Project Title: **400 MILLION BTU/HOUR FUEL GAS PRODUCTION PLANT FOR THE GATEWAY ETHANOL PROJECT**

ICCI Project Number: DEV06-1  
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**ABSTRACT**

The objective of the project was to develop a package of engineering documents and an estimate for the design of a coal gasification facility to produce fuel gas to support a typical ethanol plant producing approximately 100 million gallons/year of ethanol. The facility is based on the EPIC two-stage, fixed-bed, air-blown gasifier. The engineering package (commonly referred to as a Front End Engineering Documents or FEED package) would consist of Process Flow Diagrams (PFDs), Piping and Instrumentation Diagrams (P&IDs), General Arrangement Drawings (GAs), Electrical Single Line Drawings, Instrumentation and Control Configuration Drawings and supporting sketches for foundation, structural, piping and electrical design. These documents would be used to solicit Engineer, Procure, Construct (EPC) bids for the detailed engineering, procurement and construction of the facility. This project was also to develop a Front End Loading Level III (FEL III) estimate to an accuracy of ± 10% to use as a check on the EPC bids. The project developed FEED documents for two designs, one using a coal basis with the upper range of sulfur content and lower gasification reactivity, and one using a coal basis with very low sulfur and higher gasification reactivity. Both designs were fully documented. The estimates developed were not to the desired accuracy because of volatility in the metals market and the current very high level of activity in the equipment and systems market. Vendors were unwilling to commit the requisite time and effort to produce ± 10% quotes for a study. The resulting estimate is on the order of + 20% - 10%.

As a part of the project a new procedure for testing caking tendency was developed and tested. This procedure replaces the traditional Free Swelling Index (FSI) test (ASTM D 720 – 91) for determining the caking potential in the EPIC two-stage, fixed-bed, air-blown gasifier. The procedure was developed to mimic the slower heating cycle in the two-stage gasifier. Tests have indicated that coals having a traditional FSI as high as 5 can be used in the EPIC gasifier without encountering caking problems. The typical single stage, fixed-bed gasifier is limited to coals having an FSI of less than 2. This difference brings into consideration many more Illinois coals.
EXECUTIVE SUMMARY

The objectives of this project were to: (1) develop a standardized design for a coal gasification facility, based on the EPIC two-stage, fixed-bed, air-blown gasifier, to produce fuel gas to support a typical 100 million gallon per year ethanol plant; (2) prepare the Front End Engineering Documents (FEED) package for the design and to prepare a Front End Loading Level III (FEL III) estimate for the facility. The intent was to move to the point that the design would be commercially ready for Engineer, Procure, Construct (EPC) bids to be solicited. This would allow EPIC to approach the marketplace with a definitive product. The entire upper Midwestern portion of the United States is strongly involved in the planning and construction of ethanol plants. One intent of this project is to approach that market with an alternative to natural gas fuel for these plants. Coal gasification offers the opportunity to determine energy costs over a longer term than is typically possible with natural gas and, in most cases, to lower those costs initially. The project developed a design which would use typical Illinois basin coal as the feed to the gasifiers.

The methodology employed was traditional engineering proceeding from a basic process design to development of material balances (and heat balances as required); determining controls and preparing Process Flow Diagrams, Piping and Instrumentation Drawings, General Arrangements and Electrical Single Line Drawings. The Estimate was prepared by soliciting bids for the equipment and subsystems, preparing bulk material take-offs from the GAs and P&IDS and from foundation, structural, access and electrical designs and layouts. Engineering, project services, construction and indirect costs were estimated from prepared schedules, man power loading estimates and typical factors.

The initial basis for the facility design was to have been the Gateway Ethanol project near Alton, Illinois. The design was subsequently modified for several reasons. First, the Gateway project did not proceed as quickly as had been hoped. In fact, to date there has been no definite selection of the coal for the Gateway project. The design was therefore based on a typical Illinois Basin coal with a high sulfur content in order to allow for using any Illinois Basin coal. At the same time, it was decided to prepare an alternate design based on very low sulfur coal. This allowed a bracket of pricing to be established. Second, the Gateway project is located in an area with a very high seismic risk compared to the majority of the State of Illinois. Rather than skew the results, it was decided to use more typical seismic design criteria. Alton is in area strongly affected by the New Madrid fault. The short period Spectral Response acceleration factor for Alton is 50. The response for over half of Illinois is 20 or less. To design for 50 would involve a much more rigorous analysis of the structures and foundations and much heavier construction. It was decided to base the design on a response of 20. Finally, Alton is located in the area covered by the St. Louis Construction Trades Council union locals. The rates in that area are among the highest in the country. It was decided to base the estimate on the Springfield area Construction Trades Council as being more typical for both Illinois and the Midwest as a whole.
FEED packages were completed for both the high sulfur base design and the low sulfur alternate design. The process design went through several changes to account for all requirements and to begin the optimization of the design. A key change was increasing the output of the facility from nominally 400 MM BTU/hr to over 500 MM BTU/hr for either feed coal. This was justified by a careful analysis of the operation of the gasifier at a higher pressure than that used in previous Asian installations.

Other process modifications were implemented as a result of information brought to light by the design effort. This included changes to the tar/oil and particulate removal area. Here the original concept of an oil precipitator (ESP) followed by a cooler and then a tar wet electrostatic precipitator (WESP) was replaced by using a single variable throat wet venturi to remove all of the tar/oil mist and particulate in a single step while saturating the fuel gas for further treatment. A need for organic sulfur conversion to hydrogen sulfide was recognized and addressed by the addition of a hydrolysis step in the process. The original hydrogen sulfide removal system, which would have been designed based on a catalyst available from a technology partner in China, was replaced with a commercially available system from a US supplier. The original concept of using a once through steam generator to produce the steam for the gasifier from reclaimed, untreated water has been replaced with a water treatment system and heat recovery steam generators to produce the steam. The brine from the waste water treatment system is used to wet the ash as it is loaded for disposal. Finally, the steam jacket on the gasifier was upgraded to produce 50 psig steam. This steam is useful in the process, and is used to reheat the sour gas for the hydrolysis reactors.

Vendor quotes were solicited and received for essentially all of the major equipment and subsystems. Some of the quotes were not to level of accuracy desired due to market conditions. The overall accuracy of the final estimate is deemed to be + 20% or – 10%.

