KBR'S TRANSPORT GASIFIER (TRIG™) – AN ADVANCED GASIFICATION TECHNOLOGY FOR SNG PRODUCTION FROM LOW-RANK COALS

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Introduction

Coal gasification coupled with CO_2 management offers an environmentally conscious way of providing a secure energy source. The recent surge in natural gas prices and projected shortages in the long-term availability of LNG are making coal-derived natural gas or substitute natural gas (SNG) an attractive option to provide reliable supply of gas at a fixed price. A major advantage of SNG is its production can be located near the coal reserves and supplied to end-users by tying into existing natural gas pipeline grid system. This allows tapping the vast coal reserves in stranded areas that would otherwise be uneconomic to develop.

The KBR Transport Gasifier, also known as TRIG, is an advanced coal gasification technology that provides clean, particulate-free syngas for a wide variety of coal-based chemicals and fuels applications. In this paper, the new KBR TRIG Coal-to-SNG process is described, in which the TRIG gasifier is integrated with a conventional methanation scheme, producing about 150 million standard cubic feet per day (mscfd) of SNG from two representative low-rank coals that are abundant in the U.S.A. and worldwide. The paper further discusses the process scheme development, integration and optimization elements that build on the unique attributes of the TRIG gasification system to produce an efficient and technically robust SNG plant design.

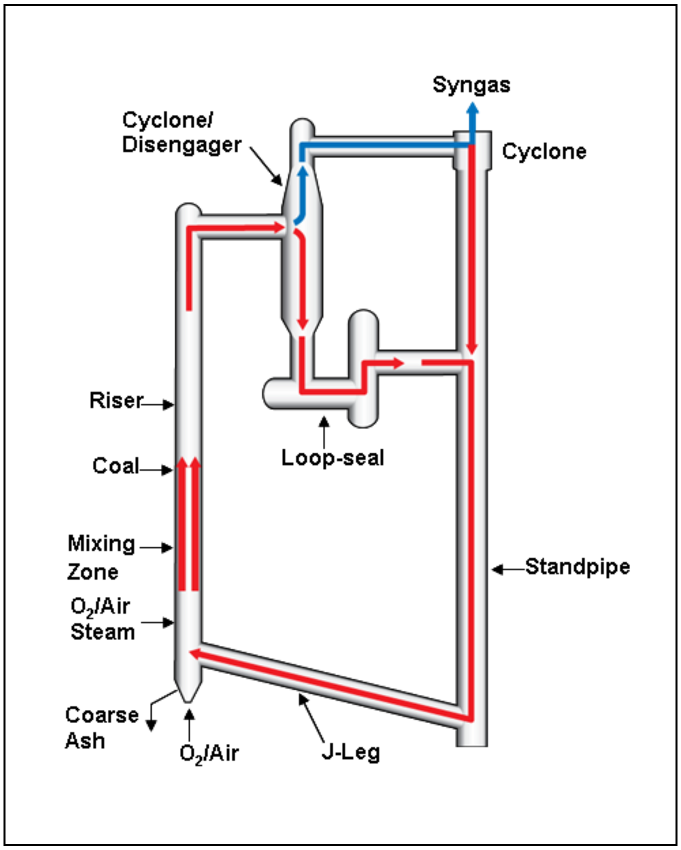
Overview of TRIG Gasification Technology

The TRIG gasifier is an advanced pressurized circulating fluidized bed gasifier that operates at moderate temperatures (1,500 – 1,950^{o}F). The mechanical design and operation of the gasifier are based on KBR's fluidized catalytic cracking (FCC) technology, which has more than 60 years of commercial operating experience. As shown in Figure 1, the TRIG gasifier is simple in design and has no internals, expansion joints, valves or other moving parts. It is designed to operate using air, pure oxygen or enriched air/oxygen mixtures as oxidant. While the air-blown mode is ideally suited for power generation applications, the oxygen-blown mode and enriched air-blown mode provide syngas for chemicals and fuels synthesis.

The TRIG gasifier features a dry feed injection system and is a non-slagging gasifier. In particular, the gasifier's continuous dry ash handling system eliminates the technical difficulties associated with slag handling and removal faced by comparable slagging gasifiers. Slagging gasifiers generally require frequent refractory change out due to the erosive nature of the high temperature fluidic slag. This can escalate maintenance costs while reducing gasifier availability. In contrast, lower operating temperatures in the TRIG gasifier allow installation of conventional, cost-effective alumina-silica type refractory that has a significantly longer life.

Low-rank coals, which account for roughly half of the worldwide coal assets play to the strength of the TRIG gasifier. These coals typically have high ash and/or moisture content. The moderate temperatures employed in the TRIG gasifier combined with the dry feed and dry ash handling systems greatly improves the gasification cold gas efficiencies and reduces the specific oxygen demand. The net impact is reduced cost and auxiliary power consumption associated with the plant's air separation unit (ASU). In addition, the operating temperature range of the gasifier is sufficient to achieve high carbon conversions while mitigating formation of tars and oils.

Figure 1: Schematic of the KBR Transport Gasifier (TRIG)



TRIG Gasifier Operation

The TRIG gasifier (Figure 1) consists of a mixing zone, riser, disengager/cyclones, loop-seal, standpipe, and a J-leg. Steam and oxidant (O_2/Air) are routed separately and mixed together in the mixing zone along with the circulating solids returning from the J-Leg. The mixing zone of the gasifier can also be referred to as a 'combustion zone', where partial oxidation reactions occur between the unreacted carbon (char) in the solids returning from the J-leg and the injected oxidant (O_2/air). Coal or other carbonaceous feedstock is fed slightly above the mixing zone in a reducing atmosphere to avoid premature combustion with the oxidant. The endothermic coal gasification reactions take place primarily in the riser above the coal feed injection point (gasification zone) by utilizing the heat generated from char combustion in the mixing zone. The circulating solids in the system act as heat carriers that seamlessly transfer heat generated from the bottom (combustion) zone to the gasification zone. This staging effect is another salient feature of the gasifier in that fresh coal is primarily utilized for gasification, while the unreacted carbon in the returning solids is sourced for heat generation.

