Clean Coal Technology Program

Advanced Coal Conversion Process Demonstration

A DOE Assessment

DOE/NETL-2005/1217

U.S. Department of Energy

Office of Fossil Energy

National Energy Technology Laboratory

April 2005

Disclaimer

Contents

List of Figures

List of Tables

Executive Summary

The U.S. Department of Energy's (DOE's) Clean Coal Technology (CCT) Program seeks to offer the energy marketplace more efficient and environmentally benign coal utilization technology options by demonstrating these technologies in industrial settings. This document is a DOE post-project assessment of one of the projects selected in Round I of the CCT Program, the Advanced Coal Conversion Process Demonstration.

High moisture content and low heating value make it expensive to ship subbituminous coal from the Powder River Basin and other sites to eastern and midwestern power plants. Western Energy Company (WECo) submitted a proposal to DOE to demonstrate a new process for lowering the moisture and sulfur contents and increasing the heating value of low rank coals. In September 1990, DOE awarded a cooperative agreement to WECo. In March 1991, the cooperative agreement was transferred to Rosebud SynCoal Partnership, created by WECo, to conduct this project. DOE provided 41 percent of the total project funding of $105.7 million. Test operations of the Advanced Coal Conversion Process (ACCP) unit, which was sited at Colstrip, Montana, adjacent to WECo's Rosebud Mine[1], commenced in June 1992. The ACCP project, with a design capacity of 68.3 tons of feed coal per hour, was completed in May 2001, at which time the plant was shut down. The demonstration unit was sized at about one tenth of the projected throughput of a commercial facility, which would consist of multiple trains.

Under the right conditions of temperature and pressure, organic matter in nature undergoes a coalification process as peat is gradually converted to lignite, subbituminous coal, bituminous coal, and finally to anthracite. This transition, in which the rank of the coal increases, is characterized by a decrease in the oxygen content of the coal and an increase in the carbon to hydrogen ratio. Lignite and subbituminous coals are young and typically have high inherent (bound) moisture and oxygen contents and correspondingly low heats of combustion. In essence, the ACCP greatly increases the rate of coalification and, in effect, raises the rank of the feed coal. In addition to drying, the major reactions that occur in the ACCP are dehydroxylation, decarboxylation, and decarbonylation through the removal of -OH, -COOH, and =CO functional groups as H_2O, CO_2, and CO. These are basically the same reactions that take place during coalification.

The ACCP is a three-stage process consisting of a first-stage dryer/reactor, a second-stage thermal reactor, and a product cooler. Raw coal, sized at 1½ inch by ½ inch, is fed to the first stage dryer/reactor, where it is heated to remove primarily surface water by direct contact with hot combustion gas (from a natural gas-fired heater) that is mixed with recirculated gas from the dryer. The dried coal is then fed to the second stage thermal reactor, which further heats the coal using a recirculating gas stream, removing water bound in the pore and surface structures of the coal and promoting chemical dehydration, decarbonylation, and decarboxylation. Particle shrinkage that occurs in the second stage liberates mineral matter and enables physical cleaning of the coal.

The coal exiting the second stage reactor drops through vertical quench coolers, where it is cooled by a process water spray. The coal then enters a vibratory cooler, where it contacts cool inert gas. The coal, cooled to below 150 ^{o}F, enters the cleaning system where it is screened into four size fractions that are fed in parallel to four deep-bed stratifiers where rough specific gravity separations are made. The low gravity (light) streams from the stratifiers are sent to the product conveyor. The high gravity (heavy) stream of the smallest size fraction is sent directly to the waste conveyor, but the heavy streams from the other size fractions are sent to fluidized

---

[1] At the end of April 2001, Westmoreland Coal Company acquired all of the capital stock of Entech's five coal related direct subsidiaries, including Western Energy Company and its wholly owned entity, Western SynCoal LLC. The SynCoal® plant was immediately shut down and permanently closed shortly thereafter. EnPro, LLC, of Wyoming purchased Western SynCoal and three associated DOE contracts from Westmoreland on January 3, 2003.

bed separators that split the processed coal into light and heavy streams. The light streams are sent to SynCoal® product handling, and the heavy waste streams, containing a high concentration of mineral matter, are sent to disposal.

The SynCoal® product is stored in a concrete silo from which it is loaded into trucks or train cars for transport to customers. The SynCoal® fines collected in the various particulate collection systems are combined and transferred to a 50-ton surge bin. Dust emissions from the plant are carefully controlled. Dust is removed from the gas exiting the vibratory cooler by twin cyclones, and the gas is cooled by water sprays before being recirculated to the vibratory cooler. Particulates are removed from the first stage process gas by a baghouse and from the second stage gas by cyclones. The baghouse prevents particulate emissions to the atmosphere.

From the start of the ACCP demonstration, the tendency of SynCoal® toward spontaneous combustion required storage of the product under an inert gas atmosphere or in a tightly sealed vessel to prevent air infiltration. A CO_2 inerting system was developed for silo storage of the SynCoal® product, and later an inert gas system was installed to reduce CO_2 costs.

After construction of the ACCP was completed in March 1992, plant operations commenced. Most startup equipment problems were solved by the middle of 1993. In May of that year, nearly 500 tons of SynCoal® was shipped to customers. In June, SynCoal® deliveries were initiated to several industrial customers. By August, the State of Montana had evaluated the facility and found it in compliance with the Air Quality Permit. The plant was able to reliably provide product to the market and was placed in service as a SynCoal® Production Facility on August 10, 1993. In addition to its improved heating value, test burns of SynCoal® at a variety of plants showed superior performance in both power generation (improved efficiency, cleaner burning) and environmental parameters (reduced emissions), thus demonstrating the beneficial qualities unique to SynCoal®.

From June 1992 through May 2001, the plant operated for 46,676 hours, processed 2,939,240 tons of coal, and shipped 1,980,279 tons of product. On average, the plant had an availability of 58.1 percent, a feed rate of 63 tons/hr, and an energy efficiency (percentage of energy input to the plant converted to salable product) of 83.7 percent. In addition to Rosebud coal, the ACCP plant successfully processed Powder River Basin (AMAX) coal from Wyoming, and Center Mine and Knife River lignites from North Dakota.

In addition to use as a fuel for power production, SynCoal® has a variety of industrial applications, such as use by cement, lime, and bentonite producers. SynCoal® was delivered to Ash Grove Cement, Holnam Cement, Wyoming Lime Producers, and Continental Lime. These companies found that SynCoal® improved both capacity and product quality in their direct-fired kiln applications, apparently because the steady flame produced by burning SynCoal® allowed tighter process control and improved process operation. Bentonite Corporation used SynCoal® as an additive in green sand molding for use in the foundry industry.

Two major problems were discovered with the SynCoal® product: dustiness and a tendency toward spontaneous combustion. Although SynCoal® has many desirable properties, the failure to satisfactorily solve the problems of dustiness and spontaneous heating made it impossible to ship and store the product in open containers, while the cost of closed containers with an inert atmosphere was economically prohibitive for bulk utility-type coal shipments.

The tendency of SynCoal® to spontaneously heat and combust is illustrated by the fact that when a SynCoal® pile of more than one or two tons is exposed to any significant air flow for periods ranging from 18 to 72 hours, the pile reaches temperatures at which spontaneous combustion or auto-ignition occurs. Spontaneous heating of run-of-mine low-rank coals is a common problem but usually occurs after open air exposure periods of days or weeks, not hours. However, thermally upgraded low-rank coals have universally displayed spontaneous heating tendencies to a greater degree than raw low-rank coals.

Because there are several steps in the production of SynCoal® in which the feed coal is fluidized in process gas or air that removes dust particles, the product is essentially dust free when it exits the process facility. However, the process changes the surface chemistry, eliminating the natural adhesive tendencies which normally hold dust particles to the coal surface; and, as occurs with all bulk materials, each transfer of the product degrades it and produces some dust. Additionally, because SynCoal® is dry, it does not have an inherent ability to trap small particles on its surface, thus allowing any dust particles that are generated by handling to be released and become fugitive.

A wide variety of additives and application techniques were tested in an effort to reduce dustiness and spontaneous combustion. A commercial anionic polymer applied in a dilute concentration with water provided effective, environmentally acceptable dust control. A companion product was identified that could be used as a rail car topping agent to reduce wind losses. The application of the dilute, water-based suppressant, known as dust and stability enhancement (DSE), also provided a temporary heat sink, helping to control spontaneous combustion for short duration shipments and stockpile storage. This work led to extensive investigation of stockpile management and blending techniques.

If the dustiness and spontaneous heating problems could be solved, the potential market for SynCoal® could include almost any coal-fired power plant. However, at its current state of process development, the market for SynCoal® is considerably more limited. Because of the upgrading and special handling costs, SynCoal® will be significantly more expensive than raw coal. Therefore, the market will consist of special situations where adding SynCoal® to the fuel mix will provide sufficient benefits to offset the additional cost. In particular, potential customers are plants with design or fuel related limitations that can benefit from decreased slagging, reduced SO_2 and NO_X emissions, and improved efficiency. In particular, power plants that have suffered derating as a result of switching to lower rank coals to meet sulfur emissions requirements are prime candidates for firing SynCoal®. The non-utility industrial sector could provide an interim market while other issues are being resolved, since these businesses are much more amenable to special handling, normally receive small quantities, and are much more sensitive to quality issues.

To evaluate the commercial potential of the SynCoal® ACCP, a reference plant design was developed. The reference plant design was based on integration of a SynCoal® module processing 100 tons/hr of lignite to provide fuel for Units 1 and 2 of the Minnkota Power Cooperative M.R. Young plant. There are a number of differences between the reference plant design and the demonstration unit, including different types of dryer/reactors and cooler, the absence of a coal cleaning step, and process heat being provided by steam from the power plant. These changes reflect a difference in philosophy in that the demonstration plant was designed as a stand-alone unit, while the reference plant was designed to be sited at a coal-fired power plant.

The capital cost estimate for the reference plant design, developed using vendor quotations for major process equipment and engineering factors for other direct costs, was $39.1 million (1997 dollars). Since this cost estimate was developed for a specific site, caution should be exercised when using it to estimate the cost of a facility at another location. Example economics were calculated using the above capital cost and the operating costs in Table 1.

