Richard A. Newby (Primary Contact)
Siemens Westinghouse Power Corporation
1310 Beulah Road
Pittsburgh, PA 15235
richard.newby@siemens.com
412-256-2210
412-256-2121 (Fax)

Francis S. Lau
Gas Technology Institute
1700 South Mount Prospect Road
Des Plaines, IL 60018
francis.lau@gastechnology.org
847-768-0592
847-768-0600 (Fax)

Rachid B. Slimane
Gas Technology Institute
1700 South Mount Prospect Road
Des Plaines, IL 60018
rachid.slimane@gastechnology.org
847-768-0606
847-768-0600 (Fax)

Suresh C. Jain
U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
Morgantown, WV 26507
jain@netl.doe.gov
304-285-4531
304-285-4403 (Fax)

Development of the Ultra-Clean Dry Cleanup Process for Coal-Based Syngases

Keywords: Sorbent injection, Sulfur species, Halides, Syngas cleaning

Introduction

Currently, natural gas is the premium fuel for the synthesis of chemicals and liquid fuels, and for fuel cell power generation. Coal gasification syngases are suitable for these applications if extensive, deep syngas cleaning is first conducted. A large cost advantage for natural gas results from the high investment costs and operating costs associated with coal handling, coal gasification, coal-syngas cleaning, and coal-syngas conditioning, compared to the respective costs for natural gas processing. As the price of natural gas increases relative to coal, coal becomes a potentially more attractive fuel for these applications, countering the natural gas processing advantages.

Commercial technology is available to clean coal-based syngases to very stringent levels. The prevalent commercial syngas cleaning process, capable of achieving very stringent syngas cleaning requirements (< 60 ppbv total sulfur species, < 10 ppbv total halides, < 0.1 ppmw particulate) for these types of applications, utilizes "Rectisol" syngas desulfurization technology. The Rectisol process uses refrigerated-methanol physical absorption of sulfur species and is expensive to build and operate. Commercial syngas cleaning processes also apply wet, low-temperature removal of halides, particulate, and other contaminants, resulting in extensive water treatment requirements. New, cheaper technologies are needed for stringent syngas cleaning duty if coal is to become competitive with natural gas, in DOE Vision 21, multi-production plants.

Objective

The Siemens Westinghouse Power Corporation (SWPC) has proposed a novel scheme for polishing sulfur species, halides, and particulate from syngas to meet stringent cleaning requirements, the "Ultra-Clean syngas polishing process." The overall development objective for

this syngas polishing process is to economically achieve the most stringent cleanup requirements for sulfur species, halide species and particulate expected for chemical and fuel synthesis applications (total sulfur species < 60 ppbv, halides < 10 ppbv, and particulate < 0.1 ppmw).

A Base Program was conducted to produce ground-work, laboratory test data and process evaluations for a conceptual feasibility assessment of this novel syngas cleaning process. Laboratory testing focussed on the identification of suitable sulfur and halide sorbents and operating temperatures for the process. This small-scale laboratory testing was also performed to provide evidence of the capability of the process to reach its stringent syngas cleaning goals.

Process evaluations were performed in the Base Program to identify process alternatives, to devise process flow schemes, and to estimate process material & energy balances, process performance, and process costs. While the work has focussed on sulfur, halide, and particulate control, considerations of ammonia, and mercury control have also been included.

Approach
The Siemens Westinghouse Power Corporation (SWPC), working with the Gas Technology Institute (GTI), is engaged in the early development of a new process for coal-syngas polishing, the "Ultra-Clean syngas polishing process". Many syngas contaminants must be controlled to very low levels to meet the downstream processing requirements for fuel cell power generation, chemical synthesis, or liquid fuel synthesis. Reduced sulfur species, halides, and particulate are the specific contaminants addressed by the SWPC Ultra-Clean syngas polishing process, although the process can also incorporate the control of other contaminant species.

Figure 1 illustrates the basic Ultra-Clean syngas polishing process concept. A coal gasifier produces a high-temperature, raw syngas containing many types of contaminants including sulfur species, halide species, and particulate. This syngas is cooled to the operating temperature of a hot, or warm (370 - 540°C, 700 - 1000°F) "bulk" desulfurization process, where a substantial amount of the sulfur is removed using a dry, regenerative sulfur sorbent. Bulk desulfurization is a developing process technology under DOE sponsorship for many years and is nearing demonstration status, although it still has several development issues (Parsons Power Group, 1997). A variety of bulk desulfurization sorbents can be used over a range of temperatures from 370 to 540°C (700 to 1000°F), and bulk sorbent regeneration is an economic necessity. Bulk sorbent attrition and deactivation represent major issues (Abbasian et al., 1997).

The Ultra-Clean syngas polishing process follows this bulk desulfurization step. The Ultra-Clean syngas polishing process is a conceptual process, untested except at laboratory scale. It consists of two sorbent injection cleanup stages in series. The major equipment components of this polishing process, barrier filter-reactors and sorbent handling and feeding equipment, have reached a mature status and have been demonstrated at large scales, but the use of barrier filters as gas-particle reactors has seen only limited testing (Newby et al., 1995).

The barrier filter provides an excellent environment for gas-particle reactions. It provides dilute gas-particle contacting with high rate of internal gas-particle recirculation and long gas-particle contact times of 5 to 10 seconds. This dilute-phase contacting is followed by packed-bed gas-particle contacting through very uniform sorbent filter cakes, with gas residence times of 0.3 to 0.8 second. These sorbent filter cakes are in a transient state of continuous growth and are subject to periodic removal by pulse gas cleaning. In contrast to the bulk desulfurizer, sorbent attrition and deactivation are of little concern in the barrier filter-reactor.

