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Investigation of the feasibility of underground coal gasification in North Dakota, United States

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ABSTRACT

Underground coal gasification (UCG) is a promising technology that has the potential to recover currently-unmineable coal resources. The technical feasibility and economic success of a UCG project is highly site specific. Any risks associated with UCG, such as subsidence, groundwater contamination, and syngas quality, should be sufficiently evaluated through a feasibility study. This paper presents a four-year UCG feasibility study utilizing lignite seams in North Dakota, United States. Four wells were drilled through the lignite seams at a selected site, and lignite and strata cores were recovered. A geological model of the formation was built, coal and rock properties were analyzed, and field hydrogeological tests and laboratory gasification tests were performed. This work provided valuable insights in rock mechanics, hydrogeology, and coal properties. The study results show that the selected site is suitable for development of a UCG plant because there are minimal induced subsidence risks, there is hydrological isolation from major aquifers and the coal produces desirable syngas quality for liquid fuel production. Methodologies developed in this study will benefit the design, optimization and management of the UCG process.

1. Introduction and motivation

Coal is one of the most important energy resources in the world and will remain so for the next several decades. However, due to the limitations of current coal mining technologies, 85% of the world coal resources is unmineable by conventional method [1]. Coal mining leads to safety concerns, subsidence, groundwater contamination, surface pollution, and greenhouse gas emissions. Coal combustion releases pollutants into the environment, including sulfur oxides (SO_x), nitrogen oxides (NO_x), mercury and particulate matter. Solid waste disposal requires significant land use. In addition, the efficiency of most pulverized coal (PC) power plants is less than 40%. Therefore, there is significant potential to improve the efficiency of coal extraction and utilization.

Underground coal gasification (UCG) is a promising clean coal technology that converts coal *in situ* into a gaseous product, commonly known as synthesis gas or syngas, through the same chemical reactions that occur in the surface gasifiers [2]. The syngas primarily consists of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and methane (CH_4). The UCG process involves drilling two wells into the coal seam, with one serving as an oxidant injection well and the other as the production well [2]. The UCG process can utilize coal seams that are too deep or too thin to be economically mined by conventional methods, thereby significantly increasing global recoverable coal reserves. Linc Energy [1] estimated that there are over 5 million petajoules (PJ) of recoverable UCG syngas in the United States, over 2.3 million PJ in Australia, 1.9 million PJ in India, and over 2.2 million PJ in China. By using UCG technology, the recoverable reserves could be increased by at least three to four times. Thus, 1.45 trillion tons of currently-unmineable coal in U.S. could be recovered by UCG [1]

UCG offers several major advantages over surface mining and gasification of coal that make it safer, cleaner, and more economical, including the following [2]:

- No laborers work underground, leading to improved safety.
- All coal is gasified in place, which reduces the surface footprint of the UCG plant by eliminating the need for a surface gasifier, thereby eliminating associated dust emissions and coal transportation, handling, and storage costs.

Abbreviations: CH_4, methane; CO, carbon monoxide; CO_2, carbon dioxide; CRIP, controlled retracting injection point; H_2, hydrogen; PC, pulverized coal; PJ, petajoule; MW h, megawatt hour; NO_x, nitrogen oxides; RMR, Rock Mass Rating; RQD, rock quality designation; SO_x, sulfur oxides; UCG, underground coal gasification.

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- All syngas generated rises to the surface at a pressure near the hydrostatic pressure of the UCG cavity, which generally facilitates its conversion to other products and aids many CO_2 capture technologies [3].
- Direct use of water and feedstock available *in situ* [4].

Syngas is a versatile product that may be upgraded to various chemicals and clean fuels or used for power generation [5]. Syngas derived from coal gasification and natural gas reforming forms the backbone of modern chemical industries [6]. Today, coal gasification faces stiff economic competition due to low natural gas prices [7]. It is estimated that UCG can cut coal gasification costs by approximately 30–40% [8]. If the produced syngas is used to generate electricity with CO_2 capture, the cost of electricity may be as low as $24 per megawatt hour (MW h), compared to $77 for integrated gasification combined cycle (IGCC) plants and $52 for supercritical PC power plants [9].

UCG technology has been developed for several decades [10]; however, there are only a few commercial-scale UCG operations, such as the Yerostigaz plant in Uzbekistan and the Majuba plant in South Africa. Environmental concerns such as groundwater pollution and stability of the cavity (subsidence due to excavation) are major obstacles to popularizing UCG [11]. This paper presents a feasibility study of UCG in North Dakota, United States. The feasibility study consists of three major tasks: (a) a coal hydrogeology study, (b) a geomechanical study, and (c) gasification tests. In the following sections, the approach and methodology are first introduced, then the three major tasks are described. Based on the results of each task, the feasibility of building a UCG plant is discussed and conclusions are derived.

