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Development of Coal Pillar In-Situ Model to Minimize Surface Subsidence during Underground Coal Gasification with Assessment of Synthetic Gas Yield

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Abstract

One of the major challenges in the commercialization of UCG is tackling environmental issues like surface subsidence. This paper presents a pillar configuration model of coal left in-situ during UCG operations and calculates its effect on the yield of synthetic gas whilst proposing a project for Khalaspir Coal Field, Bangladesh. With the energy crisis getting more difficult to manage the synthetic gas utilization in both the country's gas-driven power plants, as well as the fertilizer industries which support agriculture, UCG shows much promise for the country's economy.

Keywords: *Underground coal gasification; Coal pillar in-situ; Synthetic gas; Surface subsidence; UCG.*

1. Introduction

Conversion of coal to synthetic gas in-situ, followed by its extraction, will result in mass transfer to the surface, forming a cavity in the underground reactors. This volume removal may lead to substantial roof collapse of the cavity, and potentially subsidence above the reactor zones. Long-wall mining techniques show similar subsidence [1].

The magnitude and form of the subsidence is, however, a function of factors such as the depth and structural disposition of coal beds, the thickness, effective rock stiffness, yield strength, fracture density of the overburden, etc. [1].

In fact, evacuation of coal at depths greater than 200 m should have minimal surface expression, in part because the mechanical strength of many lithologies increases with depth within the UCG window. The distribution of deformation will also be wider [1-2].

1.1. Study area: Location and geology

The Khalaspir coalfield is situated at Pirganj upazilla of the Rangpur district, north- western Bangladesh (Figure 1). The surface is flat land with moderate vegetation, cultivated fields, and villages residing on artificially-raised grounds. The regional slope is north to south directions. The average elevation of the area is 25 m above the mean sea level [5].

Stratigraphically speaking, the Permian rock sequence containing coal lie directly on the Precambrian basement and are in turn, overlain by various rocks, as shown in Table 1. There are also a number of minor faults that cut the coal bearing sedimentary rock sequence within the coal basins [4].

The coal basin itself is an asymmetrical syncline formed by the influence of fault-fractured deformation, and its trends towards northwest-southeast. It developed during the breakup of Gondwanaland and the northward drift of the Indian plate. A set of faulted troughs or grabens had developed in the crystalline basement; the graben acted as the depositional basins for the Gondwana sedimentation in the late Carboniferous-Early Permian time in terrestrial fluvial to the lacustrine environment. Later as the Khalaspir basin developed in one of these grabens, the subsidence kept pace with the sedimentation, and the accumulation was aided by differential movements along the basin margin [5-6].

Table 1. The generalized stratigraphic succession of the Khalaspir coalfield [6]

Age	Group/Formation	Lithology	Maximum thickness(m)
Holocene	Alluvium	Gray sand and silty clay	4.26
Pleistocene	Madhupur clay residuum	Yellowish gray silty clay	6.10
Pliocene	Dupi Tila Formation	Gray to yellowish gray sandstone with uncommon mudstone	162.12
Miocene	Surma Group	Gray to dark gray mudstone, sandstone, and pebbly sand stone	184.14
Permian	Gondwana Group	Felspathic sandstone, carbonaceous sandstone, siltstone, mudstone, coal and conglomerate	814.93+
	Base not seen		

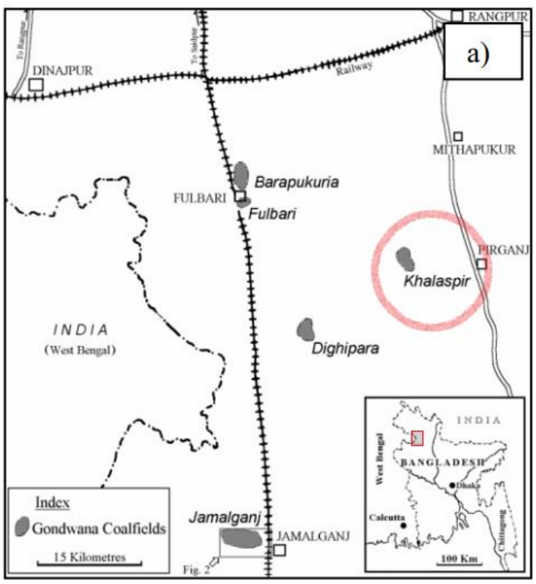


Figure 1. Location map of the study area (circled in red); Khalaspir coalfield is one of the five Gondwana Coalfields in north-western Bangladesh [8]

1.2. Prospect for UCG

Although a techno-economic feasibility study has been carried out at Khalaspir Coalfield, the data suggests that the coal is too deep to make conventional mining economical in the present time [4].