Table 1. Operating and Maintenance Costs for Example Economics

Cost Element	Cost per Year
Variable Operating Costs	$8,000,000
Fixed Operating Costs	
Operating labor	$665,600
Administration	$113,150
Maintenance labor	$2,346,000
Maintenance materials	$351,900
Total O&M costs	**$11,476,560**

The example analysis assumes that the feed is typical Rosebud Mine coal with a product yield of 69.2 percent (i.e., both SynCoal® and fines are sold as product), providing an annual production rate for the plant of 515,265 tons of SynCoal®. Based on these values, the cost of SynCoal® is in the range of about $30-$40/ton ($1.25-$1.70/million Btu, based on a product HHV of 11,675 Btu/lb), depending on whether current or constant dollars are used. Since the estimate is for a SynCoal® unit located next to a power plant, no passivation or transportation costs are included. If either of these is needed, costs would be higher.

This economic analysis indicates that the cost of SynCoal® may be in the range where tax credits or some other subsidy would be required to make it economically competitive, in spite of the technical advantage of being clean burning with a high heating value. Further development may reduce capital and operating costs and improve process competitiveness.

The overall conclusion is that, although the technology worked essentially as promised, and the SynCoal® product had beneficial effects in a variety of applications, its deficiencies of dustiness and spontaneous combustion prevent its general entry into the marketplace. Thus, although there may be niche applications for the technology, the objective of demonstrating a broadly commercially viable process was not achieved.

I. Introduction

The U.S. Department of Energy's (DOE's) Clean Coal Technology (CCT) Program seeks to offer the energy marketplace more efficient and environmentally benign coal utilization technology options by demonstrating these technologies in industrial settings. This document is a DOE post-project assessment of one of the projects selected in Round I of the CCT Program, the Advanced Coal Conversion Process Demonstration, initially described in a Report to Congress by the U. S. Department of Energy (1990).

Subbituminous coal is an important fuel, primarily because of its relatively low sulfur content and large reserves. However, its high moisture content and low heating value make it expensive to ship from the Powder River Basin and other sites to eastern and midwestern power plants. The desire to demonstrate a new process for lowering the moisture and sulfur content and increasing the heating value of subbituminous coal prompted Western Energy Company (WECo) to submit a proposal to DOE. In September 1990, DOE awarded a cooperative agreement to WECo. In March 1991, the cooperative agreement was transferred to Rosebud SynCoal Partnership, created by WECo, to conduct this project. DOE provided 41 percent of the total project funding of $105.7 million.

Test operations of the Advanced Coal Conversion Process (ACCP) Unit, sited at Colstrip, Montana, adjacent to WECo's Rosebud Mine, commenced in June 1992. Operation of the ACCP was completed in May 2001. The independent evaluation contained herein is based primarily on information from the Western SynCoal Final Technical Report (2004), as well as other references cited.

II. Project/Process Description

A. Project Description

This project consisted of the construction and operation of an Advanced Coal Conversion Process demonstration plant. The objective of this project was to demonstrate a process for upgrading subbituminous coal by reducing its moisture and sulfur content and increasing its heating value. The ACCP unit, with a capacity of 68.3 tons of feed coal per hour (two trains of 34 tons/hr each), was located next to a unit train loading facility at WECo's Rosebud Coal Mine near Colstrip, MT. Most of the coal processed was Rosebud Mine coal, but several other coals were also tested. The SynCoal® produced was tested both at utilities and at several industrial sites. The demonstration unit was designed to handle about one tenth of the projected throughput of a commercial facility.

DOE originally awarded a cooperative agreement for the project to WECo, the coal mining subsidiary of Entech, Inc., Montana Power Company's (MPC) non-utility group in Colstrip, MT. To advance the development of this technology, Entech created Western SynCoal Company, which joined with Scoria, Inc., an indirect non-utility subsidiary of Northern States Power, to form the Rosebud SynCoal Partnership. In 1991, WECo formally transferred the cooperative agreement to the Rosebud SynCoal Partnership. Test operations at the plant began in June 1992, and the plant shut down in May 2001.

B. History of Process Development

The initial concept for thermally processing low-rank coal with low pressure, superheated, recycled gas was presented to Western Energy Company[2] by an independent consultant in 1981. It was hoped that this fuel would become an alternative to high-priced oil

---

[2] Montana Power Company was the common parent corporation of a group of directly and indirectly owned subsidiaries. One of Montana Power Company's wholly-owned subsidiaries was Entech, Inc., which, together with its subsidiaries (Entech Group), comprised the non-utility businesses of Montana Power Company. One of Entech Group's subsidiaries was Western Energy Company, a coal mining company.

and gas. Under contract to Western Energy, the consultant continued to develop the ideas necessary to show the potential benefits of this approach to coal upgrading technology. As those benefits were defined and explored, Western Energy developed a laboratory design. Equipment for a bench-scale, batch mode unit was procured, installed, and operated to substantiate the theoretical concepts involved. The results were sufficiently positive to warrant further development, which led to a contract between Western Energy and the Montana College of Mineral Science and Technology to construct and operate a 200 lb/hr continuous pilot plant. This plant was constructed in 1984 at Montana Tech's Mineral Research Center in Butte, Montana. The primary purpose of the experimental work was to develop a method for thermally processing subbituminous coal and lignite using low pressure, superheated, recycled gas derived from the feed coal to produce a clean, stable product.

About a dozen different coals were tested in the pilot plant. The total processing experience (mainly on Rosebud coal) was in excess of 300 tons of coal and 4,000 operating hours. The product was tested for storage, handling, transportation, and combustion characteristics. In addition, Combustion Engineering carried out a comprehensive characterization of the product and concluded that moisture content, ash slagging potential, abrasiveness, and sulfur content were all reduced.

The process under development was referred to as the Advanced Coal Conversion Process (ACCP). Section 29 of the Internal Revenue Code, which allows a credit for the production and sale of alternative fuels, including solid synthetic fuels produced from coal, provided the incentive that justified construction of a plant using the ACCP technology. One of the requirements for favorable treatment under Section 29 is that the coal, which is converted to a solid synthetic fuel, must undergo a substantial chemical change. In 1987, Western Energy received a private letter ruling which stated that the ACCP technology and the fuel resulting from its operation would qualify for favorable treatment under Section 29.

A critical component of the development strategy was the construction of a plant based on the ACCP technology. The Entech Group sought significant funding to assist in the construction of a multimillion-dollar, 300,000-ton-per-year ACCP plant at Colstrip, Montana. In pursuing the needed funding, the Entech Group sought independent investors and funding through DOE's CCT program.

DOE approved funding for an ACCP plant in Round I of the Clean Coal Technology Program, and awarded a cooperative agreement in September1990 to Western Energy Company. The cooperative agreement provided for DOE to contribute (up to a specified maximum amount) approximately one-half of the cost for developing, constructing, and operating the plant. The government funding is subject to a repayment agreement, which provides for repayment of the government's investment out of profits from the successful commercialization of the ACCP technology. Specifically, for a 20-year period, the government has the right to receive a specified amount per ton of production from any next-generation facility using the ACCP technology.

Western Energy's efforts to seek financing resulted in an agreement with Northern States Power Company to invest in the ACCP technology. This resulted in the formation in December 1990 of a general partnership, known as the Rosebud SynCoal Partnership, consisting of Western SynCoal Company (WSC), a wholly-owned subsidiary of Western Energy, and Scoria, Inc., a wholly-owned subsidiary of NRG Energy, Inc., which, in turn, was a wholly-owned subsidiary of Northern States Power. WSC was the managing general partner of the Rosebud SynCoal Partnership. Pursuant to a novation agreement (dated March 25, 1991), Rosebud Partnership assumed Western Energy's obligations under the cooperative agreement with the DOE. Relying on the private letter ruling received from the IRS by Western Energy, the Rosebud Partnership constructed an ACCP plant with the assistance of funding from DOE.

The design basis for the ACCP was developed from data collected during operation of a pilot scale unit. This pilot unit, operated from 1984 through 1992, was capable of processing

150 pounds of raw coal per hour. The pilot plant used a single reactor for the conversion process, which is markedly different from the two-reactor system employed at the ACCP. This modification was implemented to improve thermal efficiency. The ACCP uses a natural gas-fired heater for thermal process requirements. The major energy requirement of the conversion process is the removal of the moisture from the raw coal. While some chemical reactions transform the coal during processing, the contribution of these reactions to the thermal load is considered negligible. The moisture content of the raw coal and the SynCoal® are of considerable importance, as each impacts the required process energy.

The design basis developed from the pilot plant considered the reduction of the moisture content and the loss of fine material, defined as particles smaller than 20 mesh (0.83 mm), to the particulate removal system. On the basis of that data, each ton of raw coal would produce 0.69 tons of SynCoal® to be delivered to the cleaning system; 0.07 tons of material would be collected by the particle removal system.

Following the construction of the ACCP plant, the IRS reexamined the definition of substantial chemical change, and the private letter rulings of many synthetic fuel producers (including Western Energy's) were revoked. After completing its review of the matter, however, the IRS reinstated Western Energy's favorable ruling. The reinstated ruling noted that the ACCP plant had been constructed in reliance on the original ruling. The reinstated IRS ruling also noted that, although the chemical changes arising from the actual operation of the ACCP plant were not as dramatic as outlined in the original ruling, the changes were still sufficient to satisfy the chemical change standard.

DOE contributed approximately 48 percent of the funds used for the construction of the ACCP plant and continued to provide funding for the first months of operation in accordance with the original cooperative agreement. Although DOE had no further obligation to provide funding for plant operations, it judged the plant a success and, in light of its potential, modified the cooperative agreement to provide further financial assistance. Under the modified cooperative agreement, DOE provided additional operations-related funding (to cover a portion of the cash-flow deficit of the operation of the plant). DOE's funding to supplement operating costs ended in November 1997.

In late 1997, Scoria withdrew from the Rosebud Partnership. In order to maintain the partnership's existence, Western Energy formed an additional subsidiary, SynCoal Incorporated, to become the other general partner of the Rosebud Partnership. Western SynCoal Company reorganized its activities on December 31, 1999 to create more value by reducing administrative costs and better aligning its interests with those of WECo. Under the new structure, Western SynCoal and two other entities, SynCoal Inc. and the Rosebud SynCoal Partnership, were merged into Western SynCoal LLC to streamline the organizational structure.

At the end of April 2001, Westmoreland Coal Company acquired all of the capital stock of Entech's five coal related direct subsidiaries, including Western Energy Company and its wholly owned entity, Western SynCoal LLC. The SynCoal® plant was immediately shut down and permanently closed shortly thereafter. EnPro, LLC, of Wyoming purchased Western SynCoal and three associated DOE contracts from Westmoreland on January 3, 2003.