The TRIG gasifier operates at higher superficial gas velocities, riser densities and solids circulation rates than most conventional circulating fluidized bed reactors. These unique attributes result in higher syngas throughput, enhanced mixing, and high heat and mass transfer rates. Within the riser, the gas superficial velocities are appropriately maintained such that sufficient residence time is available to maximize both carbon conversion and tar cracking. The syngas produced along with the circulating solids, move up the riser through a crossover line and enter a primary cyclone (or disengager) for bulk separation of solids from the gas. The primary cyclone removes majority of the particles in the gas-solids mixture by gravity and/or centrifugal forces. The gas and the remaining finer solids then move to a secondary cyclone that captures most of the fine particulates not collected by the primary cyclone. The syngas then leaves the unit and passes through a syngas cooler for high-grade heat recovery followed by a particulate control device. The solids collected by the primary and secondary cyclones are recycled back to the gasifier-mixing zone via an aerated loop-seal, standpipe, and J-leg arrangement. Solids inventory is maintained by withdrawing a purge of bed material (coarse ash).

TRIG Demonstration Unit (PSDF), Wilsonville, AL

The adaptation of TRIG technology for coal-based energy has been tested and proven effective through operations at the Power Systems Development Facility (PSDF) in Wilsonville, Alabama. The TRIG gasifier at PSDF is an engineering-scale, 50 tons/day demonstration unit of the technology (see Figure 2) and has been in operation since the mid-1990s. The PSDF was co-developed by KBR and Southern Company, in association with the U.S. Department of Energy (DOE).

Figure 2: TRIG Gasifier Demonstration Unit at the PSDF, Wilsonville, AL

The demonstration unit at the PSDF has been successfully operated on a wide range of coals including bituminous, sub-bituminous, and various lignites. The unit has logged thousands of hours in both air-blown and oxygen-blown configurations. Table 1 provides a sample listing of the coals successfully tested at PSDF and their characteristics. As previously mentioned, the TRIG gasifier prefers low-rank or reactive coals such as, Powder River Basin (PRB) coal and lignites – these coals are ideally suited for the short contact times available in the riser section of the gasifier where carbon conversions of 96 – 99% have been consistently achieved. The TRIG unit has also successfully tested a number of bituminous coals. While these coals can be comfortably processed at the higher end of the gasifier's operating temperature envelope, carbon conversions are generally lower (87 – 93%). When processing bituminous coals or other high rank coals, there is usually a trade-off between the slightly lower carbon conversion vs. the benefits of lower energy consumption and higher efficiencies offered by the TRIG gasifier.

Other characteristics such as moisture and total ash content of the coal are generally non-issues for processing in the TRIG unit but the sodium content in the ash and the initial ash fusion temperatures are critical. The TRIG gasifier prefers low-sodium coals and is generally operated at 200^{o}F below the ash fusion temperature to avoid particle sintering and agglomeration.

Table 1: Typical Coals tested at TRIG Demonstration Unit (PSDF, Wilsonville, AL)

Coal	PRB	Falkirk Lignite	Freedom Lignite	Mississippi Lignite	Utah Bituminous	Illinois Bituminous
Moisture, wt%	15.24	27.95	21.91	28.08	6.85	12.98
Carbon, wt%	59.28	42.53	48.76	39.14	66.36	62.42
Hydrogen, wt%	3.73	2.73	2.97	5.20	4.34	4.03
Nitrogen, wt%	0.76	0.69	0.69	0.77	1.08	1.41
Oxygen, wt%	15.10	12.04	15.06	37.12	10.71	6.27
Sulfur, wt%	0.26	0.76	0.78	0.94	0.38	0.86
Ash, wt%	5.61	13.07	9.83	16.84	10.29	12.03
Volatiles, wt%	35.70	29.67	30.87	29.38	35.61	27.52
Fixed Carbon, wt%	43.44	29.08	37.38	25.60	47.25	47.47
HHV, Btu/lb	9,887	6,973	8,068	6,616	11,246	10,932
HHV, kcal/kg	5,493	3,874	4,482	3,676	6,248	6,073
Initial Ash Fusion Temperature, (Reducing), °F	2138 - 2143	2046	2066 - 2286	2196 - 2292	2080	2254 - 2354

Status of TRIG Gasification Technology

The operational experience gained at the demonstration unit at PSDF is the basis for a planned full-scale, commercial implementation of TRIG technology to produce 600 MWe power in Mississippi, U.S.A. This Integrated Gasification Combined Cycle (IGCC) power project is being developed by Mississippi Power. Front-End Engineering Design (FEED) work on the project has been completed and additional studies are currently being investigated. The project is based on gasification of Mississippi lignite and will employ two KBR TRIG gasifiers operating in air-blown mode. Through years of operating experience at PSDF and from proprietary FCC technology, optimized commercial-scale TRIG gasifier designs are available today for both air-blown power applications as well as oxygen-blown chemicals and fuels applications.

SNG Production from Low-rank Coals via TRIG Technology

As previously mentioned, the KBR TRIG gasifier offers several advantages in processing low-rank coals. The following sections of the paper examine the applicability of the TRIG technology to one of the rapidly emerging gasification-based applications in the U.S. market – production of SNG.

KBR has performed pre-feasibility studies evaluating the technical and economic feasibility of commercially implementing coal-to-SNG at grass roots facilities in the western U.S.A. The proposed SNG facility employs KBR's TRIG gasification technology and utilizes either Powder River Basin (PRB) coal from Wyoming, or low-sodium North Dakota lignite as feedstock.

The technical solutions developed included an optimized syngas-processing scheme to maximize SNG production, while reducing the make-up water usage and overall plant energy consumption. An integrated heat recovery scheme was selected wherein the high-pressure steam produced in the methanation section is superheated in the gasification section. With this scheme, high thermodynamic efficiencies in the steam and power generation systems can be achieved, while reducing auxiliary firing requirements and its associated emissions. Details of these solutions and their benefits are described in the following sections.