Table 2. summarizes the characteristics of Khalaspir Coalfield from the perspective of UCG viability. The 8 coal zones are composed of many coal seams inter-bedded with mainly arkosic sandstone, some mudstone, conglomerates, and siltstone [5]. In this context, each coal zone is assumed to be a single coal unit.

Table 2. The parameters of Khalaspir coal compared to the optimum requirement for UCG with ways it can be enhanced [2, 4,5]

	Optimum requirement	Khalaspir (existing conditions)
Appx. total coal reserves (mil.t)	Economic	685
Coal quality	Lignite through bituminous	Low sulphur, high volatile, bituminous
Depth of coal units (m)	100-1400	257-480
Appx. thickness of coal unit (m)	>3	~2
Appx. ash content	Less than 60	About 20%
Discontinuities	Minimal	Coal units 1, 3 and 5 are discontinous
Isolation from valued aquifers	Maximal	Coal units below water level*

**Gondwana Group aquifer in confined by the Surma Group aquitard (filtration coefficient = 0.02 m/day)* [4]

As can be seen from Table 2, the depth, reserve, lateral continuity, and coal quality all seem to be ideal for UCG. Noteworthy, the Gondwana Group is a confined aquifer separated by the Dupi Tila shallow aquifer by the Surma Group, which, due to its pumping test results [4] (filtration coefficient being 0.02 m/day and trasmissivity being 4.9 m^2/day) can be considered an aquitard.

1.3 Principles of UCG using the CRIP method

The most suitable UCG technology for Khalaspir coal, given its depth and thickness of coal units, is CRIP technology. This utilizes directional drilling techniques to insert injection and production wells into a predetermined coal unit Figure 2 [1]. This is integrated with the construction of a network of deviated injection wells horizontally into each coal unit (Figure 3). Inner coiled tubing is introduced into each deviated well to position the ignition point during the UCG process.

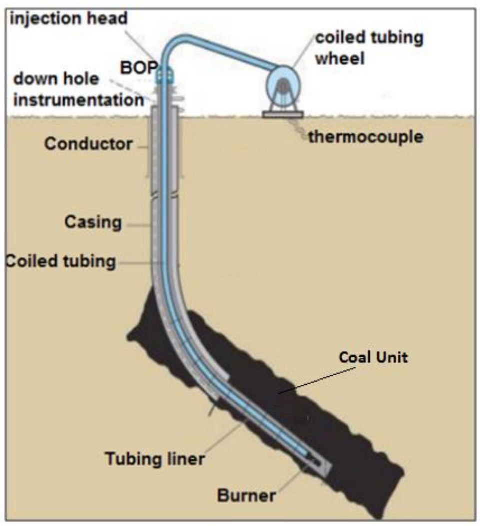


Figure 2. General components for directional drilling [1]

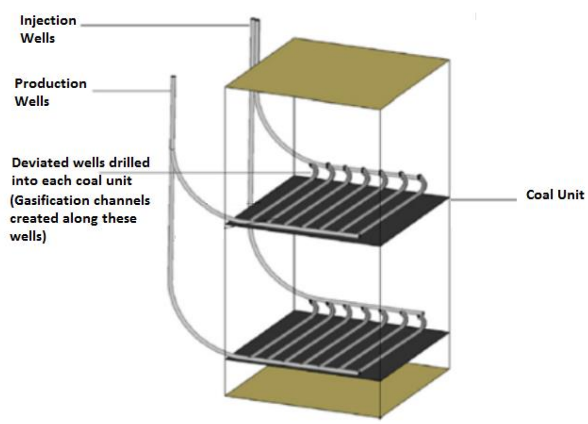


Figure 3. 3D view of well development scheme using CRIP [7]

A drill-head device then injects an oxidizing agent into the coal unit via the injection well, and thus the unit is ignited, causing subsequent conversion into a high-calorific synthetic gas, creating a burn zone. A retraction technology is used to maneuver the wells horizontally so that different burn zones can be created along the retraction pathway, which is then considered a gasification channel. CRIP also links the wells to enhance the in-situ permeability of the coal unit [2] during the extraction of the synthetic gas via the production wells.