On December 4, 2001, Western SynCoal LLC was awarded U.S. Patent 6,325,001, "Process to Improve Boiler Operation by Supplemental Firing with Thermally Beneficiated Low Rank Coal," which summarizes the SynCoal® program pursuant to the terms of the Clean Coal Technology program. Essentially, the patent claims that if a boiler is using high moisture, low rank coal feedstock, the ACCP can be used to improve boiler efficiency while reducing NO_X and SO_X emissions. Waste heat from the power station can be used to drive the ACCP process, thereby saving power consumption in circulating cooling water. The milling process uses less heat to dry the feed, and total boiler emissions are reduced by the amount of water removed during the conversion. By utilizing a technology like the Aeroglide reactor, the SynCoal® process capital and operating costs would be reduced substantially.

C. Process Description

1. As-Built Plant

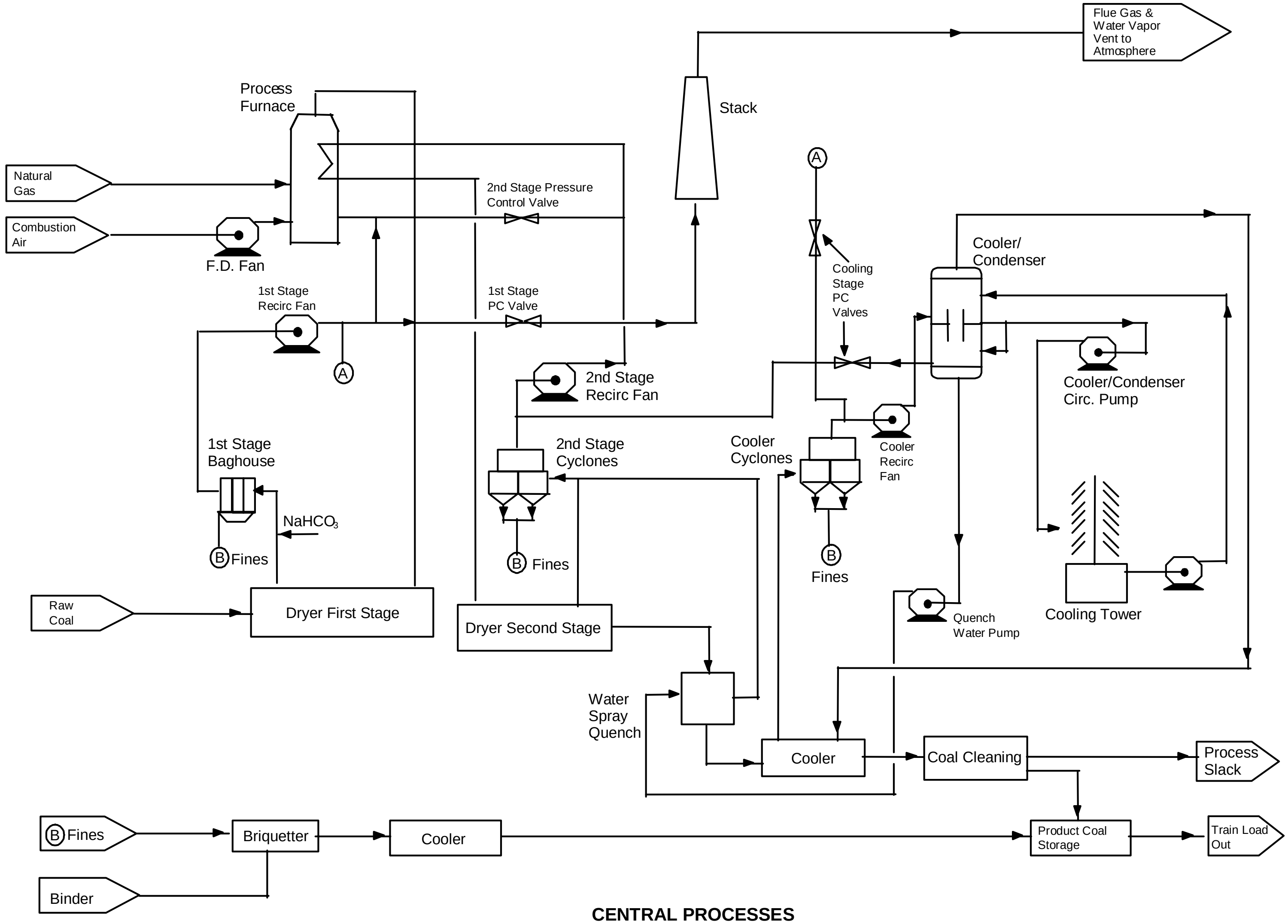
The ACCP facility is made up of two parallel units. Each unit consists of two 5 ft wide by 30 ft long vibratory fluidized bed thermal reactors in series, followed by a water spray section and a 5 ft wide by 25 ft long vibratory cooler. Each unit has a capacity of 34 tons/hr of coal. A more detailed description follows.

Figure 1 provides a simplified flow diagram of the as-built ACCP facility. Although the plant consisted of two identical parallel units, for simplicity, the following discussion describes only one of these units. Raw coal is first screened to produce a stream sized at 1½ inch by ½ inch, which is sent to a storage bin. Coal from this bin feeds the ACCP. In the first stage dryer/reactor, coal is heated by direct contact with hot combustion gases mixed with recirculated gas (almost 100 percent steam) from the dryer to remove primarily surface water from the coal. Coal exits the first stage dryer/reactor at a slightly higher temperature than required to evaporate water. The dried coal is then fed to the second stage thermal reactor, which further heats the coal using a recirculating gas stream to remove water bound in the pore and surface structures of the coal, and to promote chemical dehydration, decarbonylation, and decarboxylation. The superheated steam used as the heating agent in the second stage is produced from the water recovered from the coal. The particle shrinkage that occurs in the second stage liberates mineral matter and enables physical cleaning of the coal.

The coal exiting the second stage reactor drops through vertical quench coolers, where it is cooled by process water sprays. Steam created by this operation is drawn back into the second stage thermal reactor. The coal then enters a vibratory cooler, where it is contacted by cool inert gas. The coal, cooled to below 150°F, enters the cleaning system. Dust is removed from the gas exiting the vibratory cooler by twin cyclones, and the gas is cooled by water sprays before being recirculated to the vibratory cooler. Particulates are removed from the first stage process gas by a baghouse and from the second stage gas by cyclones. The baghouse prevents any particulate emissions from being released into the atmosphere. A dry sorbent, such as trona or sodium bicarbonate, can be injected into the gas entering the baghouse to react with sulfur dioxide (SO_2). The resultant salts are removed in the baghouse.

The ACCP was designed with three interrelated recirculating gas streams: one for the first stage reactor, one for the second stage reactor, and one for the vibratory cooler. Natural gas is combusted with air in a furnace. Before being sent to the first stage reactor, this hot gas passes through a heat exchanger where it heats the recirculated gas (consisting mainly of superheated steam) flowing to the second stage reactor. Makeup to the cooler gas stream is cooled furnace combustion gases that are routed to the cooler loop.

Some noncondensible gases (known as make gas), which include low-Btu combustible gases, are released from the coal in the second stage reactor. To keep this material from building up in the recirculated second stage gas loop, a slip stream is sent to the furnace, where it is burned as a supplemental fuel. Excess gas from the first stage reactor loop is discharged to the atmosphere through the stack. Gas exchange from the first stage loop to the cooler loop, from the cooler loop to the second stage loop, and from the second stage loop to the first stage loop (through the furnace) is controlled by pressure control valves. Gas exchange during operation is minimal from the first stage to the cooler and from the cooler to the second. However, gas flow from the second stage to the furnace can be substantial, due to the significant amount of make gas evolved from the coal in the second stage reactor. This quantity of make gas must be removed from the system to maintain steady state conditions.



MSE Drawing- Dated 11/8/92

Figure 1. Simplified Process Flow Diagram

The coal entering the cleaning system is screened into four size fractions: plus ½ inch, ½ inch by ¼ inch, ¼ inch by 8 mesh, and minus 8 mesh. These streams are fed in parallel to four deep-bed stratifiers, where a rough specific gravity separation is made using fluidizing air and a vibratory conveying action. The lower specific gravity (light) streams from the stratifiers are sent to the product conveyor. The higher specific gravity (heavy) streams from all but the minus 8 mesh stream are sent to fluidized bed separators. The heavy fraction of the minus 8 mesh stream goes directly to the waste conveyor. The fluidized bed separators split the coal into light and heavy fractions. The light streams are sent to product handling, and the heavy waste streams are sent to a storage bin for disposal, either as a useful product or for burial in a mined out pit.

The SynCoal® product is stored in a concrete silo from which it is loaded into train cars for transport to customers. The SynCoal® fines collected in the various particulate collection systems are combined and transferred to a 50-ton surge bin that either feeds the fines "hot" to a briquetter for reintroduction with the granular SynCoal® or diverts them to a ground level truck.

2. Process Modifications

During startup and operations, the ACCP facility was modified as necessary. Equipment was improved, additional equipment was installed, and new systems were designed, installed, and operated to improve overall plant performance. The most important modifications are discussed below.

In 1992, several modifications were made to the vibratory fluidized bed reactors and processing trains to improve plant performance. An unintentional internal process gas bypass that reduced the gas to coal contact was eliminated, and the seams were welded shut to reduce system leaks. The reactor bed deck holes were bored out in both the first-stage dryer/reactor and the vibratory coolers to increase process gas flow and reduce system pressure drop.

The originally designed, two-train tubular drag conveying system wore out too rapidly, which reduced its capacity to keep up with fines production. To operate closer to design conditions on the thermal coal reactors and coolers, obtain tighter control over operating conditions, and minimize product dustiness, the ACCP plant was converted to single train operation to reduce overall fines loading prior to modifying the fines handling system during the 1993 summer outage. One of the two process trains was removed from service by welding plates inside all common ducts at the point of divergence between the two process trains. This forced process gases to flow only through the one open operating process train.

The ACCP design included a briquetter for agglomeration of the process fines. However, operation of the plant as designed required that the briquetting system be completely operational. It was decided to delay operation of the briquetter to focus on successfully operating the plant; therefore, the process design was changed to include temporary fines disposal by slurry transport to an existing pit in the mine. During 1992, a temporary fines slurry disposal system was installed, and the redesigned process fines conveying and handling system was commissioned. Design of a replacement conveying system to deliver fines to either a truck loadout, slurry transport, or the briquetter was completed.