2. Approach and methodology

The Fort Union formation is primarily a nonmarine geologic unit of Paleocene age in the United States that extends from the Powder River basin in Wyoming to the Williston basin in eastern Montana and western North Dakota. The North Dakota portion of the Fort Union formation hosts significant lignite resources. Most of these lignite resources are contained in the Harmon and Hansen zones in the southwestern part of the basin and in the Hagel and Beulah-Zap coal zones in the east-central part [12]. Lignite resources in North Dakota have been investigated in detail by the North Dakota Geological Survey and the U.S. Geological Survey. Reports and maps provide the depth, thickness, lateral structure of the lignite beds, and locations of economically mineable reserves [12]. The literature can be conveniently used in primary UCG site selection with regards to depth and thickness. Studies have indicated that there is a huge lignite resource in North Dakota – about 1.27 trillion tons. However, the economically surface mineable reserve is about 25 billion tons, or only 2% of the entire resource [13]. Because of the high moisture content, lignite is lower in heating value than other coals [14]. Lignite-fed combustors usually have lower efficiency, but the high moisture content and high reactivity [15] make lignite a competitive feedstock for gasification.

The purpose of this study is to investigate the feasibility of applying UCG technology to recover lignite resources in the Harmon bed in North Dakota. The ultimate goal is to establish a commercial-scale UCG plant to feed production of higher-rank liquid fuel. In the proposed concept of a UCG plant at commercial scale, coals are gasified in multiple underground gasification panels as shown in Fig. 1 [16]. These multiple gasification panels (cavities) are arrayed as a set of parallel tunnels in the coal seam. During the operation of a UCG plant, these gasification panels will be developed sequentially to ensure continuous syngas production. Each gasification cavity can either have its own injection and production wells or share common wells. The gas transmission pipelines and other maintenance facilities on the surface are shared by the cavities [17]. The size of these gasification cavities, spacing, *in situ* stresses, and properties of the coal-bearing strata together determine the stability of the altered formation structure as well as how much coal can be recovered by the plant [18].

UCG is a complex, coupled geomechanical, hydrogeological, thermal and geochemical process with three major challenges:

- Groundwater use and protection.
- Structural stability, including induced fractures and subsidence.
- Desired syngas quality and composition.

During the UCG process, the reaction temperature can be as high as 1000 °C [19]. Fractures may be generated by these temperatures, reducing the strength of the rock mass and providing transport paths for UCG-introduced contaminants. As the UCG design procedure is highly site specific, a successful UCG project depends on good understanding of the natural properties and *in situ* geological/hydrogeological conditions of the target coal seam and its overburden and underlying rocks. Experimental and modeling work are needed to understand the coupling mechanisms. Fig. 2 displays the interaction matrix of different factors that impact the UCG process and environmental concerns. The two numbers on the up left of each box represent the row and column in the matrix. The red[1] boxes in the diagonal line are primary variables which interact with each other through interaction terms in dashed boxes. Table 1 lists important parameters of the target formation that should be investigated during site screening and their functions in process design and operation control.

The Harmon lignite bed in North Dakota may coincide with the lower Tertiary aquifer, consisting of sandstone beds interbedded with shale, mudstone, siltstone, lignite, and limestone. It is important to know the location of these aquifers with respect to the lignite bed and their isolation capability [20], as these factors may affect environmental risks and syngas quality. The feasibility study included selecting a potential UCG site in western North Dakota and examining the lignite properties, hydrogeology, and geomechanical properties of the strata at the potential site. This study consists of three major tasks:

(1) Hydrogeology study: aquifer mapping, measurement of aquifer transmissivity, and assessment of background ground-water quality.
(2) Geomechanical study: geomechanical testing of rock cores, modeling of induced stress and displacements, and assessment of structural stability.
(3) Gasification test: coal property analysis and laboratory gasification tests.

With the known general geology survey literature [12] and oil and gas well logs [13], a deep, thick, and continuous Harmon bed was identified in western North Dakota [20]. Considering available infrastructure and land, a test site was selected. At the selected location, the Harmon bed is level and approximately 26 ft (8 m) thick, with its top at a depth of 980 ft (300 m). There is another upper coal seam which is 14 ft (4 m) thick and about 286 ft (87 m) above the Harmon coal seam. Four wells were drilled through the Harmon coal seam and upper coal seam in this study. Cores of lignite and associated strata were recovered for laboratory

[1] For interpretation of color in Figs. 2 and 5, the reader is referred to the web version of this article.