The design underwent a reliability review after the FEL II stage. This review resulted in several changes. The most notable change was the substitution of redundant coal conveyors for any mass storage surge/catch up capacity. A less costly oil/water separator was identified which allowed this item to provided as one operating and one standby. This concept was carried through the gas clean-up system as well. The reactors in the gas stream portion of the system were limited to a diameter of no more that 14 feet to allow for shop fabrication. This results in parallel reactors for all clean-up items except the wet venturi. The venturi has redundant pumps to provide reliability. In the other areas, if one reactor is required to be taken off line, at least 50 – 60% of the gas can still be treated.

As a parallel effort, a new testing procedure was developed to determine the caking tendencies of various coals in the two-stage gasifier. Traditionally, fixed beds gasifiers are limited to using coal with an Free Swelling Index (FSI) of under 2.0 based on the ASTM D 720- 91 test. The ASTM test is a suitable test for single stage gasifiers where the feed is introduced into a region which has a temperature in excess of 1200°F. The EPIC two-stage gasifier introduces the coal into an area with a temperature between 280 – 400°F, depending on the moisture content of the coal. The coal is then heated to a temperature of approximately 1500°F over a period of several hours. Mimicking this
slower heating was the objective of the revised test procedure. Three coals were tested, a Powder River Basin coal with an FSI of 0, an Illinois Basin coal with an FSI of approximately 3.0 and a Kentucky coal with an FSI of approximately 5.0. None of the coals formed a “coke button” when subjected to the slower heating regimen. The conclusion is that the EPIC two-stage gasifier can use coals with an FSI of at least 5.0. Further testing will be done on coals with higher FSI numbers. This result opens the possibility of using a much wider selection of Illinois coals in the EPIC gasifier.

A survey of a number of Illinois Basin coals to determine their suitability for use in the EPIC two-stage gasifier has been performed. The results indicate that a number of coals are suitable in reactivity and performance.

The project resulted in a completely workable design for the plant. However, certain areas have been identified for further study and quality engineering during any detail design effort. These include the waste water to steam system and certain aspects of the tar/oil/particulate cleaning subsystem and the COS conversion which may be dependent upon the coal used.

The water treatment systems currently proposed for the waste water to steam system are proven technology from vendors in the water treatment field. There may be a more economical approach than using either of these systems. Further investigation is required. Discussions with boiler vendors may result in a boiler that could use water that is not fully treated.

In the other two areas, a precise definition of the composition of the tars and oils, the concentration and size distribution of the tar/oil mist and the particulate in the fuel gas and a precise ratio of COS to total sulfur may all prove to be strongly dependent on the coal used in the gasifier. These areas all would benefit from further investigation.
OBJECTIVES

The objectives of this project were, first, to develop a standardized design for a coal gasification facility, based on the EPIC two-stage, fixed-bed, air-blown gasifier, to produce fuel gas to support a typical 100 million gallon per year ethanol plant. The original design was to produce approximately 400 million BTU/hour of fuel gas by gasifying Illinois Basin coal in four EPIC 2ST-3.6 gasifiers. Having defined the scope of the facility the project was to prepare the Front End Engineering Documents (FEED) package for the design and to prepare a Front End Loading Level III (FEL III) estimate for the facility. The intent was to move to the point that the design would be commercially ready for Engineer, Procure, Construct (EPC) bids to be solicited. This would result in a commercially viable basis for offering coal gasification to support not only ethanol plants, but other energy consumers in the same size range.

The FEED package would include: Process Flow Diagrams with material balances and heat balances where appropriate; Piping and Instrumentation Diagrams; General Arrangement Drawings; Electrical Single Line Drawings and Instrumentation & Controls Configuration Diagrams. Sufficient foundation, structural and access designs would be prepared to support the take-offs required for the FEL III estimate.

The FEL III estimate was to be at an accuracy level of ± 10%. This would require a detailed engineering and construction schedule; take-offs of bulk materials including piping with fittings and supports; structural steel, access, foundation materials; siding and roofing; electrical wire, cable tray and conduit; insulation for piping, equipment and structures; heating, ventilation and air conditioning and all other materials for a complete scope. Bids would be solicited for all major equipment and subsystems; for instruments and control packages; pre-engineered buildings and other equipment as required. Manhour estimates for construction, engineering and project services would be prepared. Construction costs would be determined using the appropriate rates for the area of the project.

There were 22 discreet tasks identified in the work definition. These tasks follow the typical engineering practice for preparation of FEED packages and FEL III estimates. The tasks were:

Task 1 Prepare Preliminary Process Flow Diagrams (PFD)
Task 2 Preliminary Process Material Balance
Task 3 Major Equipment Sizing
Task 4 General Arrangement Drawings
Task 5 Piping and Instrumentation Diagrams (P&ID)
Task 6 Equipment Data Sheets
Task 7 Structural and Foundation Preliminary Design
Task 8 Prepare Electrical Single Line Diagrams
Task 9 Prepare Bid Packages
Task 10 Piping Material Summary
Task 11 Structural Support and Foundation Material Summary
INTRODUCTION AND BACKGROUND

Coal gas was the first fuel to be distributed by pipeline as early as the middle 19th century. The gas produced either as a by product of other processes or as a product in its own right has been used for heating, lighting, power generation and as a feedstock for fertilizer or fuels production for over 100 years. A century or more ago, entire towns were heated and lit by coal gas. Certain industries continued to offset natural gas requirements with coal gas produced as a by-product to other processes as late as the 1970’s. The discovery of natural gas reserves and the decline of industries which produced coal gas as a by-product eventually led to the use of coal gas essentially ending in the United States.

Coal gasification continued to be a major source of fuel and chemical feedstocks in other parts of the world. The development of the Fisher – Tropsch process led to widespread use of coal gasification in gas-to-liquids fuel production. In the 1930’s Germany developed better methods for gasification, including the Lurgi and Winkler designs to provide gas for synthesis of liquid fuels. Both the Wehrmacht and the Luftwaffe depended heavily on fuels produced from coal gas during World War II.

At the end of World War II, the use of international sanctions to attempt to force unpopular forms of governments to reform led to the isolation of The Union of South Africa. South Africa turned to the Lurgi fixed bed air-blown gasifiers to provide synthesis gas for a gas to liquid fuel program which continues today.