During 1992, a liquid carbon dioxide storage and vaporization system was installed for use in testing product stability and to provide inert gas for storage and plant startups and shutdowns. During the fourth quarter of 1994, an additional inert gas system was installed, that cooled and dried a portion of the combustion gas from the exhaust stack.

Because of increased truck sales volume, a truck loadout system was designed; installation was completed in October 1995. Previously, trucks were loaded through the existing train loadout tipple, but the tipple system was not adequate for large truck volumes, due to long load times and significant material losses related to improperly sized equipment, inaccurate loading, excessive labor charges, and interference with train loading. The new truck loadout system included handling equipment to transfer SynCoal® to a new 70-ton truck loadout bin from the 5,000-ton silo and a weighing system for accurately loading trucks.

From the start of the ACCP demonstration, the tendency of SynCoal® toward spontaneous combustion required storage of the product under an inert gas atmosphere or in tightly sealed vessels to prevent air infiltration. A CO_2 inerting system was developed for silo storage of the SynCoal® product, and later an inert gas system was installed to reduce the CO_2 costs.

It was originally assumed that sulfur dioxide emissions would need to be controlled by injecting chemical sorbents into the ductwork. However, preliminary data indicated that SO_2 production was significantly less than anticipated, meaning that the injection of sorbents was not necessary to control SO_2 emissions under operating conditions. A mass spectrometer was installed to monitor emissions and process chemistry, but the injection system was initially left in place, in the event that sulfur dioxide emissions reductions might be required.

3. Aeroglide Tests

In October 1999, SGI International and Western SynCoal signed a joint research and development agreement to test an Aeroglide tower reactor design for product char treating (finishing) and coal processing. This project included installation and operation of a small Aeroglide tower at the ACCP demonstration plant. Construction of the test system was completed in May 2000, and testing of char treating was completed in August 2000. Immediately following the conclusion of the finishing tests, coal thermal processing tests were initiated. Two runs were attempted in August and September 2000; but both were stopped, due to overheating problems in the cooling section of the test unit, before steady state conditions were established (Knottnerus and Bonner, 2001).

The tower test unit consisted of a 6 ft x 6 ft x 60 ft tall modified tower “grain dryer” manufactured by Aeroglide Corporation of Cary, NC. The complete unit included a surge bin, two indirect water cooling sections, seven direct gas contacting reactor sections, and a discharge assembly. The reactor sections allowed continuous contact between gas and coal, as the coal flowed downward through the test reactor. Solids flow and residence time in the test reactor were controlled by the speed of three rotary discharge valves in the discharge assembly. The surge bin at the top of the test reactor served as a gas seal between the process gas and the atmosphere, and as a control point for inlet solids. Gas could be circulated through the system by a process fan.

D. Need for the Technology Demonstration

Switching to low-rank coals has been a popular approach to meeting sulfur emissions limits because of their generally low sulfur content. However, in addition to being low in sulfur, these low-rank coals typically have high moisture contents and low heating values. This means that transportation costs, on a per Btu basis, are high for long distance shipping. In some cases, switching to low-rank coal has resulted in the derating of units. Therefore, any process that can increase the heating value of low-rank coals has tremendous economic potential.

Simple drying of low-rank coals has been tried, but has not proven satisfactory because the dried coal is pyrophoric and can spontaneously combust when exposed to the air. Although pilot scale demonstration of the ACCP indicated that SynCoal® would be stable, this had to be verified by subjecting larger batches to long-term storage tests. It was also necessary to have large enough batches to permit combustion tests in facilities typical of those operated by potential customers. Only after such a demonstration would commercialization of the technology be possible. Therefore, the ACCP demonstration project was essential to promote the technology.

E. Process Chemistry

Under the right temperature and pressure conditions, organic matter in nature undergoes a coalification process, as peat gradually converts to lignite, subbituminous coal, bituminous coal, and finally to anthracite. This transition is characterized by a decrease in the coal's oxygen content and an increase in the carbon to hydrogen ratio. Lignite and subbituminous coals are young and typically have a high inherent (bound) moisture and oxygen content and a correspondingly low heat of combustion. Essentially, the ACCP greatly increases the rate of coalification and, in effect, raises the rank of the feed coal. As the feed coal is heated and processed, the following changes occur:

- Moisture content is decreased
- Oxygen content is decreased
- Oxygen to carbon ratio is decreased
- Hydrogen to carbon ratio is decreased
- Sulfur content on a per unit heating value basis is decreased
- Fixed carbon is increased
- Aromaticity is increased
- Heating value is increased
- Ash content (after cleaning) on a per unit heating value basis is decreased

In addition to drying, the major reactions taking place are dehydroxylation, decarboxylation, and decarbonylation through the removal of -OH, -COOH, and =CO functional groups. Removal of these groups as H_2O, CO_2, and CO results in condensation of the coal's structure to increase its aromaticity, which in turn leads to a higher fixed carbon analysis. Table 2 presents analyses of three of the feed coals that were processed and analyses of the SynCoal® that was produced. Table 3 presents annual average feed and product analyses for 1995 through 2001.

The data in Table 2 indicate that to a large extent, when compared on a moisture free basis, both the volatile matter and the fixed carbon content of the feed coal are retained in the SynCoal® product. Normally, raw coal subjected to the temperatures used in the ACCP would undergo devolatilization. Experimental studies conducted by Solomon, et al., (1988) have shown that the degree of devolatilization of low rank coals is dependent upon the rate of heating. Slow heating, as is the case in the ACCP, favors dehydration and decarboxylation over devolatilization.

Table 2. Feed Coal and SynCoal® Analyses for Selected Coals

Feed Coal Source	**Rosebud Coal**			**Center Mine Lignite**			**Powder River Basin**		
Sample	**Raw Coal**	**SynCoal®**	**SynCoal® fines**	**Raw Coal**	**SynCoal®**	**SynCoal® Fines**	**Raw Coal**	**SynCoal®**	**SynCoal® fines**
Proximate Analysis, wt% (as received)									
Moisture	25.24	2.63	5.59	36.17	7.35	10.26	28.11	4.51	6.22
Volatile matter	29.16	36.98	35.32	27.13	39.39	36.33	31.78	41.40	39.00
Fixed carbon	36.68	51.19	49.65	30.16	46.74	43.92	35.25	47.48	48.48
Ash	8.92	9.20	9.44	6.54	6.52	9.49	4.86	6.61	6.30
HHV, Btu/lb	8,634	11,785	11,194	7,064	10,718	9,914	8,727	11,805	11,339
Equil. Moisture	24.9	14.7	20.2	34.98	20.12	21.92	28.38	14.04	20.2
Ultimate Analysis, wt% (moisture free)									
Carbon	67.61	70.00	68.64	66.19	69.24	65.94	69.13	70.13	69.20
Hydrogen	4.45	4.83	4.63	4.10	4.44	4.17	5.13	5.16	4.86
Oxygen	14.00	13.88	14.65	16.86	17.50	17.10	17.42	16.12	17.57
Nitrogen	1.02	1.26	1.16	0.92	0.95	1.04	1.09	1.20	1.14
Sulfur	0.99	0.58	0.92	1.68	0.83	1.18	0.47	0.47	0.51
Ash	11.93	9.45	10.00	10.25	7.04	10.57	6.76	6.92	6.72
C/H molar ratio	15.18	14.50	14.83	16.13	15.61	15.82	13.47	13.58	14.23
Petrographic Analysis, vol%									
Huminite	68.1	69.5	68.7	73.4	85.1	74.5	73.4	85.1	74.5
Liptinite	7.8	6.0	4.4	4.2	4.4	5.2	4.2	4.4	5.2
Inertinite	16.2	18.9	21.1	16.2	6.4	14.1	16.2	6.4	14.1
Mineral matter	7.9	5.6	5.8	6.2	4.1	6.2	6.2	4.1	6.2
Reflectance	0.38	0.45	0.44	0.33	0.36	0.36	0.35	0.38	0.40
Other Analyses									
-COOH, wt%	0.85	0.26	0.46	0.53	0.17	0.31	1.02	0.15	0.41
ASTM classification	Sub-bituminous C	High vol. C bituminous	High vol. C bituminous	Lignite A	High vol. C bituminous	Subbituminous A	Subbituminous C	High vol. C bituminous	High vol. C bituminous

Table 3. Annual Average Feed and Product Analyses

Stream	Moisture, %	Ash, %	Sulfur, %	HHV, Btu/lb	SO_2, lb/10^6 Btu
1995					
Raw Coal	25.67	9.01	0.72	8,710	1.63
SynCoal®	1.86	9.12	0.80	11,936	1.33
Fines	4.80	10.30	0.83	11,257	1.47
Waste	1.55	32.04	4.00	8,519	9.96
1996					
Raw Coal	25.14	8.71	0.74	8,722	1.69
SynCoal®	1.95	8.88	0.71	12,114	1.17
Fines	N.A.	N.A.	N.A.	N.A.	N.A.
Waste	N.A.	N.A.	N.A.	N.A.	N.A.
1997					
Raw Coal	25.17	9.13	0.81	8,713	1.86
SynCoal®	1.72	10.00	0.96	11,869	1.62
Fines	N.A.	N.A.	N.A.	N.A.	N.A.
Waste	1.66	38.36	6.82	7,863	19.26
1998					
Raw Coal	24.69	9.63	0.99	8,766	2.26
SynCoal®	1.92	9.45	0.77	11,837	1.30
Fines	5.87	15.25	0.92	10,345	1.78
Waste	2.11	31.68	6.10	8,809	14.03
1999					
Raw Coal	24.46	9.96	0.91	8,723	2.08
SynCoal®	1.96	10.47	0.76	11,704	1.29
Fines	5.74	14.51	0.88	10,401	1.69
Waste	2.52	32.44	5.18	8,659	11.84
2000					
Raw Coal	24.17	9.30	0.78	8,864	1.76
SynCoal®	2.18	9.17	0.71	11,841	1.19
Fines	6.51	10.68	0.84	10,956	1.53
Waste	2.08	37.90	5.92	7,850	15.79
2001					
Raw Coal	24.20	8.65	0.72	8,976	1.60
SynCoal®	1.95	9.33	0.72	11,868	1.21
Fines	7.06	10.18	0.84	10,947	1.53
Waste	3.22	23.37	3.86	9,787	7.89

N.A. = Not Available

F. Project Objective and Statement of Work

The cooperative agreement awarded on September 21, 1990, states that the main objective of the project was to demonstrate a process to upgrade low-rank subbituminous and lignite coals and produce a stable upgraded coal product with a moisture content as low as 1 percent, a sulfur content as low as 0.3 percent, and a heating value up to 12,000 Btu/lb. A related objective was to demonstrate that the process could reliably operate in a continuous mode and produce technical, economic, environmental, and operating data to support commercialization of the technology by the industrial community and the electric power generation industry. The cooperative agreement further stated that the participant would be responsible for all aspects of the project. The work was divided into three phases: I. Design and Permitting; II. Construction and Startup; and III. Operation, Data Collection, and Reporting. This post project assessment deals mainly with Phase III, and only incidentally deals with Phases I and II.