2. Methodology

2.1. Well layout assumptions

Naketen *et al.* [7] developed a well layout (Figure 3) to optimize the UCG process, and this can be determined by considering the parameters given in Table 3. This well development should ensure that all other parameters considered in this paper are significant.

Table 3. Parameters of well development scheme for Khalaspir as compared with the well layout proposed by Nakaten *et al.* [7] based on former UCG trails

	Nakaten *et al.* [6]	Khalaspir coal
b:h	2:1	21.8 :10*
Horizontal well spacing (m)	16 to 48	42 (assumed, b+w*)
Number of coal units	4	8 [4]
Number of injection wells per coal unit	2	2 (assumed)
Number of production wells per coal unit	2	2 (assumed)

* *details in Table 4*

2.2. Principles of pillar configuration

The proposed pillar configuration consists of a cuboid coal unit (area of which has been determined as described in Figure 5) along whose length the CRIP method will gasify coal to form synthetic gas. It is assumed that the gasification is done along the east-west direction and that each of the 8 available coal zones, although containing interbeds of various rocks, is one coal unit.

The retraction technology used to maneuver the injection wells horizontally creates burn zones along each gasification channel, which, when depleted of coal and synthetic gas, leaves behind a void "room". Given that well layout is optimal (Table 3) "rib pillars" of coal maybe left in between as postulated in Figure 4.

2.3. Formulae

2.3.1. Area of in-situ coal pillars

Figure 4 shows the pillar configuration spatial view, which is assumed to be consistent throughout the 8 coal units. Equation (1) can be used to determine the total area of in-situ coal pillars to be left in place.

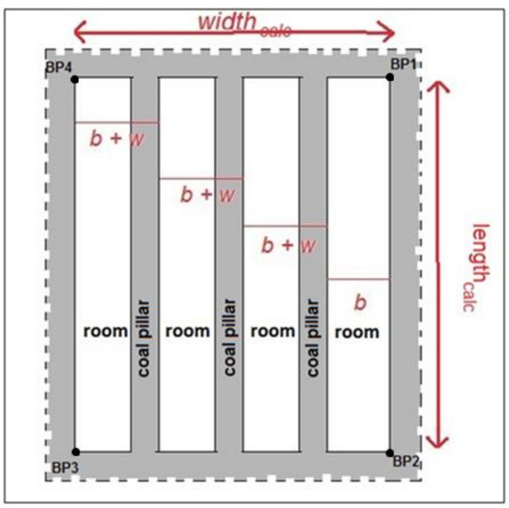


Figure 4. The room and rib pillar configuration general plan view if n=3 (note that the dotted lines represent lateral continuity of coal beyond the area of study). The BP (indicated by black dots) are exactly the same as those identified in Figure 5, when gasification is carried out in the east-west direction

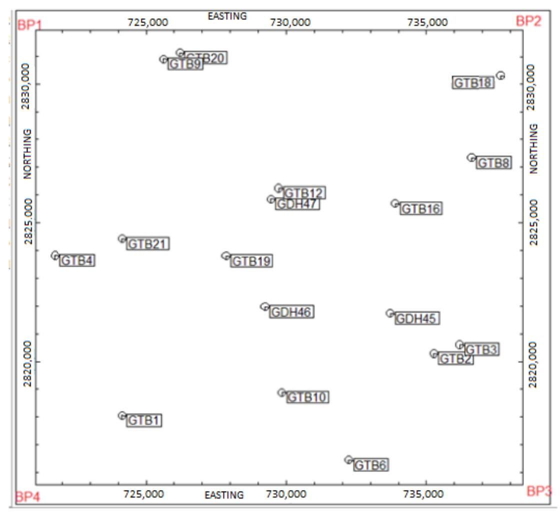


Figure 5. Reproduced borehole location map using data from Appendix A, represented as a screen shot of theRockworks15 workspace. BP were approximated in order to measure *Length_{calc}* and *Width_{calc}* values

$$Area_{pillar} = w.Lenght_{calc}.\frac{Width_{calc}-b}{w+b} \quad (1)$$

The value for pillar width (w) can be determined by the derivative Equation (2) [8].