In China, the Lurgi and two stage technology arrived, via the USSR in the late 1940’s and found almost immediate application in both coal to liquid fuel and gas to fertilizer production. Today, China has the most widespread use of coal gasification in the world. The Chinese began with a basic two stage design and have made improvements over the years. Most of their gasifiers operate at atmospheric pressure and use air as the oxidant rather than employing an air separation plant to produce oxygen. The initial designs were used primarily on anthracite or coke to produce synthesis gas for conversion to ammonia. The Chinese companies worked to improve the basic two-stage design by improving the “coke oven”, or distillation, stage at the top of the unit. This design is used to process bituminous and sub-bituminous coals to produce fuel gas. The design has been built in
both 3.0 meter and 3.6 meter diameters. It is this air-blown, two-stage, fixed-bed gasifier design which is the basis for the EPIC system.

Recent developments have caused a very significant increase in the demand for ethanol, spurring a boom in the development of ethanol plants throughout the upper Midwestern section of the US. Developers are also looking for ways to reduce their operating costs and to provide predictable operating costs. With the volatility in the natural gas market, coal gasification has become a prominent alternative source of energy. A major objective of this project was to arrive at a commercially acceptable design package, using Illinois Coal to support, primarily, this boom in ethanol plant development, but also other energy consumers in the same size range. The ethanol projects identified by EPIC at the outset of this project and located in the area of the Illinois Coal basin represent a potential consumption of 3.7 million tons per year of coal. The base design in this project is applicable for a wide range of Illinois coals. The analysis at the end of this report discusses the applicability of certain Illinois coals for this process.

GASIFIER OPERATION

The EPIC gasifier was developed in China from designs originated by Italian and German companies in the late 1920s to 1930s. In the lower part of the EPIC two-stage gasifier, producer gas reactions take place between carbon in the char and oxygen in the air to provide a hot gas, which is, predominantly, carbon monoxide and nitrogen. This hot gas rises through the middle level, where some level of hydro-gasification takes place, producing methane, and certain shift reactions take place producing hydrogen and carbon dioxide from carbon monoxide and steam in the gas. In the upper levels the heat causes pyrolisis of the coal that releases oils and tars and finally dries out any water that was in the coal.

The use of coke ovens over the years has provided the experience necessary to maximize the carbon content in the char while removing no more than is necessary of the volatile matter. In this way a more or less smokeless char can be produced and fewer problems created in disposing of the tars and oil produced. See the figure below for the EPIC Two-stage gasifier. (Model 2ST -3.6 shown.)

A framework of refractory bricks is built in the upper part of the gasifier that provide large vertical passages through which the coal travels and narrower passages in the brick walls through which some of the gas produced in the lower stage feeds to a lower outlet. The rest of the gas rises through the coal and exits through the top. The gasifier internals are long lasting. The typical life of the refractory is ten years or more.
The lower portion of the gasifier is the reactor where the char is converted to gas by introducing steam and air. This area has a steam jacket to control the inner and outer wall temperatures.

By adjusting the relative amounts of gas exiting the upper and lower levels the amount and quality of the oils and tars can be controlled so that the tar is relatively light and can be easily separated from the gas. This adjustment is made possible by control valves on both the upper and lower gas outlets.

In all gasifiers there will be a quantity of hydrogen sulfide produced which is proportional to the sulfur content of the coal. The efficiency of conversion of the coal to clean gas is about 80-83%, (BTU’s in the fuel gas divided by BTU’s in the coal feed) but will depend on the amount of sulfur and ash that has to be removed. The sulfur, in particular, contributes to the heating value of the coal, but actually reduces the heating value of the fuel gas because of the hydrogen that is tied to the sulfur in hydrogen sulfide.

Although there is a small loss of efficiency due to the heat lost in the removed ash, the major effect of ash content is a reduction in the output of the gasifier. Typically it is best if the ash content of the coal is no more than 10 to 12% but it can go as high as 18% without adversely affecting the performance of the gasifier. Beyond this, the throughput will be limited to the capacity of the grate to remove the ash.
The heating value of the fuel gas is primarily dependent upon the coal composition, but, in general, will range from approximately 170 BTU/scf to 200 BTU/scf (LHV).

PLANT CONFIGURATION

The standardized plant can be conceptualized in five major blocks and an auxiliaries category. These are: 1) Coal receiving and handling including any fines handling; 2) the gasifier block including air delivery and steam generation; 3) the tar/oil and particulate removal system including recycle systems to the gasifiers; 4) sulfur and mercury removal including sulfur handling; 5) ash handling including any silos and loading equipment; and 6) auxiliaries including electrical distribution equipment, controls equipment, plant and instrument air compressors and driers, boiler water conditioning systems, water softening systems, etc.

The coal receiving and handling block will receive the coal, or other feed material, move it to the gasifier block, meter the feed to the gasifier block for contractual purposes, and optionally screen and either agglomerate or dispose of fines.

The gasifier block is the heart of the facility. It is here that the coal, or blend of coal and other feed material, is converted into fuel gas. The block will typically consist of feeders and conveyors to move the coal through surge bins to the lock hoppers which feed the gasifiers; the lock hoppers with a system to vent gases to the process vent header; the gasifiers with the individual steam drums; a boiler feed polishing package system; the air blowers to provide compressed air to the gasifiers; the upper gas cyclones; the lower gas cyclones; the steam generators which provide process steam to the gasifiers; and the ash conveyor to move ash from the gasifiers to the ash disposal point.

The purpose of the tar/oil and particulate removal block is to remove the tars, oils and particulate from the fuel gas stream and to cool and humidify (if necessary) the fuel gas prior to the sulfur and mercury removal block. The current design will use a variable throat venturi to remove the tars, oils and particulate from the fuel gas; a separator to separate the oils, particulate and water discharged from the venturi; a tar/oil tank to receive the tars and oils; and pumps to move the combined tar and oils to the gasifier injection nozzles.