In general, Phase III activities involved equipment testing and modification, data gathering using both online monitors and offline analyses of feed and product samples, combustion tests in utility and industrial boilers, environmental testing and evaluation, and economic analysis. A major goal was to determine the effect of process variables, such as temperature, residence time, and coal type, on process performance and product properties. As the project progressed, it became apparent that SynCoal® had two significant drawbacks: dustiness and a tendency toward spontaneous combustion. Considerable effort was expended to overcome these problems, which required resources that were originally intended to be expended on other aspects of the project.

Because of equipment problems and the difficulties indicated above, the startup phase of the project consumed about 15 months. To compensate for this delay, in May 1995, a Phase IIIB was initiated, which extended the project by 20 months and provided some additional funding. The goal of Phase IIIB was process optimization and commercial evaluation.

III. Review of Technical and Environmental Performance

A. Technical Performance

1. Operations

The ACCP was designed to process 68 tons of raw Rosebud Mine coal per hour with an availability of 75 percent. Each ton of feed was expected to produce 0.61 tons of cleaned SynCoal®, 0.10 tons of fines collected in the particulate removal system, and 0.07 tons of waste material containing high concentrations of ash and pyrite. Lost moisture and gases account for the rest.

Construction of the ACCP was completed in March 1992, and plant operations commenced that same year with equipment shakedown and process trials. Innovative technology demonstration plants inherently encounter startup difficulties, and the ACCP was no exception. Equipment suitability and operational questions were addressed well into the second quarter of 1993. In May 1993, nearly 500 tons of SynCoal® were shipped to customers. In June, SynCoal® deliveries were initiated to several industrial customers. By August, the State of Montana determined that the plant was in compliance with the Air Quality Permit. The plant was able to reliably provide product to the market and was placed in service as a SynCoal® Production Facility on August 10, 1993. By January 1994, SynCoal® was being supplied to Ash Grove Cement under a long-term contract.

Production and sale of SynCoal® continued through 1998, but was constantly limited by product storage capacity. An agreement in 1998 with the Colstrip Unit 2 generation station provided sales and consumption of all product not sold to other customers, allowing the facility to operate with greater overall availability. During this agreement period, 1999 and 2000, when operations were not constrained by product storage capacity, plant availability was 71.4 percent, very close to the target of 75 percent availability.

The agreement with Colstrip contained provisions to assess and monitor the performance of the product in terms of power generation and environmental parameters. Superior performance in both these areas indicates the beneficial qualities unique to SynCoal® beyond its improved heating value.

Final efforts focused on production optimization and high return product applications. SynCoal® was evaluated as a low-end activated carbon supplement to reduce or remove hydrocarbon contaminants from water sources in a joint effort with the DOE. Niche markets in metallurgy and industrial processing were also developed.

At startup, the ACCP demonstration did not meet the design product yields. In 1999, the reported loss was about 5.5 percent of the raw coal feed. For the first three quarters of 2000, the reported loss of about 5.1 percent resulted from normal operations and spillage. Each time the ACCP was put into service, there was a period when the raw coal was not adequately processed, and the product did not meet specifications. The same was true during shutdowns. These startup and shutdown losses appear to represent about 3.5 percent of the total feed coal, but would be reduced if the number of startup/shutdown sequences were reduced. Spillage occurred at various points and was not necessarily limited to product.

2. Mechanical Problems

As is true of almost any new plant, there were many equipment problems to be overcome. Some of the more important problems included: the rotary airlocks between process reactors were under-powered and jammed, shutting down the entire unit; the fines gathering and conveying system was severely undersized and wore out rapidly; and problems with fan bearings, conveyors, and the vibrating reactor vessels. In general, these problems were solved or mitigated by improved design, repair, or replacement. The lessons learned in overcoming these difficulties can be applied to the next generation of plants.

3. Alternative Feedstock Testing

Three different coals were fed to the facility in 1993 and early 1994. In May 1993, 190 tons of Center, North Dakota lignite was processed at the ACCP demonstration facility, producing a 10,718 Btu/lb product (52 percent increase in HHV) with 47 percent less sulfur and 7 percent less ash (see Table 2). In September 1993, a second batch of 532 tons of Center lignite was processed and yielded a product with a higher heating value of 10,567 Btu/lb (50 percent increase in HHV). Sulfur reduction was 48 percent, and ash reduction was 27 percent.

About 190 tons of this SynCoal® was burned in the Milton R. Young Power Station Unit 1, located near Center, North Dakota. This test showed dramatic improvement in cyclone combustion performance, improved slag tapping, and a 13 percent reduction in boiler air flow, reducing the auxiliary power loads on the forced draft and induced draft fans. In addition, the boiler efficiency increased from 82 percent to over 86 percent, corresponding to a decrease in heat rate of 123 Btu/kWh.

Test runs were also made on 290 tons of Knife River, North Dakota, lignite and 681 tons of Amax subbituminous coal from Wyoming. The SynCoals® produced from these feeds had higher heating values of 10,670 and 11,700 Btu/lb, respectively.

4. Test Burns

Test burns of SynCoal® were conducted at Montana Power's 160-MWe J. E. Corette Power Plant in Billings, Montana between mid-1992 and April 1996. These test burns involved 321,528 tons of dust and stability enhanced (DSE) SynCoal® in a variety of blends with coal (15-85 percent SynCoal®). Test results indicated that a fifty-fifty blend of SynCoal® and raw coal provided improved performance; SO_2 emissions were reduced by 21 percent at normal operating load with no noticeable impact on NO_X emissions. Furthermore, the use of SynCoal® permitted deslagging of the boiler at full load, thereby eliminating costly sootblowing operations. This also provided reduced gas flow resistance in the boiler and convection passage, thereby reducing fan horsepower and improving heat transfer in the boiler. The net result was an increase in steady state power generation capacity of about 3-MWe, while also reducing the frequency of scheduled load reductions necessary to deslag the boiler surfaces.

In addition to the test burn at the Corette Plant, test burns were also performed at other facilities, including Western Sugar Company, Holnam Cement, Inc., Dairyland Power, the University of North Dakota, Packaging Corporation of America, the Fremont Department of Utilities, Minnkota Power Cooperative, Colstrip Energy Limited Partnership, Wyoming Lime Producers, Pete Lien & Sons, Barrick Goldstrike, and Colstrip Unit 2. In general, these tests showed that SynCoal® performed well, and in some cases, proved to be far superior to the fuel it replaced.

5. Industrial Uses

In addition to use as a fuel for power production, SynCoal® has application in a variety of industrial settings, such as use by cement, lime, and bentonite producers. From 1993 to the end of the project, over 580,000 tons of SynCoal® was delivered to Ash Grove Cement, Holnam Cement, Wyoming Lime Producers, and Continental Lime. They found that SynCoal® improved both capacity and product quality in their direct-fired kiln applications, apparently because the steady flame produced by burning SynCoal® allowed tighter process control and improved process operation.

Bentonite Corporation used SynCoal® as an additive in green sand molding for use in the foundry industry. They found SynCoal® to be a very consistent product that allowed their green sand binder customers to reduce the quantity of additives and improve the quality of their castings.

6. Problems with the Product

Two major problems exist with the SynCoal® product: dustiness and a tendency toward spontaneous combustion. Although SynCoal® has many desirable properties, the failure to satisfactorily solve the problems of dustiness and spontaneous heating made it impossible to ship and store the product in open containers, but the cost of closed containers with an inert atmosphere was economically prohibitive.

The tendency of SynCoal® to spontaneously heat and combust is illustrated by the fact that when a pile of more than one or two tons is exposed to any significant air flow for periods ranging from 18 to 72 hours, the pile reaches temperatures at which spontaneous combustion or auto-ignition occurs. The temperature at which the SynCoal® was delivered to storage could be a factor, but this aspect was not fully investigated, because alternative product handling techniques were pursued first. Spontaneous heating of run-of-mine low-rank coals is a common problem, but usually occurs after open air exposure periods of days or weeks, not hours. However, thermally upgraded low-rank coals have universally displayed spontaneous heating tendencies to a greater degree than raw low-rank coals.

Because several steps in the production of SynCoal® fluidize the feed coal in process gas or air that removes dust particles, the product is essentially dust free when it exits the process facility. However, the process changes the surface chemistry, eliminating the natural adhesive tendencies that normally hold dust particles to the coal surface and, as occurs with all bulk materials, each transfer of the product degrades it and produces some dust. Additionally, because SynCoal® is dry, it does not have an inherent ability to trap small particles on its surfaces. This allows any dust particles that are generated by handling to be released and become fugitive.

A wide variety of additives and application techniques were tested in an effort to reduce dustiness and spontaneous combustion. A commercial anionic polymer applied in a dilute concentration in water provided effective, environmentally acceptable dust control. A companion product was identified that could be used as a rail car topping agent to reduce wind losses. The application of the dilute water-based suppressant, known as dust and stability enhancement (DSE), also provided a temporary heat sink, helping control spontaneous combustion for short duration shipments and stockpile storage. This work led to extensive investigation of stockpile management and blending techniques.

7. Operating Performance over the Life of the Project

This section provides general operating statistics over the life of the project, including information on typical material and energy balances, production rates, and shipment quantities.

a. Material and Energy Balance

A typical material and energy balance around the ACCP, based on testing conducted in May 1994, is shown in Figure 2. The results are for Rosebud coal, which is the coal that was normally processed through the ACCP demonstration facility. An energy conversion of 87.1 percent was achieved. Loss of moisture from drying the coal accounts for the weight difference between input and output.