$$w > (2.4.92.10^{-3}.hH) + 2h \quad (2)$$

where coal depth (H) is approximated to be 685 m from Table 2 (comparative to 1411 to 1800 m as mentioned in Nakaten *et al.* [7]) and coal unit thickness (h) is approximated to be 10 m from Appendix B (comparative to 4 to 12 m as mentioned in Nakaten *et al.* [7]). It is assumed this value remains the same for all 8 coal units.

Noteworthy, the pillar width will depend on pillar capacity, which in turn depends upon various engineering factors, is not in the scope of this paper. All other required parameters are given in Table 4 and Appendix B.

Table 4. Parameters to determine the area of pillar left in-situ

b	Lenght of single room (m)	21.3	Measured (Figure 6); comparative to 8 to 24 m [7]
w	Width of single pillar (m)	20	Assumed based on Equation (2)
$Length_{calc}$	Length of coal unit (m)	3133.7	Measured*
$Width_{calc}$	Width of coal unit (m)	2406.88	Measured*

Measurement done using Rockworks software after construction of the borehole location map (shown in Figure 5); It is assumed this remains constant for each coal unit gasified

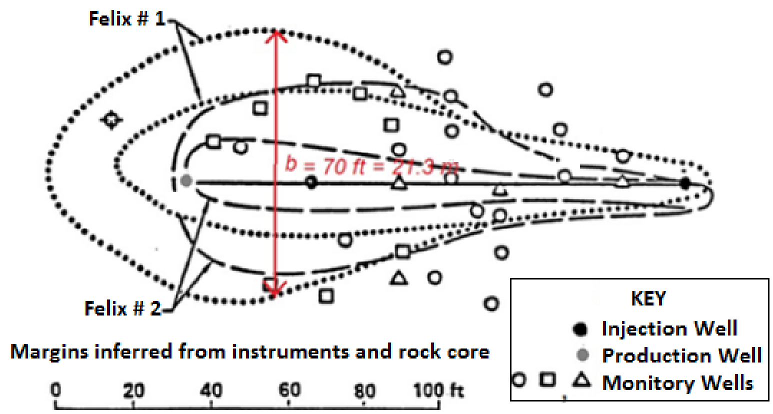


Figure 6. Possible gas cavity configuration plan view and the measurement of 'b', derived from the Felix 1 and 2 experiments [9]

2.3.2. Volume of synthetic gas produced

Naketen et al. [7] also considered synthesis gas composition as an internal project assumption based on former UCG trails. Given the parameter from Table 5 is applicable, the amount of synthetic gas per ton of coal amounts 2431.667 m3/t using Equation (3).

Table 5. Parameters for determination of synthetic gas amount produced per tonne of gasified coal and reserve of coal to be gasified in tonnes

CV_{syn}	Synthetic gas CV (MJ/m^3)	7.5*	Nakaten *et al.* [7]
CV_{coal}	Approximate coal calorific value (MJ/kg)	29.18**	Hofgen International Ltd., [4]
n_{UCtt}	UCG gasification efficiency, (%)	62.5	Naketen *et al.* [7]
q	Relative density of coal	1.23	Hofgen International Limited, 2006 [4]
A_{theory}	Total in-situ coal spatial area (km^2)	7.54244	Calculated and comparative with Hofgen International Limited, 2006 [4]
A_{pillar}	Total spatial area of coal pillars (km^2)	3.62019	Calculated

