petrochemical plant). Methane and air mixtures drained by mine vacuum stations is distributed through a network of pipelines to surface storage facilities. YCG typically injects air into the gas mixture as needed to maintain an average 45% methane concentration within the distribution system. Methane not used for town gas (the majority) is vented to the atmosphere.

Several alternative utilization strategies were evaluated for the 144,000 to 290,000 m^3/day CMM waste stream at Yangquan. This gas volume is far too small to justify constructing a new gas pipeline to Taiyuan. Conventional gas turbines were also rejected because of large fluctuations in gas volume and quality (largely attributed to disruptions in mining resulting from extensive karsting), not readily tolerated by turbines.

The most feasible utilization method at Yangquan is an array of small reciprocating internal combustion engines to generate electricity. This technique has been successfully applied at the Tower and Appin coal mines near Sydney, Australia, where 94 individual 1-MW gas engines have been on line almost continuously since 1996 (Lloyd, 1998). Energy Development Limited (Australia) designed and operates this facility and performed an evaluation for a similar but slightly smaller power system at Yangquan.

Under the Base Case gas supply scenario, the Yangquan CMM-Power facility would have the following characteristics:

- One power station adjacent to Mine 5 with initial capacity of 15 MW, scaling up to 20 MW capacity in the year 2005.

- A second power station adjacent to Xinjing Drainage Station, utilizing the combined outputs of the Mine 3 and Xinjing, with an initial capacity of about 20 MW, possibly rising to about 30 MW capacity in year 2005.

- Mines 1, 2, and 4 would provide CMM for the Yangquan City gas distribution system and not be available for power generation.

The projected financial performance of CMM power generation at Yangquan is favorable. No major economic or environmental obstacles were identified. In addition to power sales to the mines or the regional grid, the project could generate over over 30 Mt of CO_2 equivalent greenhouse gas (GHG) emissions reductions over its life, potentially worth $20 million (NPV) at a traded value of $2/t.

CONCLUSIONS

1) It is technically and economically feasible to generate approximately 30 to 40 MW of power at Yangquan, by combusting the current 144,000 m^3/day excess CMM stream within an array of small (1-MW) reciprocating engines. Power capacity could rise to as much as 50 MW by 2005.

2) Yangquan's coalbed methane (CBM) potential, using vertical fracced wells in the virgin unmined areas, remains highly uncertain. Initial data suggest low permeability and undersaturated reservoir conditions. Exploratory in-situ testing is needed.

3) CMM reserves are more than adequate to provide fuel for the power generation project over its lifetime. However, given that coal production directly impacts CMM production, the future pace of gas utilization should be guided by the outlook for coal production and marketing.

4) Horizontal borehole drilling technology using steerable downhole motors could be used to identify karsts in advance of mining, improving mining continuity and therefore CMM gas production and quality. This technology also could potentially save millions of dollars per year in lost coal production. Other potential enhancements include fused HDPE pipe for gas gathering and improved monitoring of gas quantity/quality.

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REFERENCES

Dong, Qiantai, 1995. Brief Discussion on the Exploration of Coalbed Methane in Yangquan-Yushe Area. *United Nations International Conference on Coal Bed Methane Development and Utilization, October 17-21, Beijing, China,* p. 87-96.

Ministry of Coal Industry, Handan Design Institute, 1998. Pre-Feasibility Study of Coalbed Methane Development and Utilization at Yangquan Coal Group Co., Ltd.

ICF Consulting, Advanced Resources International, Inc., REI Drilling, Inc., Energy Developments Limited, China Coalbed Methane Clearinghouse, 2000. Preparing a Coal Mine Methane

Demonstration Project, Yangquan Coal Mine, People's Republic of China: Final Report. Prepared for Asian Development Bank, Manila, Philippines, Contract No. COCS/99-151.

Liu, Zilong, 2000. The Methane Emission Reduce Method and Effect in Yangquan Mining Field. *Proceedings Second International Conference on Methane Mitigation, Novosibirsk, Russia, June 18-23*, p. 519-524.

Liu, Zilong and Bai Wenxian, 1997. Coalbed Methane Development, Utilization and Prospect in Yangquan Coal Mining Area. *China Coalbed Methane*, December, p. 15-20.

Lloyd, L.D., 1998. State-of-the-Art Power System Converts Methane to Energy at Australian Coal Mines. *Seminar and Roundtable on Coalbed Methane Development and Potential, The World Bank and U.S. Environmental Protection Agency, September 10, Washington, D.C.*

Murray, D.K., 1997. Coalbed Methane Production Potential of Anthracite Reservoirs. *International Coalbed Methane Symposium, May 12-16, University of Alabama, Tuscaloosa*, p. 397-407.