The sulfur and mercury removal system will: provide for hydrolysis of COS to H₂S; remove mercury in an activated carbon adsorption bed; and will remove sulfur in a reduction – oxidation (REDOX) type hydrogen sulfide (H₂S) removal system which will produce dry elemental sulfur. This block will include: 1) a reheater to heat the fuel gas prior to the hydrolysis reactors; 2) the hydrolysis catalytic reactor(s); 3) a cooler to reduce the temperature to approximately 100°F; 3) the mercury adsorption bed; 4) an absorber to remove 99%+ of the H₂S from the fuel gas with the required reagent feed pumps; 5) a scavenger system to remove H₂S to a residual level ≤ 10 ppm; 6) the oxidation reactor system; 7) chemical receiving and storage system; 8) the thickened sulfur slurry transfer pumps; 9) the sulfur dewatering equipment; 10) surfactant and catalyst receiving, storage and metering equipment; and 11) the sulfur loading equipment.
The ash handling system will take the ash from the gasifiers and move it to a storage silo and provide a means to load the ash from the silo to trucks for ultimate disposal. The system will consist of: 1) a pneumatic conveying system to move the ash from the gasifiers to the silo; 2) a silo to store 250 tons of ash; 3) a bin vent for the silo; and 4) dust suppressing unloading equipment to load the ash into trucks.

The balance of plant equipment will include, but not be limited to: 1) electrical power distribution equipment; 2) plant water connection and distribution system; 3) start-up steam connection and distribution; 4) instrumentation including the interface to the customer’s distributed control system (DCS); 5) flare stack system; 6) boiler feed water demineralization package system; 7) water softening system; 8) air compressors with receivers, oil separators and driers to provide plant air for operators and instrument air for instruments and ash conveying; 9) a hydraulic power pack to support the hydraulic drive systems on the gasifier grates; 10) fuel gas booster compressors; 11) fire suppression system; 12) foundations and structural steel to support the equipment; 13) all required access stairs, ladders and platforms; 14) grounding grid; 15) all required piping, valves and connections; 16) process vent header system with injection blowers; 17) a thermal oxidizer; 18) enclosures including heating, ventilation and air conditioning; 19) fuel gas metering delivery system; 20) natural gas piping for the gasifier start-up burners; 21) potable water piping to eyewash and wash stations; 22) nitrogen supply to purge the system on shut down; 23) storm water and drainage system; 24) emergency waste water disposal tanker; and 25) the waste water treatment system.

DESIGN BASIS

The original plan was to base the design on the Gateway Ethanol Project which is planned for location in Alton, IL. However several factors led to the design basis being revised.

First, the Gateway project did not progress as quickly as anticipated. At the time that a decision was required on the design coal in order to develop the material balances and equipment sizing, the Gateway project had not committed to a coal supply. The decision was made to use as a design coal, a specification based on a typical Illinois coal with a slightly higher than typical sulfur content. The sulfur content was adjusted to provide a design case which would encompass all reasonable possibilities.

Second, Alton is in a seismic area which is strongly influenced by the New Madrid fault. The Short Period Spectral Response Acceleration for Alton is 50 vs less than 20 for over half of Illinois. The Long Period response is 16 vs less than 10. These factors would require a rigorous computer analysis for all of the structural and foundation designs, as well as heavier construction. Rather than skew the estimate, it was decided to use the lower factors as the design basis.

Finally, the Alton area is covered by construction union locals in the St. Louis area. This area has some of the highest labor rates in the country. The rates for the Springfield area locals were chosen as being more representative of the state as a whole.
EXPERIMENTAL PROCEDURES

This project followed the basic procedures of the Front End Loading process, which has become an engineering standard in many organizations. The procedure allows for feasibility checks throughout the design process. There are carefully designed steps, each producing an estimate of increasing accuracy.

Typically the first phase, Front End Loading I (FEL I) produces a conceptual process design and an estimate in the ± 40% range. This is used as a basic feasibility check for the conceptual process design.

The next phase (FEL II) typically produces completed Process Flow Diagrams, Piping & Instrumentation Drawings, General Arrangements, major equipment sizing and may produce electrical and instrumentation design drawings. Specifications for equipment are developed to allow for “budget” quality bids from vendors (± 20 -25%). Basic material take-offs are performed with the majority of the bulk materials being estimated from previous data and standard factors. The end of this phase will produce an FEL II estimate with an accuracy of ± 25%, a preliminary engineering schedule and a construction schedule. Should the estimate be deemed uneconomic to pursue the options are to either abandon the project or to revise the process design to reduce the costs.

The FEL III phase will produce more detailed P&IDs, more rigorous take-offs of bulk materials, revised and improved specifications with the intent of obtaining firm bids from vendors and construction companies, a detailed engineering estimate and schedule and a detailed construction schedule.

RESULTS AND DISCUSSION

The project successfully completed FEED packages for two standard plant designs. One design uses as the design coal a typical Illinois Basin coal with a sulfur content of 3.3% to provide a design at the high end of the sulfur range. The alternate design uses a lower sulfur (0.3%) subbituminous coal. The packages both include all of the documentation which is required to solicit firm EPC bids from contractors. In addition to the Process Flow Diagrams, Piping & Instrumentation Diagrams, General Arrangement Drawings, Electrical Single Line Drawings and I&C Configuration Drawings listed in the objectives, the packages include written design basis documents for the Process Design and for each engineering discipline.

The final estimates were not to the level of accuracy which was the objective. Current market conditions are such that many vendors are unwilling to devote the effort to produce a ± 10% price when the effort is a study rather than an immediate purchase. In particular, the coal handling system, which was solicited as a design, procure and install subsystem from the truck receiving hopper to the surge bin in the gasifier structure was bid at an accuracy of ± 20%. The hydrogen sulfide removal system vendor would only provide an estimate with an accuracy of ± 30%. These two subsystems account for approximately 25% of the total cost of the equipment and materials. There were other
items for which firm bids were not forthcoming. To the extent possible, the construction manhours, engineering and project services costs were estimated to the ± 10% accuracy.

The major accomplishments in the project were in the refinement of the process design, the plant reliability review which, when performed, resulted in significant changes to the philosophy of the design, and in identifying areas of possible economic improvement for further investigation.

**TASKS 1 - 3**
**PROCESS DESIGN DEVELOPMENT AND MODIFICATION**

The initial effort was devoted to developing a process design and using it as a basis for an FEL II package. This included preparing material balances and major equipment sizing. These tasks were repeated after the FEL II stage when the process revisions were identified and implemented.