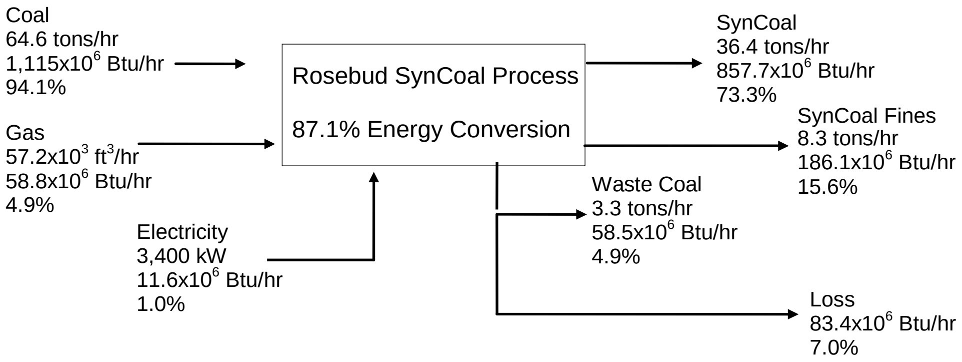


Figure 2. General Material and Energy Balance

Table 4 provides mass balance information on an annual basis for 1995 through 2001. This information is based upon total quantities into and out of the demonstration process facility.

The known weight loss is the water removed from the raw coal. The unknown weight loss is all the other unaccounted losses, including the noncondensable portion of the make gas.

Table 4. Yearly Material Balances

Year	Input, tons	Output, tons				
	Feed Coal	SynCoal®	Fines	Waste	Water	Unknown
1995	479,621	258,187	52,167	23,771	115,777	29,719
1996	370,395	198,274	44,409	18,520	86,852	22,340
1997	395,449	213,600	47,466	23,484	93,175	17,724
1998	163,272	87,679	19,485	9,751	38,824	7,533
1999	419,297	226,314	50,292	25,148	94,384	23,159
2000	441,380	292,052*	---	27,424	95,006	26,898
2001	112,931	73,500*	---	7,757	25,754	5,920
Total (1995-2001)	**2,382,345**	**1,349,606**	**213,819**	**135,855**	**549,772**	**133,293**
Average, %	**100.0**	**53.9****	**11.7****	**5.7**	**23.1**	**5.6**

* SynCoal®/fines blend
** Based on estimated fines production for 2000 and 2001

Table 5 shows energy balances for the plant on an annual basis for the years 1995 through 2001. All unaccounted for energy is identified as losses, which includes all combustible make gas and fines that were combusted in the process furnace. The overall average for these years was 83.7 percent of the energy input converted to salable product.

Table 5. Yearly Energy Balances

Year	Input, million Btu			Output, million Btu			
	Coal	Gas	Power	SynCoal®	Fines	Waste	Loss
1995	8,361,713	472,615	91,211	6,613,440	1,188,365	387,515	736,219
1996	6,462,652	363,793	77,989	4,774,438	1,037,661	310,613	781,722
1997	6,891,100	383,218	77,355	5,036,035	1,115,166	404,136	796,336
1998	2,950,229	158,497	37,566	2,065,936	444,122	171,788	464,446
1999	7,319,458	423,452	81,600	5,311,816	1,046,149	436,142	1,030,403
2000	7,824,788	337,092	86,919	6,916,424*	---	430,552	901,823
2001	2,026,749	98,153	21,654	1,744,193*	---	148,586	253,777
Avg, %	**93.9**	**5.0**	**1.1**	**69.6****	**14.1****	**5.1**	**11.2**

* SynCoal®/SynCoal® fines blend
** Based on estimates of fines production for 2000 and 2001

b. Summary of Operating Data

Figure 3 shows production as a function of design capacity during the life of the project. Early in the project, operating problems prevented achieving design capacity. However, after these problems were solved, there were periods in which the unit ran at or above the design production rate.

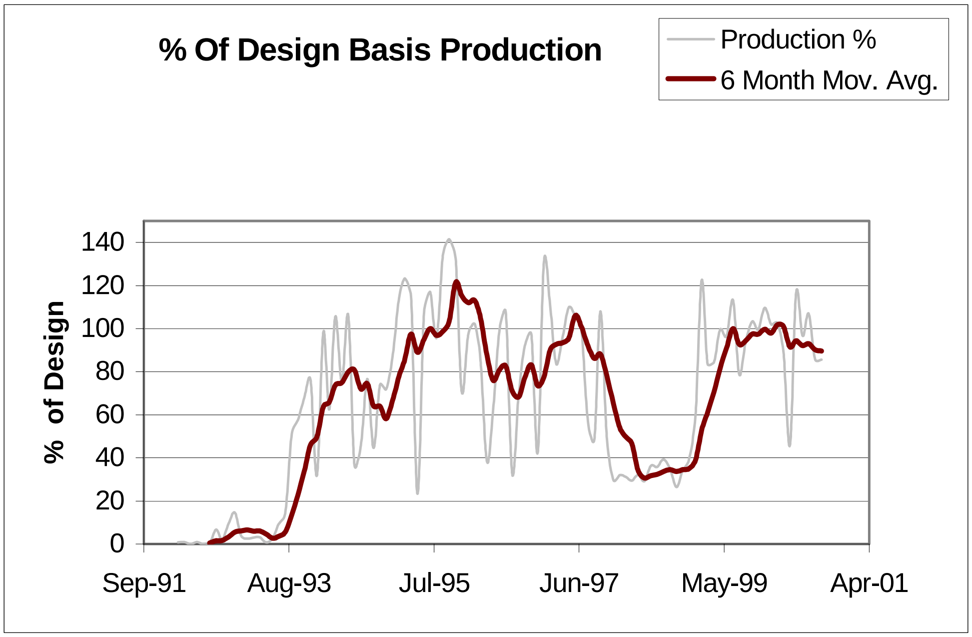


Figure 3. Production as Function of Design Capacity

The relationships in Table 6 were used to calculate the operating data for the ACCP demonstration over the life of the project. Table 7 provides a quarterly summary of the operating data.

Table 6. Operating Data Relationships

Quantity	Calculation
period, hr	days in reporting period x 24 hr/day
availability rate, %	100 x operating hr/period hr
average feed rate, tons/hr	tons coal fed/operating hr
rated design capacity, tons	days in reporting period x 1,232.88 tons/day
capacity factor, %	100 x tons processed/rated design capacity
forced outage rate, %	100 x forced outage hr/(forced outage hr + operating hr)

Table 7. Summary of Operating Data

Period	Hours			Rate		Feed, tons	Average Feed Rate, tons/hr	Capacity Factor, %	Shipments, tons
	Operating	Planned Maint.	Forced Outage	Avail-ability, %	Forced Outage, %				
1st Qtr ‘92	33	711	0	4.4	0.0	700	21.2	1.8	181
2nd Qtr ‘92	231	1,074	879	10.6	79.2	5,664	24.5	5.1	426
3rd Qtr ‘92	492	408	1,308	22.3	72.7	12,021	24.4	10.6	1,733
4th Qtr ‘92	601	656	951	27.2	61.3	10,301	17.1	9.1	3,226
Total ‘92	**1,357**	**2,849**	**3,138**	**18.5**	**69.8**	**28,686**	**21.1**	**7.6**	**5,566**
1st Qtr ‘93	1,020	373	767	47.2	42.9	21,735	21.3	19.6	5,202
2nd Qtr ‘93	811	413	960	37.1	54.2	20,441	25.2	18.2	1,712
3rd Qtr ‘93	973	157	1,078	44.1	52.6	36,703	37.7	32.4	6,561
4th Qtr ‘93	1,828	153	227	82.8	11.1	78,542	43.0	69.3	44,053
Total ‘93	**4,632**	**1,096**	**3,032**	**52.9**	**39.6**	**157,421**	**34.0**	**35.0**	**57,528**
1st Qtr ‘94	1,599	181	380	74.0	19.2	106,117	66.4	95.6	50,475
2nd Qtr ‘94	1,640	145	399	75.1	19.6	109,066	66.5	97.2	58,070
3rd Qtr ‘94	1,153	565	490	52.2	29.8	78,522	68.1	69.2	47,062
4th Qtr ‘94	1,336	135	737	60.5	35.6	77,084	57.7	68.0	49,840
Total ‘94	**5,728**	**1,026**	**2,006**	**65.4**	**25.9**	**370,789**	**64.7**	**82.4**	**205,447**
1st Qtr ‘95	1,665	79	416	77.1	20.0	112,725	67.7	101.6	68,223
2nd Qtr ‘95	1,439	662	83	65.9	5.5	98,712	68.6	88.0	65,360
3rd Qtr ‘95	1,896	24	288	85.9	13.2	134,530	71.0	118.6	80,010
4th Qtr ‘95	1,844	111	253	83.5	12.1	133,654	72.5	117.8	102,095
Total ‘95	**6,844**	**876**	**1,040**	**78.1**	**13.2**	**479,621**	**70.1**	**106.6**	**315,688**
1st Qtr ‘96	1,556	0	628	71.3	28.8	100,062	64.3	89.2	67,568
2nd Qtr ‘96	1,115	820	249	51.1	18.3	75,095	67.4	66.9	46,445
3rd Qtr ‘96	1,361	581	266	61.6	16.4	85,006	62.5	74.9	60,035
4th Qtr ‘96	1,720	78	410	77.9	19.3	110,232	64.1	97.2	64,718
Total ‘96	**5,752**	**1,479**	**1,553**	**65.5**	**21.3**	**370,395**	**64.4**	**82.1**	**238,766**
1st Qtr ‘97	1,438	0	722	66.6	33.4	96,928	67.4	87.4	59,976
2nd Qtr ‘97	1,710	13	461	78.3	21.2	117,411	68.7	104.7	72,570
3rd Qtr ‘97	1,487	296	425	67.4	22.2	98,624	66.3	87.0	229,321
4th Qtr ‘97	1,182	541	485	53.5	29.1	82,486	69.8	72.7	51,308
Total ‘97	**5,817**	**850**	**2,093**	**66.4**	**26.5**	**395,449**	**68.0**	**87.9**	**413,175**

Table 7. Summary of Operating Data (continued)