Description of the new KBR TRIG Coal-to-SNG Process

In the new KBR coal-to-SNG process, the proprietary TRIG gasification technology is integrated with a conventional methanation scheme to make pipeline-quality SNG from two different coals – Wyoming PRB and North Dakota lignite. For this paper, the SNG plant is assumed a mine-mouth facility with a nominal SNG capacity of about 150 mscfd. This capacity requires syngas from three TRIG gasifiers operating in oxygen-blown mode. The size and design of the TRIG gasifier have been kept the same as KBR's standard commercial offering. For the PRB case, there is excess syngas capacity, which is used as fuel gas to achieve power balance. The entire SNG facility was assumed to be air-cooled wherever practical to minimize water usage – deemed an important requirement in the locations considered.

Figure 3 depicts a simplified block flow diagram illustrating the connectivity between major process units. A cluster of three TRIG gasifiers supply the necessary syngas feed with the appropriate H_2:CO ratio to the methanation unit. The main process units include gasification, shift, COS hydrolysis, ammonia scrubbing, mercury removal, acid gas removal, sulfur removal, CO_2 compression, methanation, and SNG drying and compression.

The as received composition for the two coals considered in the study are shown in Table 2. As shown in the table, the PRB coal has a relatively low heating value and sulfur content as compared to other bituminous or anthracite coals. PRB coal is the single largest mined coal in the U.S. and has been routinely used for baseline tests in the demonstration TRIG gasifier. The lignite assumed for this study is representative of the coal from Freedom Mine, ND. It has slightly higher moisture and about twice the sulfur and ash content of the PRB coal, which results in a reduced higher heating value (HHV). Both coals are ideal feedstocks that gasify well in the TRIG unit yielding high carbon conversions.

Figure 3: Block Flow Diagram of KBR TRIG Coal-to-SNG Process

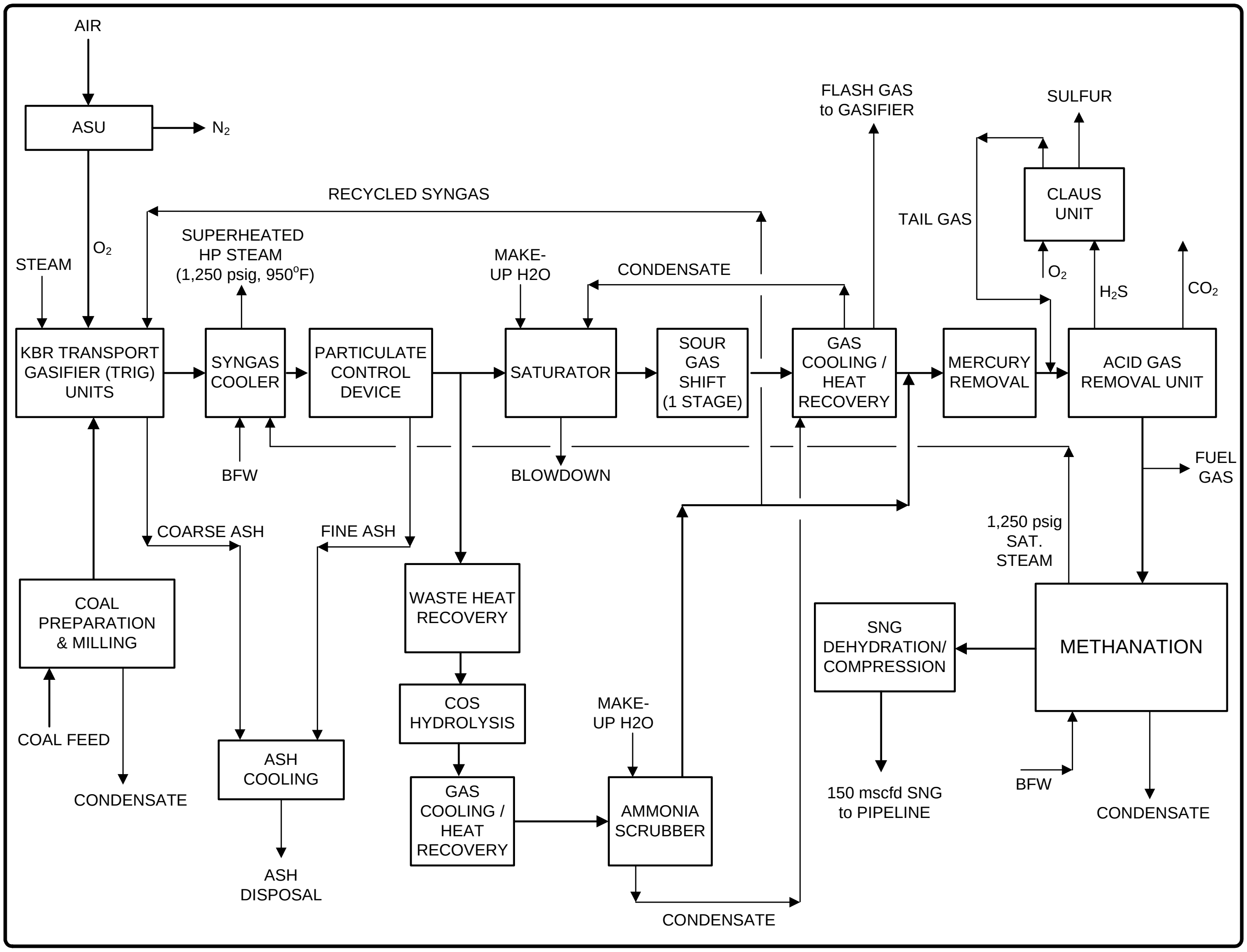


Table 2: As Received Coal Compositions – PRB and Lignite

Coal	Wyoming PRB	North Dakota Lignite
Component	Wt%	Wt%
C	51.75	44.21
O	11.52	12.45
H	3.41	2.71
N	0.71	0.68
S	0.26	0.60
Cl	0.011	0.005
F	0.004	0.00
Moisture	27.21	29.82
Ash	5.13	9.53
HHV, BTU/lb	8,764	7,335