The process modifications which were identified and implemented included changes to the tar/oil and particulate removal systems; addition of organic sulfur hydrolysis; a change in the type of hydrogen sulfide removal system and the vendor; a significant change in the method of producing steam for the gasifiers from the reclaimed water and an upgrade to the gasifier steam jacket.

**Tar/Oil and Particulate System Changes**

A previous design effort on a two gasifier plant had developed a process flow diagram for this area which had separate cyclones for the upper and lower gas streams, the heat recovery boiler on the lower gas stream then a wet venturi with a mist entrainment separator followed by a wet electrostatic precipitator, both treating the combined gas streams. This is shown (with a booster compressor for that plant) in the following figure.
Quench Venturi, Mist Entrainment Separator and Wet Electrostatic Precipitator and Fuel Gas Booster Compressor

This configuration required a large amount of recirculating water. At the time that the previous design was done, an API type oil/water separator was specified. This device included a drag chain and screw conveyor to discharge any solids. This was chosen based on a set of criteria which included a significant amount of solid particulate in the water. This particulate would come from dust carry over from the gasifier. The API separator was a large and expensive item.

At the beginning of this project, the engineering subcontractor, Aker-Kvaerner Technical Services (AKTS) suggested a process approach which had been included in the study done by McKee Engineers and Constructors for the Erie Mining Company in 1979. This study was funded by the Department of Energy Contract No. ET-78-C-01-2578, Demonstration Plant Design Manual, Erie Mining Company, Coal Gasification Project. That study used an electrostatic precipitator on the upper gas stream to remove any tar mist, followed by combining and cooling the two gas streams, then a wet electrostatic precipitator for oil and dust removal. A plan view of this arrangement is shown here.
This design was carried until the FEL II estimate stage. At that time several factors combined to result in a change. First, the precipitator manufacturers were reluctant to quote single field precipitators for the oil ESP without having separator cyclones on the upper gas. Only one manufacturer would quote the two precipitators, and that manufacturer was reluctant to guarantee the specified outlet concentration. Another manufacturer offered an unsolicited bid for a single variable throat venturi to remove all of the tar, oil and particulate. At the same time, a careful analysis of space velocities internal to the gasifier led to the conclusion that the particulate carry over was being over specified. This led to a lower concentration of particulate reaching the oil/water separator. The original vendor for the API separator essentially doubled the price for a unit with less total liquid loading (assuming the two ESP arrangement), while a competitor offered an inclined plate separator at roughly ¼ the original price. Having concluded that the particulate loading would be lower, the API separator was replaced with the inclined plate unit. At the same time, the two ESP arrangement was replaced with the single venturi arrangement, with cyclones on both the upper and lower gas streams. The additional liquid flow was not considered to be a penalty because the separator was now smaller and less costly. The move to a venturi also removed the requirement to reheat and recirculate a portion of the fuel gas to provide a purge stream for the ESP insulator bushings. Traditionally, these bushings are purged with heated air to prevent leakage of the treated gas to the atmosphere. Clearly that could not be done in
this case, because the introduction of oxygen into the fuel gas results in an explosive mixture. The final arrangement is shown in elevation here.

Single Variable Throat Venturi Arrangement

Organic Sulfur Hydrolysis Addition

The intent of the EPIC gasification facility was to provide fuel gas with $\leq 10$ ppm sulfur as H$_2$S in the final product. In analyzing data from various sources, it became apparent that the organic sulfur (mainly COS) content of the fuel gas would exceed this value. The REDOX type H$_2$S removal systems that were to be included in the system would not have a significant effect on this concentration, or, at least, would not reduce the organic sulfur loading to a point that would allow achievement of the overall sulfur limit. It was, therefore, necessary to add a step to convert the COS to H$_2$S. It was decided to include a hydrolysis reactor to convert COS to H$_2$S using the reaction:

$$\text{COS} + \text{H}_2\text{O} \rightarrow \text{H}_2\text{S} + \text{CO}_2$$

Initially the Chinese supplier for the 888 REDOX system which EPIC intended to use provided a design which incorporated a wet absorber to reduce the H$_2$S concentration, followed by a heater, then the hydrolysis catalytic reactor, a cooler and a second wet absorber to remove the H$_2$S produced in the hydrolysis step. There were several inquiries
about this arrangement resulting in the conclusion that it is a reasonably standard arrangement for treating sour gas.

Original Process Train  
With Two Wet Absorbers

The initial design used the process line up proposed by the Chinese. A preliminary cost estimate indicated that this would be prohibitively expensive. An alternative was developed using a dry adsorbent reactor for the final H₂S removal. This was perceived as saving a significant investment in additional pumps and as saving in operating power.

Revised Process Train  
With Dry Adsorbers

This approach was carried until the 888 REDOX system was dropped for other reasons discussed below. At that time, an inquiry was made to Sud Chemie about doing a sour shift hydrolysis. The response was that at the concentrations of H₂S that were specified, even for the high sulfur coal, this was possible. The Sud Chemie catalyst would operate
at approximately 280 -300° F. This still required a heater to reheat the sour gas after the venturi and a cooler to cool the fuel gas before the mercury adsorbers and the REDOX H2S system. The advantage was that shifting the COS before the REDOX system eliminated a second H2S removal step.

**Final Process Train**

**With Hydrolysis Before REDOX System**

**H2S System Change**

The original concept was to use the catalytic reduction-oxidation H2S removal system designed by Changchun Dongshi Technology Trading Company, Ltd (Dongshi) of Changchun, Peoples Republic of China. This system uses a proprietary catalyst to promote oxidation of the NaHS formed in the reduction phase in the absorber tower. The 888 catalyst acts as an oxygen carrier. It adsorbs oxygen on the surface of the catalyst and then releases it as the oxygen in solution is depleted by reacting with the NaHS. This is an improvement on the Stretford process which uses a Na2CO3 - NaHCO3 solution to absorb the H2S from the gas stream. The oxidation step uses the traditional sulfur foam generating type of oxidation tank where the sulfur crystals are relatively small (5 microns diameter) and are floated to the top of the tank and over a weir by the foam formed with the injection of the oxidizing air. The preliminary estimates for the cost of the system as designed by Dongshi was rather high compared to competing systems. The costs were seen to be in the packed tower absorbers and in the oxidation tanks. The absorbers were designed with three levels of random dumped packing, each level 5 meters deep. The oxidation tank, due to the nature of the oxidation was to be 8 meters in diameter and 8.75 meters high. In addition, the system required a separate tank to collect the sulfur foam from the overflow section. Finally, the system uses melters to remove the sulfur from the solution yielding a molten sulfur product.