**Assuming the synthesis gas has a composition of H_2: CH_4: CO = 21:11:10 and oxidant O_2:N_2 ratio of 3:2*
***Average derived from multiple boreholes*

$$X_{syn}^{coal} = \frac{CV_{coal} - \eta_{UCG}}{CV_{syn}} \quad (3)$$

Meanwhile, Hofgen International Limited [4] proposed Equation (4) to calculate the reserve of coal. It is assumed that UCG operations should be able to gasify this entire reserve, given the parameters from Table 5 and Appendix B are applicable.

$$Reserve = H.S.q \quad (4)$$

For UCG without pillars, the value for the spatial area of coal (S) amounts to 7.54244 km^2 as calculated using Equation (5) whereas in the case of pillar development it amounts to 3.92225 km^2 calculated using Equation (6).

$$S = A_{theory} \quad (5) \qquad S = A_{theory} - A_{pillar} \quad (6)$$

Equation (7) thus gives the approximate volume of synthetic gas (V).

$$V = X_{syn}^{coal}.Reserve \quad (7)$$

3. Results, discussion, and recommendations

Given that UCG operations are carried out using the CRIP method at Khalaspir with the calculated reserve of 424.803 mil ton spread across an area of 7.54244 km2, and UCG efficiency is 62.5% the amount of synthetic gas yield is predicted as 36.47936 Tcf. If rib pillars of total area 3.62019 km^2 are left in place during CRIP operations, the reserve becomes 220.9078 mil ton, and this amounts to 18.97014 Tcf synthetic gas, which still has high economic value for utilization in Bangladesh.

The formal pillar designs, involving engineering calculations, proper safety factor calculations, and dimension determination, need to be integrated with economics statistics and project-derived data.

This is to be coupled with UCG project development, which maybe classified into three main steps.

Firstly, a preliminary period of proactive trial runs:

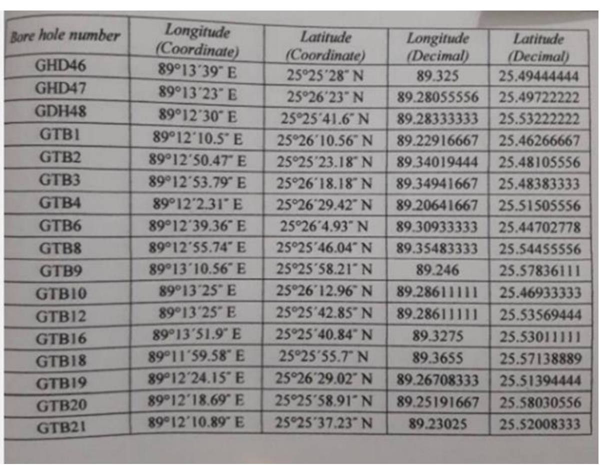
1. Extensive geophysical survey, sampling and lab examination including GIS and remote sensing for site characterization
2. On-site experiments of in-situ responses via monitoring and measurement (thermocouple, spectrometry, real time mapping, etc.)
3. Viability study using empirical calculations based on primary data
4. Water quality assessments and hydrogeological experiments
5. Cavity growth modeling and temperature variation studies
6. Plan of the time periods for daily gasification schemes, coal depletion rate for each zone and decommissioning time spans

Secondly, once a database has been established through trial runs, the necessary procedure must be drawn up and implementation plans made. The decisions must lie on the head geologists and engineers at the site and must be based on the experimental results.

And finally, the decommissioning procedure must ensure an environmental restoration of the site and prevention of long term or future contamination incidents. Only then will UCG be truly ready for utilization

Appendix A

Table 6. Latitude/longitude coordinate database acquired from Hosaf International Limited [3]