The main processing units in TRIG gasification to SNG scheme are as follows:

Syngas Generation
- Coal Preparation
- Air Separation
- Coal Gasification
- Syngas Cooler
- Particulate Control
- Syngas Saturation
- Sour Gas Shift
- COS Hydrolysis

Syngas Purification
- Ammonia Scrubbing
- Mercury Removal
- Acid Gas Removal
- CO_2 Management

SNG Synthesis
- Methanation Unit
- SNG Drying & Compression

Utility Section
- Steam & Power Systems

Each of the above steps is described in detail below:

SYNGAS GENERATION

Coal Preparation

As received coal is crushed to the required size and fed to a system of fluidized bed coal dryers, the dryers utilize low-grade process heat to dry coal to the desired moisture levels. Dried, pulverized coal is then transferred to coal storage bins. Because the TRIG gasifier can accept larger-sized coal particles (~ 400 microns) than other high temperature gasifiers, required crushing energy is less. Coal is then fed to the pressurized TRIG unit through a system of lock hoppers and pneumatically conveyed using recycled syngas. Coal is injected at a location slightly above the gasifier-mixing zone. The coal particles fluidize, mix with the circulating solids, and heat up rapidly as they enter the gasifier.

Air Separation

The TRIG gasifier for the SNG application uses pure oxygen as the oxidant to reduce inerts in the syngas. Oxygen is provided by a cryogenic air separation unit (ASU) supplied by a suitable process licensor. To maintain a reasonable size and energy consumption of the ASU, oxygen purity of about 99.5 mol% is selected. The main impurities in the oxygen stream are argon and nitrogen. Oxygen is supplied to the gasifier at about 600 psia and ambient temperature. The ASU also supplies high pressure (HP) and low pressure (LP) gaseous nitrogen for use within the gasification facility. The specific oxygen consumption for the PRB and lignite cases are 0.75 and 0.66 tons of oxygen per ton of coal on a moisture and ash free (MAF) basis. The difference in specific oxygen consumption between PRB and lignite cases is due to the slight variation in gasifier operating temperatures and the difference in oxygen composition between the two coals.

Coal Gasification

Partially dried, pulverized coal, oxygen and steam are fed to the TRIG gasifier near the mixing zone where they contact the circulating solids. Coal gasification reactions take place in the resulting fluidized bed operating in the high velocity 'transport regime'. The flow of oxygen is carefully controlled to limit carbon combustion within the gasifier. Steam is added to the gasifier, both as a reactant and as a moderator to control the reaction temperature. For this study, the gasifier operating temperatures selected were 1,700^{o}F for the PRB case and 1,650^{o}F for the lignite case. These operating temperatures were chosen to maximize methane concentration in the syngas while ensuring the highest possible carbon conversions are attained. This is possible because, for a given coal, the maximum carbon conversion in the TRIG unit remains constant over a range of temperature and only drops when the temperature is further reduced. Methane concentration at a constant pressure, however, is inversely correlated with temperature – with a lower operating temperature producing more methane. Therefore, the gasifier operating temperatures selected for this study represents the lower-end of the temperature range for which carbon conversions are uncompromised for both PRB and lignite coals.

The syngas produced along with the solids then move up the riser and enter a system of primary and secondary cyclones where most of the particles larger than 10 microns are separated and recycled back to the gasifier. The hot syngas exiting the top of the second stage cyclone then enters a system of primary syngas coolers at a pressure of about 522 psia. A small portion of the recycled syngas is compressed and sent back to the gasifier for coal conveying and as fluidizing gas within the gasifier. Typical syngas composition at the gasifier exit for the PRB and the lignite cases are shown in Table 3.

Table 3: Typical Syngas Composition at TRIG Gasifier exit for the PRB and lignite coals

Coal	**Wyoming PRB**	**North Dakota Lignite**
Temperature	1,700^{o}F	1,650^{o}F
Pressure	522 psia	522 psia
Component	Mol% (wet basis)	Mol% (wet basis)
CO	39.7	35.6
H_2	28.5	25.6
CO_2	14.3	17.5
CH_4	4.3	6.1
NH_3	0.4	0.4
H_2O	12.6	14.4
N_2	0.09	0.09
Ar	0.08	0.07
H_2S	750 ppmv	2,007 ppmv
HCN	250 ppmv	274 ppmv
COS	40 ppmv	106 ppmv
HF	18 ppmv	nil
HCl	30 ppmv	15 ppmv

Syngas Cooler

The main purposes of the syngas cooler are (1) to recover high-grade process heat from syngas leaving gasifiers, and (2) to provide necessary superheat for steam generated within the syngas cooler and steam generated from the plant's methanation section. To accommodate the integration between the methanation unit and the syngas cooler, HP steam header pressure was fixed at 1,250 psig in both process units.

Hot syngas containing traces of fine particles exits the TRIG gasifier at 1,650 – 1,700°F and is cooled to about 700°F in the syngas cooler. It consists of three exchanger sections – Steam Generator, Superheater, and Economizer. The first section of the syngas cooler is the Steam Generator. Here, HP steam is produced and the syngas is cooled to approximately 1,350°F. The middle section of the syngas cooler is the Superheater. Here, HP steam from the steam drum within the syngas cooler area along with 1,250 psig saturated HP steam from the methanation section is superheated to 950°F. The final section of the syngas cooler is the Economizer. Here, the syngas is cooled to about 700°F. Boiler feed water enters the Economizer at 385°F at 1,250 psig. Water is then heated to about 574°F and flows to the HP steam drum.