It was decided to develop a design of an alternate absorber and oxidation vessel using the 888 catalyst. The absorber was envisioned as either an open spray tower or a mobile bed tower or a combination of the two types. The intent was to use a cone bottom oxidation
tank and to produce sulfur crystals large enough to settle to the bottom of the tank as a concentrated slurry which could be pumped directly from the cone bottom. After several months of effort to characterize the kinetics of the 888 reactions adequately to design a system, it was concluded that there was not enough data forthcoming to complete a design. A preliminary design was included in the FEL II estimate in March. The costs were significantly higher than the competing, commercially available system. It was decided to replace the 888 system with the LO CAT® offered by Gas Technology Products, LLC.

The LO CAT® system uses a chelated iron intermediary rather than a catalyst to promote the reactions and uses KOH as the reagent as opposed to the Na₂CO₃ - NaHCO₃ reagent. The LO CAT® also uses a mobile bed absorber and recirculates a slurry containing 3 – 5% by weight sulfur crystals. This allows crystal growth to result in settling of the sulfur in the cone bottom of the oxidation tank. The tank is approximately 16 feet in diameter. Finally, this system uses vacuum filters to produce a dry appearing, damp powder product which is perceived as preferable to molten sulfur. The vacuum filters also allow some operational flexibility which eliminates any requirement for a blowdown stream from the absorber loop.

Waste Water Handling

The EPIC gasification system is envisioned as a zero liquid discharge facility. The original concept was to collect the blow down from the venturi loop (or WESP), the condensate from the fuel gas cooler, the water discharge from the tar/oil water separator, any process sump discharge and any other blow down streams in the waste water tank. From there, the waste water would be fed to once trough steam generators (OTSG) located on the lower gas outlet of each gasifier. The steam from the flash tank would be fed to the gasifier as process steam and the underflow brine from the flash tank would be injected into the gasifier as liquid through nozzles in the gasification zone.

The loop was originally designed with the venturi discharge and the condensate from the cooler going to the separator independently. The first modification was to use the cooler condensate as the make up to the venturi loop as opposed to introducing fresh water into this loop. This resulted in a significantly smaller amount of water circulating in the system. Also, at the FEL II stage a vendor was identified who would offer an inclined plate separator to replace the API type separator.

It was at the FEL II stage that the problem of the OTSG came to light. We were unable to obtain any bids for boilers of any type using the waste water. After examining the objections of the vendors, it was decided to add a water treatment system to produce boiler feed water from the waste water. The brine from the water treatment system would be used to wet the ash as it was loaded for disposal. Two vendors offered preliminary systems for this function, but neither would offer a firm bid. In both cases the vendor required a steam stripper to remove the phenols and ammonia from the waste water prior to treatment. One system envisioned using a reverse osmosis step to produce fresh water and concentrate the brine, followed by a crystallizer to further concentrate the brine and
produce more fresh water. The other vendor proposed to use chemical oxidation followed by microfiltration to produce the clean water and brine.

Water Jacket Upgrade

The final process change involved the water jacket of the gasifier. As originally designed the water jacket produces steam at approximately 10 psig. This is sufficient to inject into the gasifier when the gasifier is operated at atmospheric pressure, as in China. EPIC intends to operate the gasifiers at approximately 14 psig to increase the production rate. At that pressure, 10 psig steam is not usable. And, in any case, the intent was to use steam produced from the waste water using the lower gas heat. It was decided to have AKTS redesign the gasifier steam jacket to produce 55 psig steam. This steam is now used in the sour gas heater for the hydrolysis reactors.

RELIABILITY REVIEW

As a part of the FEL II review, an analysis was made of factors which could lead to interruptions in the plant operation. There were several areas which were felt to be vulnerable: the coal handling and storage system; the tar-oil/water separators; the venturi system; and the entire line up of single reactors. The rationale for each area is discussed below along with descriptions of the changes that were made.

Coal Handling & Storage

The original lay out of the coal delivery system used a single belt conveyor line to move the combined coal and agglomerated material to a pair of 500 ton storage bunkers located in a building bay beside the gasifiers. From each bunker a single flex wall type elevator moved the coal to a shuttle belt conveyor. Each of the reversing, shuttle belt conveyors would fill two surge hoppers atop the gasifiers. Each gasifier would have an individual surge hopper.

There purpose of the 500 ton bunkers was to provide a surge capacity in case the coal conveyors failed. The analysis indicated that providing a system of redundant conveyors should be more cost effective. The system was redesigned to incorporate dual belt conveyors (one operating, one standby) from the agglomeration building to a surge bin located above the gasifiers in one end of the structure. From this bin, two drag chain conveyors (one operating, one standby) would be fed with variable speed feeders. The drag chains would go to each gasifier feed bin with an open chute connection. As each bin was filled, the coal would be dragged to the next bin. The feeder speed is to be varied to maintain a full surge bin at the last gasifier in line. An overflow chute is provided to empty the conveyors as required. This system has complete redundancy from the agglomeration building to the individual gasifier feed bins.
Coal Bunker Arrangement Elevation 1 and Elevation 2 (below)
Redundant Separators

The tar-oil/water API separator was identified in the reliability review as one element that could force a shutdown. At the same time, a review of the internal space velocities in the gasifier showed that the carryover of coal dust and ash had been overestimated. The space velocities in certain critical areas are low enough to preclude any significant carryover of coal dust or ash. Accordingly, the specifications for the cyclones and venturi were revised. The resulting material balances showed that the requirement for an API type separator with the drag chain and screw conveyor to discharge ash was no longer there. A vendor had responded with an offering of an inclined plate separator at a substantial savings vs the API separator. The decision was made to use the inclined plate separator and to use two parallel separators, one operating and one spare, to increase the reliability of the operation. The arrangement also allows for both separators to be operated should the separation require more retention time than anticipated.