Period	Hours			Rate		Feed, tons	Average Feed Rate, tons/hr	Capacity Factor, %	Shipments, tons
	Operating	Planned Maint.	Forced Outage	Avail-ability, %	Forced Outage, %				
1st Qtr '98	587	1,538	35	27.2	5.6	39,292	66.9	35.4	23,228
2nd Qtr '98	624	1,499	61	28.6	8.9	38,508	61.7	34.3	22,653
3rd Qtr '98	755	1,364	89	34.2	10.6	51,844	68.7	45.7	27,841
4th Qtr '98	509	1,654	45	23.1	8.1	33,628	66.1	29.7	23,852
Total '98	**2,475**	**6,055**	**230**	**28.3**	**8.5**	**163,272**	**66.0**	**36.3**	**97,574**
1st Qtr '99	1,244	515	401	57.6	24.4	85,567	68.8	77.1	55,462
2nd Qtr '99	1,566	324	294	71.7	15.8	105,769	67.5	94.3	66,875
3rd Qtr '99	1,656	359	193	75.0	10.4	113,309	68.4	99.9	72,150
4th Qtr '99	1,661	333	214	75.2	11.4	114,651	69.0	101.1	74,163
Total '99	**6,127**	**1,531**	**1,102**	**69.9**	**15.2**	**419,296**	**68.4**	**93.2**	**268,650**
1st Qtr '00	1,665	315	204	76.2	10.9	115,750	69.5	103.2	78,577
2nd Qtr '00	1,417	518	249	64.9	15.0	97,330	68.7	86.8	62,884
3rd Qtr '00	1,604	241	363	72.6	18.5	111,358	69.4	98.2	72,455
4th Qtr '00	1,712	241	255	77.5	13.0	116,942	68.3	103.1	77,688
Total '00	**6,398**	**1,315**	**1,071**	**72.8**	**14.3**	**441,380**	**69.0**	**97.8**	**291,604**
1st Qtr '01	1,234	140	766	57.1	38.3	90,434	73.3	81.5	56,860
2nd Qtr '01	312	338	70	43.3	18.3	22,497	72.1	60.8	29,421
Total '01	**1,546**	**478**	**836**	**53.7**	**35.1**	**112,931**	**73.1**	**76.3**	**86,281**
Project Total	**46,676**	**17,555**	**16,101**	**58.1**	**25.7**	**2,939,240**	**63.0**	**71.2**	**1,980,279**

The difference in weight between the amount of feed coal and the amount of SynCoal® product is due to loss of water and gases, samples removed for analysis, and fines that were captured in the dust handling system and returned to the mine for disposal. Very little dust was actually lost to the atmosphere. Overall, the plant had an availability of 58.1 percent and an average feed rate of 63 tons/hr. The plant operated for 46,676 hours, processed 2,939,240 tons of raw coal, and shipped 1,980,279 tons of products. Table 8 presents a summary of SynCoal® shipments for the life of the project.

Table 8. Summary of SynCoal® Shipments (tons)

Customer	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Total
Industrial											
Ash Grove Cement			34,686	28,677	35,468	42,589	42,852	40,645	33,237	12,341	270,495
Bentonite Corporation		2,437	10,172	9,734	9,241	11,755	14,476	8,730	9,278	4,379	84,581
Wyoming Lime Producers		90	25	2,367	11,785	14,405	20,293	17,138	18,449	6,860	91,412
Continental Lime*		226	7,564	1,160	10,673		19,803	27,463	22,735	8,455	98,079
Holnam Cement			1,580	3,287				43,559	52,257	19,401	120,084
Empire Sand & Gravel			2,368	1,399	2,316	946	150				7,179
Packaging Corporation				641							641
Univ. of North Dakota				209							209
Stillwater Mine					10						10
Western Sugar			188								188
NSP Sherburne			400								400
EG&G			15								15
Pete Lien & Sons					36	1,355					1,391
Nonindustrial											
Department of Energy					25						25
Barrick Goldstrike									1,866	495	2,361
Utility											
Colstrip Units 1 & 2					97,902	179,020		131,115	153,782	34,350	596,169
Colstrip Units 3 & 4	2,029	39,853	62,420	110,506	8,073						222,881
MPC J.E. Corette Plant	3,144	13,281	84,243	156,564	60,857						318,089
CELP	393			317							710
Northern States Power		1,641									1,641
Dairyland Power			410								410
Fremont Utilities			1,376	465	2,380						4,221
Minnkota Power Coop.				362							362
Western Energy Co.						163,105					163,105
Total	**5,566**	**57,528**	**205,447**	**315,688**	**238,766**	**413,175**	**97,574**	**268,650**	**291,604**	**86,281**	**1,980,279**

*Includes shipments to Graymont, the new name of Continental Lime.

B. Environmental Performance

In general, the project met all environmental permit requirements. From an environmental standpoint, the primary problem was the inherent dustiness of the unstabilized SynCoal® product. Fugitive dust in the coal-cleaning area was controlled by placing hoods over the dust sources and conveying the dust laden air to fabric filters. The bag filters effectively removed coal dust before the air was discharged. The Department of Health and Environmental Sciences completed stack tests on the east and west baghouse outlet ducts and the first-stage drying gas baghouse stack in 1993. The emission rates of 0.0013 and 0.0027 grains/dry standard cubic foot (limit of 0.018 gr/dscf) and 0.015 gr/dscf (limit of 0.031 gr/dscf), respectively, were well within the limits stated in the air quality permit. A stack emissions survey was conducted in May 1994. The survey determined the emissions of particulates, sulfur dioxide, oxides of nitrogen, carbon monoxide, total hydrocarbons, and hydrogen sulfide from the process stack. The principal conclusions based on average results are shown in Table 9.

Table 9. ACCP Emissions Results

Emissions	Result
Particulate matter from the process stack	0.0259 gr/dscf (2.56 lb/hr)*
Nitrogen oxides	4.50 lb/hr (54.5 ppm)
Carbon monoxide	9.61 lb/hr (191.5 ppm)
Total hydrocarbons as propane (less methane and ethane)	2.93 lb/hr (37.1 ppm)
Sulfur dioxide	0.227 lb/hr (2.0 ppm)
Hydrogen sulfide	0.007 lb/hr (0.12 ppm)

*Permit limit is 0.031 gr/dscf

IV. Market Analysis

A. Market Size

If the dustiness and spontaneous heating problems could be solved, the potential market for SynCoal® would include almost any coal-fired power plant. However, at its current state of process development, the market for SynCoal® is considerably more limited. Because of the upgrading and special handling costs, SynCoal® will be significantly more expensive than raw coal. Therefore, the market will consist of special situations where adding SynCoal® to the fuel mix will provide sufficient benefits to offset the additional cost. Potential clients are plants with design or fuel related limitations that can benefit from decreased slagging, reduced SO_2 emissions, and improved efficiency. In particular, power plants that have suffered derating as a result of switching to lower rank coals to meet sulfur emissions requirements would be prime candidates for firing SynCoal®.

The non-utility industrial sector could provide an interim market while other issues are being resolved, since these businesses are much more amenable to special handling, normally receive small quantities, and are much more sensitive to quality issues. A technique has been developed to ship SynCoal® in covered hopper rail cars or pneumatic trucks that allows long haul distances and, combined with inerted bin storage, provides safe and efficient handling.

B. Economics

In order to evaluate the commercial potential of the SynCoal® Advanced Coal Conversion Process, UniField Engineering, Inc. and the Western SynCoal® Engineering Team (1998) developed a Reference Plant Design. The reference plant design was based on integration of a SynCoal® module to process 100 tons/hr of lignite to provide fuel for Units 1 and 2 at the Minnkota Power Cooperative M.R. Young plant. There are a number of differences between the demonstration unit and the reference plant design. The reference plant design uses static bedplate fluid bed units for the dryer and reactor, whereas the demonstration plant uses vibratory fluid bed units; the reference plant design incorporates indirect cooling in a rotary drum, while the demonstration plant uses direct cooling in a vibratory fluidized bed; the reference plant design does not include the gravity coal cleaning step used in the demonstration plant; and process heating needs in the reference plant design are derived from steam provided by the power plant, whereas the demonstration plant uses natural gas.

These changes reflect a difference in philosophy between the demonstration plant and the reference plant design. The demonstration plant was designed as a stand-alone unit, so it required an independent source of heat. It was also designed to produce a cleaned product, since that might be important for some applications of SynCoal®. On the other hand, the reference plant was designed to be sited at a coal-fired power plant, so its heat requirements could be integrated into the power plant's operations. Furthermore, cleaning the SynCoal® is not of great significance for this mine-mouth application, since whether the ash comes from the cleaning process or from the furnace, it will still have to be disposed of, most likely in the mine or an ash landfill. Since some heating value is lost in the cleaning process, the capital required to provide SynCoal® cleaning may not represent a profitable investment for a unit sited at a power plant with a scrubber.

Engineering assumptions for the M.R. Young Power Station version of the reference plant design are as follows.

- Design availability was 80 percent.
- Plant construction adjacent to an existing power station that provides 2,400 psig, 1,000 °F steam, with condensate returned to the boiler feed water system.
- Other utilities are tied into the power plant's systems.
- Process gas from the SynCoal® facility is incinerated in the power plant's furnace.
- Operating and maintenance crews are integrated with those of the power plant.
- Feed lignite is provided by the existing raw lignite feed system at approximately 1,000 tons/hr at about 36 percent moisture and stored in a 1,800 ton capacity bin.
- All process material captured by the particulate removal system is blended into the product stream on a continuous basis.
- A cooling tower, air compressor, and a desiccant drying system are furnished as part of the SynCoal® facility.
- No product stabilization facilities are provided.

A detailed description of the reference plant design is presented in Western SynCoal's final report (2004).

1. Capital Cost

A capital cost estimate for the reference plant design was developed using vendor quotations for major process equipment and engineering factors for other direct costs. This estimate is presented in Table 10. It was found that the equipment cost for process heating was similar, regardless of the method of heating. Therefore, the design cost developed for the M.R. Young Station would not change substantially, even if a different heating system were used. Since this cost estimate was developed for a specific site, it should be used with caution for estimating the cost of a facility at another location.

Table 10. Reference Plant Design Capital Cost Estimate (1997 Dollars)

Description	Cost
Engineering and Permits	$875,000
Site Work	$286,300
Concrete	$738,400
Masonry	$155,700
Metals	$1,722,300
Moisture/Thermal Protection	$721,300
Doors and Windows	$9,100
Process Equipment	$12,584,600
Mechanical Work	$5,419,700
Electrical Work	$2,957,650
Direct Cost	**$25,470,050**
Indirect Cost	$6,867,600
Contingency	$2,263,636
Profit	$1,730,064
Startup	$623,721
Project Owners Cost	$2,128,101
Total Project	**$39,083,172**

2. Operating Cost

Operating costs are a function of site-specific factors and can vary considerably from one location to another. Rather than provide specific operating costs, the reference plant report presented the relationships shown in Tables 11 and 12 that define the requirements for feedstock, utilities, and manpower. These values can be converted into costs for a particular location by using site-specific values.