It is important to note the TRIG gasification scheme's ability to superheat the entire HP steam from the methanation section within the syngas cooler. In particular, it presents a significant advantage over the 'Quench' gasification designs employing conventional methanation (low- or medium-temperature) schemes, where there is typically inadequate heat within the methanation section to provide the desired superheat levels. In such cases, additional superheat will need to be provided by auxiliary firing, which increases both fuel consumption and plant emissions. In contrast, the present TRIG configuration integrated with the methanation unit is able to achieve the desired steam superheat levels and efficiency with no additional emissions.

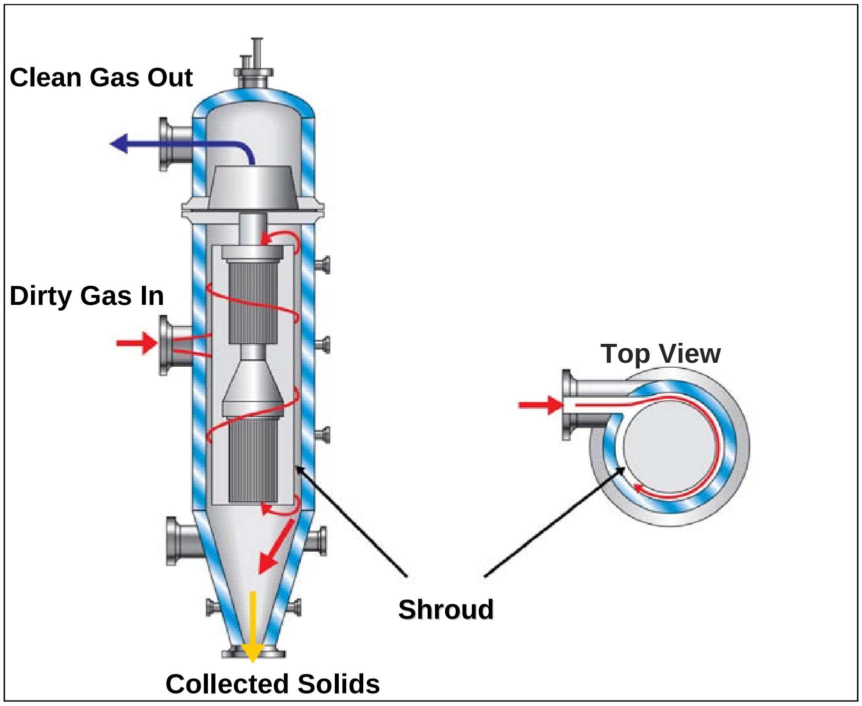
Particulate Control Device (PCD)

Gas exiting the syngas cooler at about 700°F flows through PCD, a proprietary filter (designed by a suitable vendor) that removes remaining particulate matter as fine ash. Removing fine particulates from syngas is an integral part of any gasifier system as it can foul or corrode downstream equipment, reducing performance or causing equipment failure.

Figure 4 shows a simplified sketch of the PCD employed in the TRIG gasification system. It uses rigid, barrier-type, filter elements to remove essentially all of the fine particulates in the syngas stream. The inlet solids concentration in the syngas to the PCD is about 20,000 ppmw and is reduced to less than 0.1 ppmw upon exit. A small amount of high-pressure recycled syngas is used to pulse-clean filters as they accumulate particles from the unfiltered syngas. Downstream of each filter element, a safeguard (fail-safe) device is installed to protect downstream equipment from particulate-related damage in the event of an isolated filter element failure. The particulate stream (fine ash) is depressurized to atmospheric pressure and removed via a proprietary continuous fine ash removal system.

The PCD is a critical component of the TRIG gasifier development as it ensures the syngas produced is particulate-free, eliminating dirty water or grey water systems that are a feature of most other commercially available gasification processes. The elimination of grey water systems also implies unique heat integration and water recovery possibilities. KBR has developed proprietary technologies around the core TRIG unit to maximize heat and condensate recovery. These novel features are incorporated in present coal-to-SNG process scheme. Additional information on PCD and details on filter elements used can be found in Ref. 1.

Figure 4: Sketch of the Particulate Control Device (PCD)



Syngas Saturator

As shown in Figure 1, a portion of the raw syngas that needs to be shifted passes through the syngas saturator. This step is required because raw gas from the TRIG unit does not contain desired moisture (steam) levels required at the inlet of sour shift catalyst beds. The primary function of the saturator, therefore, is to raise the moisture level for the portion of raw gas that requires shifting. The fraction of total gas that requires to be shifted is set by the desired H2:CO ratio at the inlet of the methanation unit. The syngas saturator primarily uses recycled process condensate as the main source of water to saturate gas. A small amount of fresh demineralized make-up water is also added to maintain the water balance. In the present configuration, around 70-75% of total saturator heat requirement is met by the sensible heat available in the syngas, plus medium- to low-grade heat available elsewhere in the process. The remaining 25-30% of saturator reboiling heat duty is met by indirect steam reboiling using 650-psig medium pressure (MP) steam. It should be noted that there is no live steam addition to the saturator – this configuration minimizes overall water make-up and reduces saturator blowdown. In both PRB and lignite cases, a minimum blowdown is maintained from the saturator. This stream would contain small amounts of dissolved gases, virtually no suspended or dissolved solids, and in some cases, traces of hydrogen halides absorbed from raw syngas. This blowdown is sent to the process condensate stripper for further treatment.

As indicated before, it is important to note that the saturator utilized in the TRIG gasification scheme is not a particulate scrubber. A particulate scrubber is not used because syngas entering the saturator from the PCD is essentially free of any solids. The implementation of the PCD eliminates the need for water scrubbing of solids and greatly simplifies the design of the saturator and its condensate recovery scheme. More details on the operation of the saturator are provided in Ref. 2.