Parallel Reactors

With the exception of the venturi, the sour gas heater and the gas cooler, the balance of the gas train consists of unit operations each of which has two parallel reactors. This is true of the COS hydrolysis, mercury adsorption, initial H\textsubscript{2}S absorption in the mobile bed absorber and for the H\textsubscript{2}S scavenging in the packed towers. This came about, in part, by the desire to keep the tank and tower diameters less than 14 feet (12 feet if possible) to maximize shop fabrication and reduce field manhours. This has the added benefit of allowing approximately 55 – 60% of the production to continue to be treated if there is a problem with one of the two reactors. The analysis concluded that the spare pump associated with the venturi will suffice to provide reliability for the venturi. The sour gas heater and gas cooler are designed so that individual tubes can be temporarily plugged if necessary.

**TASKS 4 – 8**

**PLANT DESIGN PREPARATION**

The initial plant layout and design was prepared to support the FEL II estimating phase. At this point detailed P&IDs were prepared along with initial issues of the General Arrangements and Electrical Single Line Diagrams and an Instrumentation Configuration Diagram. Preliminary foundation designs were prepared to estimate the foundation materials and equipment data sheets were prepared for all of the major equipment items and systems. Budget quality bids were obtained for major equipment and subsystems to support the FEL II estimate.

After the process revisions identified in the FEL II review were implemented, these documents were revised and refined to support the FEL II estimating
TASKS 9 – 18
FORMAL COST DETERMINATION

After implementation of the process and design revisions which arose from the FEL II and Reliability reviews, formal documents were prepared and used to produce a more accurate FEL II estimate.

The preliminary General Arrangement drawings were extended to include plan layouts at each operating level of the gasifier structure, and to include additional sections of the balance of the equipment layout.

Equipment data sheets were revised to reflect the changed process conditions and to incorporate, in some cases, calculated values as opposed to estimated values for equipment sizing.

Bulk material take-offs were revised to reflect the process and arrangement revisions and were extended to include areas which were previously estimated from historical records and factors. An example of this sort of refinement was in the bulk piping estimate. The FEL II estimate was initially based on actual take-offs for pipe over 4” in size and a factored estimate for under 4” pipe based on historical data. When the estimate was challenged additional take-offs were done for the under 4” pipe. These, along with the more complete take-offs prepared for the FEL II stage indicated that the smaller pipe accounts for roughly 50% of the pipe in this project as opposed to the 10 – 15 % factor typically used in FEL II estimates.

At this stage, firm price bids were requested from vendors for essentially all of the major equipment and all of the subsystems. It was at this juncture that the current level of construction activity caused a problem. Many vendors were unable or unwilling to devote the time and effort to prepare firm bids to support the study.

TASKS 19 & 20
ENGINEERING AND CONSTRUCTION SCHEDULES AND ESTIMATES

Aker-Kvaerner Technical Services prepared a detailed engineering schedule for the project and from this schedule prepared an estimate of engineering manhours and costs.

Working with the assistance of Aker-Kvaerner Songer Construction, a construction schedule and estimate was prepared. This was based on a recent survey of construction labor rates in the Springfield area.
**TASKS 21 & 22**

**FINAL COST CONSOLIDATION**

As bids were received for the equipment and subsystems, questions and clarifications were pursued with the vendors and evaluations were prepared. Bid evaluations were prepared and the selected bids were incorporated into the overall cost tabulation.

As noted above the final estimate is could not be brought to the ±10% level due to the budget nature of some major subsystem bids. The overall accuracy is considered to be +20% - 10%.

**AREAS FOR FURTHER INVESTIGATION**

The project brought to light several areas where further study may result in some economic benefit. Most of these areas arise due to the nature of the systems in Asia. The gas clean-up requirement is much less stringent. The systems are relatively simple and provide no suitable testing locations. Any feedback of operating experience is through the medium of annual users’ conferences where papers are presented.

**Particulate, Tar & Oil Concentrations, Composition and Particle Size Distribution**

As a result of system designs, there is very little operating data on such parameters as the particle size distribution of dust or ash in the fuel gas exiting the gasifier. The same is true of the exact composition, break down and mist particle size for the tars and oils in the fuel gas exiting the gasifier. This uncertainty has led to the adoption of the variable throat venturi. Among the devices considered for tar/oil and particulate removal the venturi is the least sensitive to variations in particle size distribution and to the composition of the tar/oil portion. Investigation in this area, particularly the opportunity to test operating gasifiers, could lead to the elimination of either of the particulate removal cyclones, and, ultimately, to the adoption of ESP’s and/or WESP’s for this area.

**H₂S: COS Ratio**

Data exists from operational Lurgi gasifiers that shows the COS fraction will be 4 -6% of the total of sulfur species in the fuel gas. The literature search and anecdotal evidence show a ratio of approximately 10% of the total sulfur occurring as COS. For the current project, a design basis of COS being equal to 10% of the total sulfur was adopted. Clearly, this ratio can be a function of the particular coal being used, as well as a function of the gasifier operation. Refinement of this estimate may lead to a reduction in the amount of the hydrolysis catalyst required. This could have a significant impact on the overall economics of the facility.
Waste Water Analysis & Treatment

As discussed above, the original concept of using the reclaimed, or waste, water to produce gasification steam in a once through steam generator was replaced when no vendors would quote the OTSG. A final selection for the waste water treatment system could not be made because definitive bids were not forthcoming for this system. There were two possible schemes put forward by vendors. Both systems required steam stripping of the waste water to remove the bulk of the organic compounds. This was incorporated into the design.

The first system would have employed a reverse osmosis separator to produce clean water and brine. The brine would be further concentrated in a crystallizer, producing more clean water. The concentrated brine could be used to wet the ash as it is loaded for disposal.

The second system proposed using chemical oxidation to produce insoluble salts, followed by microfiltration to produce the clean water. The microfiltration blow down would again be used to wet the ash.

The final choice of a system, or the possibility of coming to an agreement with a vendor for the boiler, is an area of continuing effort.

OTHER ACCOMPLISHMENTS

There were two other areas of investigation undertaken during the project. The first was to examine the caking tendencies of various coals during the slower heating cycle used in the EPIC 2ST-3.6 gasifier. The second was a survey of Illinois coals to determine the relative applicability of the coals as gasifier feed stock.