Table 11. Reference Plant Design Variable Costs ($/ton of SynCoal® Product)

Quantity	Calculation
product yield (fraction)	product (tons)/feed (tons)
feedstock ($/ton)	price ($/ton of feed coal)/product yield
water removed (tons/ton)	water in feed (wt fraction)/product yield – water in product (wt fraction)
fuel cost ($/ton)	2.2 x water removed x cost ($/million Btu)/heat transfer efficiency (fraction)
power cost ($/ton)	36 x cost ($/kWh)/product yield
cooling water cost ($/ton)	0.25 x cost ($/1,000 gal)

Table 12. Reference Plant Design Fixed Costs ($/year)

Quanity	Calculation
labor cost	number of operators x average annual wage
administration cost	0.17 x labor cost
maintenance cost	0.06 x initial capital
supplies	0.15 x maintenance cost
insurance cost	0.01 x asset value
property taxes	0.01 x asset value

Costs presented here are examples only, and can vary widely with location. They do not include local income or ad valorem taxes or special costs.

3. Economics

To provide economics for an example case, the values presented in Tables 13 and 14 were used. The example analysis assumes that the feed is typical Rosebud mine coal (see Table 2) and that both SynCoal® and SynCoal® fines can be sold as product. Figure 2 indicates that a typical SynCoal® product yield is 69.2 percent. Based on this yield, the annual production rate for the plant is 515,265 tons of SynCoal®. For the example case, variable operating costs are about $8.0 million/yr (see Table 14). Fixed costs are: operating labor, $665,600/yr; administration, $113,150/yr; maintenance labor, $2,346,000/yr; and maintenance materials, $351,900/yr, for a total O&M cost of $3,476,650/yr. Table 15 presents the economic analysis for the example case. Based on the assumed values, the cost of SynCoal® is in the range of about $30-$40/ton ($1.25-$1.70/million Btu based on a SynCoal® product HHV of 11,675 Btu/lb), depending on whether current or constant dollars are used. In this example, the SynCoal® unit is built next to a power plant, so no passivation or transportation costs are included. If either of these is needed, costs would be higher.

The results of this economic analysis indicate that the cost of SynCoal® may fall in the range where tax credits or other subsidies would be required to make it economically competitive, in spite of the technical advantages of being clean burning with a high heating value. Further development may reduce capital and operating costs and improve process competitiveness. The most promising opportunity may be to improve the performance of existing power plants that have been down-rated because of fuel switching from bituminous coal to lower-rank coal to meet environmental regulations.

To evaluate the effect of potential process improvements on the economics of the ACCP, the following assumptions were made: investment reduced by 40 percent to $23.5 million;

operating labor cost reduced by 50 percent; power consumption reduced by 50 percent; and capacity factor increased to 90 percent. Repeating the economic analysis with these changes decreases SynCoal® cost to $30.45/ton (current dollars) or $23.30/ton (constant dollars).

Table 13. Basis for Economic Evaluation

Economic Parameter	Value
Feed Capacity	100 tons of lignite feed per hour
Product Rate	69.2 tons of SynCoal® per hour
Capacity Factor	85%
Plant Capital Cost	$39,100,000
Feed Coal HHV (as received)	8,634 Btu/lb
Coal Cost	$0.50/million Btu ($8.63/ton)
Number of Operators	8 (4 shifts of 2 operators each)
Labor Rate (including burden)	$40/hr
Administration Cost	17% of labor cost
Hours per Man Year	2080
Maintenance Labor	6% of capital cost
Maintenance Material	15% of maintenance labor

Table 14. Variable Operating Costs

Cost Item	Units per ton of SynCoal®	Unit Cost	$/ton of product	$/yr
Feed Coal	1.445 tons	$8.63/ton	12.47	6,425,400
Steam	920 lb	$0.50/1,000 lb	0.46	237,000
Electric Power	52 kWh	$0.05/kWh	2.60	1,339,700
Cooling Water	250 gal	$0.10/1,000 gal	0.025	12,900
Total Variable Operating Cost				**8,015,000**

Table 15. Economics of SynCoal® Production (100 ton/hr of lignite feed)

Cost Factor	Base, $$10^3$	Current Dollars		Constant Dollars	
		Factor	$/ton	Factor	$/ton
Capital Charge	39,100	0.160	12.14	0.124	9.41
Fixed O&M Cost	3,477	1.314	8.87	1.000	6.75
Variable Operating Cost	8,015	1.314	20.44	1.000	15.55
Levelized Cost of SynCoal®			**41.45**		**31.71**

Corresponding cost on a heating value basis is \$1.30/million Btu (current dollars) or \$1.00/million Btu (constant dollars). Thus, even under optimistic assumptions, the cost of SynCoal® is at least double that of the raw coal feed on a dollars per Btu basis. This will limit application of the process to situations where the increased cost can be justified by the benefits from increased capacity and cleaner operations.

C. Commercialization Plan

Western SynCoal LLC is continuing to pursue commercialization opportunities focused on next generation projects, both domestically and internationally, which satisfy unique niche markets that can benefit from SynCoal® in the short term. These efforts have generated a number of prospects, but have not yet resulted in any new projects.

After Westmoreland acquired Western Energy Company/Western SynCoal LLC, the suspension of operations at the ACCP was the only viable business decision, since the new consolidated tax return would not allow utilization of the Section 29 credits or the associated net operating losses to partially offset operating costs. Following acquisition, Westmoreland could not economically continue to operate the ACCP, and the plant was shut down.

V. Conclusions

After problems typical of plant startups were overcome, the ACCP ran essentially as designed; that is, it was able to operate at design capacity and produce SynCoal® with the expected moisture and sulfur contents. The product was tested in a variety of applications, both industrial and utility, and proved to have benefits for both applications. Its uniform properties and low moisture and sulfur contents provided superior performance. Unfortunately, SynCoal® proved to be dust prone and was also prone to spontaneously combust if left exposed to the atmosphere in a pile of more than one or two tons. These tendencies presented serious handling problems that made untreated SynCoal® unsuitable for shipment in open hopper cars. Thus, the SynCoal® had to be used almost immediately after production or stored in an airtight container.

Considerable effort was expended in studying the spontaneous combustion problem in an attempt to find a solution. Although this effort was partially successful, no fully satisfactory passivation procedure was developed. Rehydrating the coal extended storage life, but did not fully overcome the problem of spontaneous combustion. Moreover, rehydration lowered the product's heating value, which negated part of the benefit of drying the coal.

In spite of these problems, the SynCoal® demonstration plant was able to establish several long-term industrial and specialty customers on a commercial basis, and there is potential for a SynCoal® facility sited at a power plant so that the product could be burned as soon as produced with only temporary storage (to provide surge capacity) in an inert-gas-blanketed silo. If waste heat from the power plant can be used to provide at least part of the energy for the SynCoal® plant, this could be a particularly attractive arrangement. Process improvements, such as using an Aeroglide tower in place of the vibrating fluidized bed reactors, could also lead to cost reductions that would improve process economics.

The overall conclusion is that, although the technology worked essentially as promised, the product had certain deficiencies that prevented its general entry into the marketplace. Thus, although there may be niche applications for the technology, the objective of demonstrating a broadly commercially viable process was not achieved.

VI. References

Knottnerus, B. and H. Bonner. 2001. "Aeroglide Tower Reactor Testing at the ACCP Plant, Colstrip, Montana—Interim Report."

Soloman, P. R., D. G. Hanblen, R. M. Carangelo, M. A. Serio, and G. V. Deshpande. 1988. "General Model of Coal Devolatilization," *Energy and Fuels*, Vol. 2, No. 4:405.

UniField Engineers, Inc. and the Western SynCoal® Engineering Team. 1998. "SynCoal® Reference Plant Design Report."

U.S. Department of Energy. 1990. "Comprehensive Report to Congress—Clean Coal Technology Program—Advanced Coal Conversion Process Demonstration." DOE/FE-0192P. Springfield, VA. National Technical Information Service.

U.S. Department of Energy. August 1997. "Clean Coal Technology—Upgrading of Low-Rank Coals." Topical Report No. 10.

Western SynCoal LLC. 2004. "Final Technical Report—Advanced Coal Conversion Process Demonstration." DE-FC-90PC89664.

VII. Bibliography

MSM Technical Consulting, Inc. 1998. "Environmental Report." DOE Contract: DE-FC22-90PC8966

Richards, J. 1997. "ACCP Inert Gas System—Design and Operation Description."

Sheldon, R.W., and S.J. Heintz. 1993. "Rosebud SynCoal® Partnership Advanced Coal Conversion Process Demonstration Project," presented at the Second Annual Clean Coal Technology Conference, September 7-9, 1993, Atlanta, Georgia.

Sheldon, R.W., and S.J. Heintz. 1994. "Rosebud SynCoal Partnership SynCoal® Demonstration—Technology Development Update," presented at the Third Annual Clean Coal Technology Conference, September 6-8, 1994, Chicago, Illinois.

Sheldon, R.W., R.M. Kornosky, W.J. O'Dowd, and J.B. Renk, III. 1995. "Rosebud SynCoal Partnership SynCoal® Demonstration—Technology Development Update," presented at the Fourth Annual Clean Coal Technology Conference, September 5-8, 1995, Denver, Colorado.

Sheldon, R.W. 1997. "Rosebud SynCoal Partnership SynCoal® Demonstration—Technology Update," presented at the Fifth Annual Clean Coal Technology Conference , January 7-10, Tampa, Florida.

Sheldon, R.W., and J.B. Renk, III. 1998. "Advanced Coal Conversion Process Demonstration," presented at the Sixth Annual Clean Coal Technology Conference, April 28-May 1, 1998, Reno, Nevada.

U.S. Dept. of Energy. 1991. “Environmental Assessment—Advanced Coal Conversion Process Demonstration Project—Clean Coal Technology Program.” DOE/EA-0469. Springfield, VA. National Technical Information Service.

Viall, A.J., J.M. Richards, and R.W. Sheldon. 1992. “Rosebud SynCoal® Partnership Advanced Coal Conversion Process Demonstration Project,” presented at the First Annual Clean Coal Technology Conference, September 22-24, 1992, Cleveland, Ohio.