Sour Gas Shift

The overhead gas from the saturator is pre-heated and passes through a system of parallel, single-stage sour gas shift catalytic beds. The steam-to-dry gas molar ratio at inlet to the catalyst beds is about 0.95. Carbon monoxide conversion is optimized by adjusting inlet temperature to the shift unit in the range of 500 – 550^{o}F so that the appropriate H2:CO ratios in the feed gas to the methanation unit can be achieved for both start of run (SOR) and end of run (EOR) conditions. Carbonyl sulfide (COS) in the syngas is almost completely hydrolyzed to hydrogen sulfide. This eliminates the requirement for a dedicated COS hydrolysis unit for shifted gas.

As part of the overall heat integration philosophy developed for this study, the heat recovery from the shift reactor effluent was maximized and utilized for the following services:

- Feed pre-heat to the sour gas shift reactors
- Part of the heat duty for the upstream syngas saturator
- Pre-heat for recycled condensate and make-up water to syngas saturator
- Heat duty for acid gas removal unit reboilers
- Part of the heat for coal drying
- Deaerator feed water pre-heating

After recovering most of the heat in the shifted gas effluent, it is passed through an air cooler to reject the last, unrecoverable portion of the heat.

COS Hydrolysis

After recovering part of the high-grade heat in the unshifted raw syngas leaving the PCD, it passes through a number of parallel, carbonyl sulfide (COS) hydrolysis reactors to reduce the COS concentration in the unshifted syngas. The hydrolysis reaction essentially proceeds to equilibrium, reducing COS concentration in the exit gas to about 1 ppmv. There is no added steam addition at the inlet to the COS catalyst beds as the moisture present in the syngas is sufficient for the hydrolysis reaction. The heat in the unshifted syngas leaving the COS hydrolysis reactor is utilized for boiler feed water (BFW) pre-heating and part of the low-grade heat required for coal drying. After heat recovery, unshifted gas passes on to the ammonia scrubbing section.

SYNGAS PURIFICATION

Ammonia Scrubbing

As shown in Figure 1, a dedicated ammonia scrubber is included only in the unshifted gas line due to insufficient water in the syngas to condense the ammonia. In contrast, when the shifted gas effluent is cooled almost all of the ammonia is condensed. In the ammonia scrubber, the unshifted raw syngas is scrubbed with water recovered from coal drying at about 130°F to remove ammonia, remaining chlorides and fluorides. Water leaving the ammonia scrubber is mixed with condensate generated from cooling the shifted gas effluent. The combined condensate stream is then pumped to about 600 psig, pre-heated and flashed. The flash gas contains significant amounts of ammonia vapors along with some carbon dioxide and hydrogen sulfide. These gases are recycled to the gasifier where bulk of the ammonia is converted into elemental nitrogen and hydrogen. The hot condensate from the flash drum is then recycled to the syngas saturator.

Mercury Removal

Unshifted syngas leaving the ammonia scrubber and cooled shifted syngas are mixed upstream of the mercury removal unit. The combined gas stream is pre-heated to about 150^{o}F and passes through mercury removal guard beds. It consists of activated carbon beds that adsorb any mercury present in the syngas. Mercury-free syngas is then sent to the acid gas removal unit for sulfur and carbon dioxide removal.

Acid Gas Removal

Raw syngas leaving the mercury removal unit enters the acid gas removal unit (AGRU). A physical solvent based, two-stage AGRU was selected and the process data was supplied by a suitable process licensor. Since carbon dioxide (CO_2) is also a reactant in the methanation unit, the treated gas CO_2 specification was arbitrarily set at 0.5 mol%. The total sulfur in the treated gas was less than 0.1 ppmv. Treated gas is sent to the methanation unit.

Most of the captured carbon dioxide from raw syngas is recovered as a low-pressure CO_2-rich stream (>95% CO_2) with a hydrogen sulfide (H_2S) content of less than 20 ppmv. The CO_2 stream also meets typical pipeline-specifications for hydrocarbons and inerts. Low-pressure CO_2 stream is sent to the CO_2 compression unit. Sulfur removed from raw syngas is concentrated as a H_2S-rich stream and sent to a conventional oxygen-fired Claus Unit for sulfur recovery. Tail gas from the Claus unit is compressed and recycled to upstream of the acid gas removal unit to reduce emissions associated with tail gas treatment.

CO_2 Management

The current KBR TRIG gasification scheme to make SNG is designed to accommodate any future carbon capture and storage (CCS) requirements. This is accomplished by having a design that is inclusive of an AGRU that maximizes CO_2 recovery and meets the most stringent CO_2 pipeline specifications, and by adding a CO_2 compression unit. The low-pressure CO_2 recovered from the acid gas removal unit is sent to a CO_2 compression unit, where the CO_2 is routed through one or more compression trains to provide a dense-phase fluid with a discharge pressure of about 2,200 psig. The compressed CO_2 at these pressures is expected to be suitable for either Enhanced Oil Recovery (EOR) and/or Sequestration. Based on KBR's experience in large-scale CO_2 compression design, a standard four-stage intercooled Centrifugal Compressor configuration (with electric drives) was adopted for this study. The requirement for dehydration will be assessed in later phases as it largely depends on the acid gas removal technology selected and ambient conditions to which the CO_2 pipeline may be exposed. The total amount of compressed CO_2 available for the PRB and lignite cases is approximately, 290 and 260 mscfd, respectively.

SNG SYNTHESIS

Methanation Scheme Development

The KBR TRIG-based methanation scheme developed for this study assumes the equilibrium-limited methanation reactor concept. The scheme involves recycling sufficient quantity of product gas to quench heat liberated by robust exothermic methanation reactions. The maximum permissible temperature in the methanator beds was limited to about 900^{o}F. This temperature is within the proven range of methanation catalysts employed in typical commercial-scale SNG plants. KBR has significant expertise in methanation scheme development and design based on previous work and from interactions with various methanation catalyst providers. The methanation scheme adopted for the present study incorporates this experience and represents a technically robust design.