Bore hole number	Longitude (Coordinate)	Latitude (Coordinate)	Longitude (Decimal)	Latitude (Decimal)
GHD46	89°13′39″ E	25°25′28″ N	89.325	25.49444444
GHD47	89°13′23″ E	25°26′23″ N	89.28055556	25.49722222
GDH48	89°12′30″ E	25°25′41.6″ N	89.28333333	25.53222222
GTB1	89°12′10.5″ E	25°26′10.56″ N	89.22916667	25.46266667
GTB2	89°12′50.47″ E	25°25′23.18″ N	89.34019444	25.48105556
GTB3	89°12′53.79″ E	25°26′18.18″ N	89.34941667	25.48383333
GTB4	89°12′2.31″ E	25°26′29.42″ N	89.20641667	25.51505556
GTB6	89°12′39.36″ E	25°26′4.93″ N	89.30933333	25.44702778
GTB8	89°12′55.74″ E	25°25′46.04″ N	89.35483333	25.54455556
GTB9	89°13′10.56″ E	25°25′58.21″ N	89.246	25.57836111
GTB10	89°13′25″ E	25°26′12.96″ N	89.28611111	25.46933333
GTB12	89°13′25″ E	25°25′42.85″ N	89.28611111	25.53569444
GTB16	89°13′51.9″ E	25°25′40.84″ N	89.3275	25.53011111
GTB18	89°11′59.58″ E	25°25′55.7″ N	89.3655	25.57138889
GTB19	89°12′24.15″ E	25°26′29.02″ N	89.26708333	25.51394444
GTB20	89°12′18.69″ E	25°25′58.91″ N	89.25191667	25.58030556
GTB21	89°12′10.89″ E	25°25′37.23″ N	89.23025	25.52008333

Appendix B

Table 7. Average thickness of coal units [4]

Coal unit	Average thickness (m)*
1	9.80
2	10.16
3	2.01
4	11.12
5	2.97
6	6.25
7	2.08
8	1.39

** Average derived from multiple boreholes*

Nomenclature

Symbol	*Denotes*	*Units*
A	*Spatial area of coal reserve*	*km^2*
b	*Length of single room between two adjacent rib pillars*	*m*
BP	*Base point*	
CRIP	*Control reduction injection point*	
CV_{coal}	*Calorific value of Khalaspir coal*	*MJ/kg*

Symbol	*Denotes*	*Units*
CV_{syn}	*Calorific value of synthetic gas*	MJ/m^3
EIA	*Environmental impact assessment*	
h	*Coal unit thickness*	*m*
H	*Coal depth*	*m*
$Length_{calc}$	*Length of coal unit measured between base points*	*m*
n	*Number of coal pillars*	
n_{UCG}	*Underground coal gasification efficiency*	
q	*Relative density of coal*	
R	*Calculated reserve of coal in-situ*	*mil ton*
S	*Spatial area of coal unit*	km^2
V	*Volume of synthetic gas yield*	*Tcf*
w	*Width of single pillar*	*m*
$Width_{calc}$	*Width of coal unit measured between base points*	*m*
X_{coal}^{syn}	*Volume of synthetic gas per tonne gasified*	m^3/ton
UCG	*Underground coal gasification*	

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References

[1] Burton E, Friedmann J, Upadhye R. U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48., Best Practices in Underground Coal Gasification (2006).

[2] Brown KM. In Situ Coal Gasification: An Emerging Technology, J. American Society of Mining and Reclamation, 2012; 1(1): 103-122.

[3] Kempka T, Plötz ML, Hamann J, Deowan SA, Azzam R. Carbon dioxide utilisation for carbamide production by application of the coupled UCG-urea process. Energy Procedia 2010; 4:2200-2205.

[4] Hofgen International Limited, Shangdong-Ludi Xinwen Mining Group, China, Jinan, Techno-economic Feasibility Study of Khalaspir Coal Mine Project (2006).

[5] Imam B. Energy Resources of Bangladesh, 2nd Edition, University Grants Commission of Bangladesh, 2013.

[6] Islam MN. Geology of the Khalaspir Coal Basin, Records of the Geological Society of Bangladesh. 1992; Vol. 6.

[7] Nakaten N, Schlüter R, Azzam R, Kempka T. Development of a Techno-economic Model for Dynamic Calculation of Cost of Electricity, Energy demand and CO_2 Emissions of an Integrated UCG–CCS process. Energy, 2014; 66: 779–779.

[8] Yu Y, Chen S-E, Deng Ka-Zh, Wang P, Fan H-D. Subsidence Mechanism and Stability Assessment Methods for Partial Extraction Mines for Sustainable Development of Mining Cities-A Review. Sustainability 2018; 10: 113.

[9] Shrisat VA. Modelling of Cavity Growth in Underground Coal Gasification. Master of Sciences Thesis, Texas Technical University, May 1989.

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