Free Swelling Index Investigation

Almost since the invention of the fixed bed gasifier, the guideline for selection of coal included limiting the free swelling index to 2.0 or less. This was to avoid caking of the coal in the fixed bed. This caking could lead to channelized flow and improper devolatilization of some portion of the coal.

The standard test for Free Swelling Index is ASTM D 720 – 91, Standard Test Method for Free-Swelling Index of Coal. In reviewing this standard two items draw attention.

First, in the first paragraph the standard states “The results may be used as an indication of the caking characteristic of the coal when burned as a fuel. The test is not recommended as a method for the determination of expansion of coals in coke ovens.” Since the upper stage of the two stage gasifier is in essence a coke oven, this would indicate that the standard is not necessarily applicable.

Second, the standard requires introducing the sample into an oven at 800 ± 10º C (1472 ± 18º F) and then heating the sample to 850 ± 5º C (1508 ± 9º F) in one additional minute.
The two stage gasifier introduces the coal into an area that is between 280 – 400 °F and then heats it to approximately 1500 °F over a period of several hours. It was postulated that this slower, more gentle heating cycle may result in a different caking tendency for the coal. Accordingly, an EPIC Modified FSI procedure was developed by Robert Jackson and George Becker. Samples of three different coals were obtained through the cooperation of Peabody Energy. The samples were tested using both the ASTM standard and the EPIC Modified procedure. The tests were conducted by SGS Mineral Services in St. Rose, LA.

Three coals were tested: NARM, a Powder River Basin subbituminous coal, Black Beauty, an Illinois coal, and Willow Lake. With the slower heating of the EPIC Modified procedure none of the three coals formed the characteristic “coke button”. In fact, the NARM coal reduced in volume almost to the point of being consumed. In the standard ASTM test the coals were assigned FSI numbers of: NARM – 0; Black Beauty - 2.5; and Willow Lake – 5.0. We conclude that coals with a Free-Swelling Index of up to 5.0 can be used in the EPIC 2ST-3.6 gasifier. It would be prudent, however, to test any proposed coal using the EPIC Modified procedure.

A copy of the EPIC Modified procedure is included on a CD-ROM with this report.

Survey of Illinois Coals

As stated above, the design coal used for the base design in this project was an amalgam of Illinois coals constructed to give a representative plant design which would be applicable across a number of coals. Performance calculations were prepared for five Illinois basin coals, the design coal and one Powder River Basin (PRB) coal. An index of relative gasification efficiency was calculated for each. The following table shows these results.
<table>
<thead>
<tr>
<th>ITEM</th>
<th>DESIGN COAL</th>
<th>GATEWAY</th>
<th>RIOLA</th>
<th>ILLINOIS MEDIUM SULFUR</th>
<th>WILLOW LAKE</th>
<th>TURRIS</th>
<th>TYPICAL PRB</th>
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<tr>
<td>Carbon</td>
<td>60.34</td>
<td>63.85</td>
<td>61.28</td>
<td>60.28</td>
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<td>3.84</td>
<td>4.49</td>
<td>4.63</td>
<td>4.46</td>
<td>3.48</td>
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<tr>
<td>Nitrogen</td>
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<td>1.41</td>
<td>1.31</td>
<td>1.17</td>
<td>1.36</td>
<td>1.11</td>
<td>0.58</td>
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<tr>
<td>Oxygen</td>
<td>9.37</td>
<td>5.37</td>
<td>5.51</td>
<td>9.36</td>
<td>6.44</td>
<td>7.44</td>
<td>11.47</td>
</tr>
<tr>
<td>Sulfur</td>
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<td>1.50</td>
<td>3.20</td>
<td>2.78</td>
<td>3.31</td>
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<td>13.50</td>
<td>8.26</td>
<td>10.50</td>
<td>8.70</td>
<td>16.98</td>
<td>26.68</td>
</tr>
<tr>
<td>Ash</td>
<td>11.00</td>
<td>8.60</td>
<td>18.30</td>
<td>11.00</td>
<td>9.44</td>
<td>9.30</td>
<td>5.32</td>
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<td><strong>EPIC Index</strong></td>
<td><strong>9.62</strong></td>
<td><strong>9.69</strong></td>
<td><strong>9.56</strong></td>
<td><strong>9.65</strong></td>
<td><strong>9.66</strong></td>
<td><strong>9.72</strong></td>
<td><strong>10.00</strong></td>
</tr>
</tbody>
</table>
CONCLUSIONS AND RECOMMENDATIONS

The project developed viable process designs for the gasification facility for two coal specifications. The coals chosen represent a bracket of the range of coals expected to be used in facilities of this type. Several process arrangements were considered. The final arrangement represents the best fit for the current design criteria, including some very helpful vendor input. EPIC is in a position to offer this design for customers using a wide variety of Illinois and other coals.

The Total Installed Cost estimates which were developed are as accurate as is possible given the reluctance of vendors, in today’s market, to devote a significant amount of time to quotes to support a study. The engineering, construction and project support costs are accurate to within ± 10 %, and the bulk material take-offs and costs have a similar level of confidence. The equipment costs are less certain because firm prices for certain major subsystems could not be obtained.

There are some alternate systems for the hydrogen sulfide removal, COS hydrolysis or removal, and waste water usage which will continue to be investigated. These may or may not result in improvements in the plant economics.

Efforts to refine the area of water treatment and boiler design are continuing with the goal of arriving at a design which reduces the amount of treatment required while maintaining an acceptable operating regime for the steam generation.

The cost estimate will be updated as projects are designed and procured. At that time, more accurate costs for some of the major systems will become available.

The items identified in the body of the report as areas for further investigation are primarily those for which engineering judgment and theoretical calculations have gone as far as is reasonably possible. Further refinement of these design criteria will require either a test facility or an operating plant where extensive testing can be conducted. A potential host site for a test facility has been identified in Illinois which could benefit a broad spectrum of Illinois industries and coal suppliers.

REFERENCES

McKee Engineers and Constructors, 1979, Demonstration Plant Design Manual, Erie Mining Company, Coal Gasification Project, Department of Energy Contract Number ET-78-C-01-2578.

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