Methanation Unit

Treated gas leaving the acid gas removal section enters the methanation unit. Table 4 indicates the estimated syngas composition for both PRB and lignite cases at inlet to the methanation unit. The hydrogen content in the feed gas represents the stoichiometric requirement for complete conversion of carbon oxides (CO and CO_2) in the feed gas to SNG.

From Table 4, two important aspects are noted:

1. The feed gas methane concentration is about 5.70 and 8.71 mol% for the PRB and lignite cases, respectively. As mentioned before, for this SNG application, the methane concentrations in the syngas have been maximized by adjusting the gasifier operating temperatures. The high methane concentration in feed gas not only represents product value but also significantly reduces product gas recycle requirements to quench the heat of reaction. The ability to maximize methane concentration in feed gas is an important advantage of the TRIG gasification system. The net impact when utilizing feed gas with higher methane content is reduced auxiliary power consumption and capital costs associated with the methanation unit.

2. The N_2+Ar content of feed gas to the methanation unit are about 0.22 and 0.25 mol% for both coals, which represents very low inerts content. Typically, N_2+Ar content of syngas can be traced back to the ASU oxygen purity, plus the amount of N_2 present in feedstock (fuel N_2). In the TRIG gasifier when processing most coals, about 80% of the fuel N_2 is converted to ammonia, which is easily separable from the syngas. Thus, with the TRIG gasification system it is possible to produce a syngas stream that is low in nitrogen (and total inerts) by removing most of the fuel nitrogen as ammonia. The low inerts content shown in Table 4 reflects this significant benefit, particularly for the SNG application where low-inerts gas can boost the SNG higher heating value (HHV).

Table 4: Estimated Feed Gas Composition to the Methanation Unit – PRB and Lignite

Coal	**PRB**	**Lignite**
Temperature	81°F	81°F
Pressure	400 psia	400 psia
Component	Mol% (dry basis)	Mol% (dry basis)
CO	22.89	22.14
H_2	70.68	68.41
CO_2	0.50	0.50
CH_4	5.70	8.71
N_2	0.12	0.14
Ar	0.10	0.11
H_2S + COS	< 0.1 ppmv	< 0.1 ppmv

The heat in the effluent from the methanator beds and from recycle compression is primarily utilized for the following services:

- 1,250 psig saturated steam generation
- Methanation feed pre-heat
- Methanation section boiler feed water (BFW) pre-heat

SNG Drying & Compression

The wet SNG leaving the methanation unit is air-cooled to about 110^{o}F and the condensed water is removed. It is then dehydrated to about 7 lbs of water per mscf in a conventional tri-ethylene glycol (TEG) unit. The dry SNG leaving the TEG unit passes through an SNG compression step, followed by after-cooling. SNG product is delivered at 1,000 psig and about 110^{o}F. Higher heating value (HHV) is estimated to meet or exceed an assumed pipeline specification of 970 BTU/scf on a dry basis.

By-products from the methanation unit are HP saturated steam and process condensate. As mentioned earlier, the 1,250-psig HP saturated steam produced in the methanation unit is routed to the syngas cooler, where it is superheated to about 950^{o}F and sent to the steam turbines for power generation. Condensate recovered from the methanation unit is re-used as make-up water for various process units.

Overall Plant Consumption & Production Figures

Table 5 summarizes estimated feed requirements and by-product production figures for the two cases – PRB and lignite, each producing about 150 mscfd SNG product with a higher heating value of at least 970 BTU/scf. The data presented in Table 5 are preliminary figures only and based on the conceptual scheme developed. Overall plant inside battery limit (ISBL) and outside battery limit (OSBL) auxiliary power load and power generation from the steam system are discussed in the next section.

As noted before, the data in Table 5 represents maximum syngas capacity of three TRIG gasifiers operating in oxygen-blown mode. Because the PRB case has some excess capacity (in addition to meeting the target 150 mscfd SNG), there is additional syngas shown as fuel gas. Conversely, additional syngas can also be used to make more SNG. This paper does not discuss the latter option.

The overall process make-up water requirements for two cases are also shown in Table 5. The net make-up water figures are obtained from a detailed water balance that considers make-up required for process units and steam system blowdowns, plus water lost in reaction (shift). The contribution from water recovered in coal drying, condensate from methanation, and treated water from condensate stripper is included in determining the net make-up. For the lignite case, this net make-up requirement is much smaller compared to the PRB case due to slightly more water recovered from coal drying, less water lost in shifting (less syngas), and a smaller blowdown from the steam system (less steam production).

Table 5: Summary of Feed and By-product Figures

Coal	Coal feed rate, tons/day		O_2, ton/ton coal[3]	Make-up water, GPM	Fuel Gas		CO_2, tons/day	Sulfur, tons/day	Ash, tons/day
	AR[1]	AF[2]			mscfd	BTU/scf (HHV)			
PRB	**14,565**	**12,912**	**0.75**	**300**	**67**	**360**	**16,437**	**36**	**898**
Lignite	**15,446**	**13,202**	**0.66**	**70**	**0**	**n/a**	**14,931**	**88**	**1,677**

Notes:

1. AR = As Received. AR moisture for PRB coal = 27.21 wt%; Lignite = 29.82 wt%
2. AF = As Fed. AF moisture content for PRB coal = 17.89 wt%; Lignite = 17.89 wt%
3. Moisture and Ash Free Basis

UTILITY SECTION

Steam & Power Systems

The following section discusses the SNG facility's auxiliary power load requirements, power generation concepts, and options to meet the balance of power demand.

The OSBL steam and power systems include the steam generation system and the electric power generation system. The ISBL process units produce substantial amounts of steam from waste heat recovery, which is used to make significant electric power in the steam turbine generators (STGs). The specific configuration options depend on decisions regarding the electric power balance. If sufficient electric power is reliably available at a competitive price from the local utility grid, then the design is simplified. If this is not the case, then the plant will effectively operate electrically in 'island mode' and will have to generate all power on-site. The basic design options considered include:

- Base Case – Purchase the balance of power requirements from the grid
- Option 1 – Island operation with balance of power from fired boilers and larger STGs
- Option 2 – Island operation with balance of power primarily from gas turbine generators (GTGs), heat recovery steam generators (HRSGs), and slightly larger STGs

Tables 6 and 7 summarize the basic performance parameters for the steam and power generation systems for the PRB and lignite cases.

PRB Case Description

With the PRB coal, there is a surplus of syngas (fuel gas) produced based on the target SNG production rate of 150 mscfd. In the Base Case option, this surplus syngas is used as boiler fuel to make more electric power in the STGs, and the balance of electric power is purchased off-site. In Options 1 & 2, the balance of power is generated on-site. With a fixed amount of syngas production from the gasifiers, using syngas as fuel generally reduces the net production of SNG in Option 1 as indicated. In Option 2, a small surplus of syngas is available after meeting the power generation requirements (i.e., the figures show slightly more power generation than load for Option 2). This is due to the higher efficiency of Option 2 vs. Option 1. The excess syngas can be used to increase SNG production marginally or the cogen cycle can be de-tuned (i.e. GTG load reduced and HRSG duct firing increased) to keep the syngas requirement in balance.

Table 6: Power Consumption & Generation Summary – PRB (150 mscfd SNG, plus Fuel Gas)

Case		Base	Option 1	Option 2
Power Balance Description		**purchase power**	**fire boiler & use larger STGs**	**add 2x Fr. 6B GTG+HRSG cogen**
Electrical Load Summary	MW			
ISBL		111.9	111.9	111.9
ASU		132.6	132.6	132.6
CO2 Compression		66.3	66.3	66.3
OSBL Misc.		23.9	25.5	21.1
Total		334.7	336.3	331.9
Electrical Supply Summary	MW			
STGs		293.1	336.3	258.8
GTG		n/a	n/a	74.2
Outside Purchase		41.6	n/a	-1.1
Total		334.7	336.3	331.9
Fuel To Steam/Power Gen	MMBTU/h HHV			
Package Boilers		-	1536.0	-
GTGs		-	-	886.4
HRSGs		-	-	114.8
Total Consumption	MMBTU/h HHV	0.0	1,536.0	1,001.2
Surplus Syngas Available	MMBTU/h HHV	1,001.2	1,001.2	1,001.2
Other Syngas to Fuel		-	534.8	0.0
Total Syngas to Fuel		1,001.2	1,536.0	1,001.2
SNG Production Reduction	mscfd	0.0	10.8	0.0

Lignite Case Description

For the lignite case, in the Base Case option, the balance of electric power is purchased from off-site. In Options 1 & 2, the balance of power is generated on-site. Since no additional fuel gas is available, the extra fuel requirement for Options 1 & 2 is shown as an equivalent reduction in SNG production.

Comparison of Balance of Power Generation Options

The best configuration option for a given project will be in part dependent on the selected site. If the site has access to reliable electricity from the local utility grid at a competitive price, then the base case would likely be the best option due to its lower installed cost.

In the case of a remote site, which is more likely, Options 1 & 2 generate all the required electric power on-site. Although installed costs for Options 1& 2 are similar, it is likely that Option 2 is preferred. Option 2 includes a cogen component, which is inherently more efficient and produces more net SNG for sale. In addition, in island operation mode, the use of GTGs will likely enhance overall plant production by providing a more tolerant and therefore reliable electrical generation system.

Table 7: Power Consumption & Generation Summary – lignite (150 mscfd SNG)

Case		Base	Option 1	Option 2
Power Balance Description		purchase power	fire boiler & use larger STGs	add 2x Fr. 6B GTG+HRSG cogen
Electrical Load Summary	MW			
ISBL		105.3	105.3	105.3
ASU		110.3	110.3	110.3
CO2 Compression		60.0	60.0	60.0
OSBL Misc.		17.4	23.5	18.8
Total		292.9	299.1	294.4
Electrical Supply Summary	MW			
STGs		184.8	299.1	220.1
GTG		n/a	n/a	74.2
Outside Purchase		108.1	n/a	n/a
Total		292.9	299.1	294.4
Fuel To Steam/Power Gen	MMBTU/h HHV			
Package Boilers		-	1353.9	-
GTGs		-	-	883.6
HRSGs		-	-	unfired
Total Consumption	MMBTU/h HHV	0.0	1,353.9	883.6
Surplus Syngas Available	MMBTU/h HHV	-	-	-
Other Syngas to Fuel		-	1,353.9	883.6
Total Syngas to Fuel		0.0	1,353.9	883.6
SNG Production Reduction	mscfd	0.0	27.9	18.2

Power Generation Optimization Opportunities

Depending on technical configuration and predicted capital cost, the following opportunities to improve project performance will be considered in the later phases of the study:

- ASU Driver Selection – Electric motor drivers are currently selected; however, steam turbine drivers on the main compressors in the ASU may offer some cost savings on a net project basis including a corresponding reduction in capacity and cost of STGs.
- Mechanical Drivers – Particularly for Options 1 & 2, which are electrically isolated in island operation. Consideration of using steam turbine drivers for many of the major mechanical drivers such as BFW pumps, FD fans, air compressors, etc. may help improve overall plant reliability. Using steam turbine drivers reduces capacity of the electrical system and makes the overall system more fault-tolerant to temporary disruptions in operation.
- BSG and EPG Optimization – Based on final design parameters; capacity, number of units, and driver type (diesel engine or gas turbine) for black-start generators (BSGs) and essential power generators (EPGs) can be optimized.

Conclusions

A new KBR TRIG gasification-based coal-to-SNG process has been developed and presented in this paper. The process shown is well suited for a wide range of feedstocks, particularly low-rank coals that are low-cost and abundant. The process scheme offers a technically robust and energy-efficient design, with several advantages over comparable gasification processes. The economics of building mine-mouth 150 mscfd coal-to-SNG facilities using KBR's TRIG gasification technology is currently being investigated for various western U.S. locations.

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