The bulk-desulfurized syngas is reduced in temperature to the operating temperature of the first stage. The first stage reduces the concentration of the primary contaminants (sulfur and halide species) to about the 1 to 2 ppmv level in a barrier filter-reactor, by injecting appropriate, fine sulfur and halide sorbent particles into the syngas stream. Sorbent attrition products from the bulk desulfurizer will also be captured in the Stage I filter-reactor and may contribute to Stage I sulfur removal. In Stage I, various halide sorbent materials (e.g., sodium-based) and various metal oxide-based, sulfur sorbent materials (e.g., zinc, copper, iron, and manganese-based) can be applied as fine particles (-325 mesh) injected into the syngas stream. The sulfur species inlet content and the sulfur sorbent consumption rate are 1-2 orders-of-magnitude smaller in Stage I than they are at the bulk desulfurization stage. Pulse cleaning of the Stage I filter-reactor will be needed every 1/2 to 5 hours, with this pulse cleaning being distributed between a number a parallel sets of filter elements.

The partially-cleaned, Stage I syngas is lowered further in temperature to the operating temperature of the second stage. In Stage II, a second set of sorbent particles is injected to reduce the sulfur and halide species to their final levels. The Stage II barrier filter-reactor limits the penetration of particulate to less than 0.1 ppmw. Sorbent materials similar to those in Stage I may be used in Stage II, but their chemical and physical properties may differ from those in Stage I to promote better overall reactivity at the lower operating temperature of Stage II. In Stage II, the sulfur and halide species contents are 1-2 orders of magnitude lower than in Stage I, requiring much smaller sorbent feed rates than in Stage I. Pulse cleaning of the Stage II filter-reactor will be needed every 5 to 50 hours.

The Ultra-Clean syngas polishing process is classified as a "dry" syngas cleaning scheme, producing no condensate streams, and using once-through sorbents. It is possible to incorporate the removal of other contaminants, such as ammonia and mercury, into Stage II of the process.

Project Description
A 56-month, two-phase program is being conducted by the Siemens Westinghouse Power Corporation (SWPC) under U.S. Department of Energy, National Energy Technology Laboratory (DOE/NETL) support. The 23-month Base Program has been completed. Its focus was laboratory-scale sorbent performance testing and process conceptual performance and economic evaluations. The Gas Technology Institute (GTI) performed the laboratory testing in their specialized facilities. The 33-month Optional Program is underway and will conduct integrated, bench-scale proof-of-principle tests of sorbents and gas-sorbent filter-reactors at a 10 ton/day coal gasifier test facility.

Results
The Base Program identified a specific set of zinc-based and sodium-based sorbents having the capability of meeting the process performance requirements for each stage by means of thermodynamic assessment, past sorbent development experience, and comprehensive laboratory testing. The selected sorbent characteristics and stage operating conditions are:

- Stage I temperature: 499°C,
- Stage I sulfur sorbent type: IGTSS-362C (Zn/Ti mole ratio ≈1),
- Stage I halide sorbent type: trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$),
- Stage I sorbents size distribution: -325 mesh, mass-mean diameter about 20 μm,
- Stage II temperature: 288°C,

- Stage II sulfur sorbent type: G-72E (70 wt% Zn),
- Stage II HCl sorbent type: G-92C (6.4 wt% Na),
- Stage II sorbents size distribution: -325 mesh, mass-mean diameter about 20 μm.

The Stage I sorbent selection is influenced by the assumed bulk desulfurization section's operation at about 540°C using a zinc-based sorbent. If a lower-temperature bulk desulfurization sorbent were assumed (for example, an iron-based sorbent operating at 400°C), the Stage I sorbent and operation temperature would be modified to be compatible (for example, using an iron or copper-based sorbent operating at about 350°C). The Stage I sulfur sorbent, IGTSS-362C, is a manufactured, zinc-based sorbent previously developed by GTI in granular form for high-temperature H_2S removal. The Stage I halide sorbent, trona, is a cheap, commercially available, natural mineral. The Stage II sorbents, G-72E (zinc-based) and G-92C (sodium-based), are both commercial, Süd Chemie catalyst pellet materials.

The small-scale laboratory testing provided evidence of the capability of the process to reach its stringent syngas cleaning goals and also explored the sensitivity of the sorbent performance to the major process parameters. Tests with individual sorbents, and mixtures of sulfur and halide sorbents were conducted in simulated coal syngas containing individually H_2S, HCl, or mixtures of these contaminants. These parametric tests were conducted at near-atmospheric pressure, in a packed bed test facility, having the process schematic shown in Figure 2. The laboratory tests used a simulated, coal-based syngas passing through thin packed beds of sorbents operated at face velocities representative of sorbent filter cakes in the Ultra-Clean syngas polishing filter-reactors. Typical break-through data, such as shown in Figure 3, were collected to measure the sorbent reaction performance. Sectional analysis of the packed bed sorbent reaction products to confirm the reaction mechanisms and conversions were included. The laboratory test procedures, equipment, and test results have been previously described (Slimane et al., 2001).

Uncertainties exist in making gas contaminant measurements as low as 60 ppbv for H_2S and 10 ppbv for HCl, and a critical element of the program has been the development of reliable procedures and equipment to make these measurements. State-of-the-art equipment test rig and sampling line equipment and operating procedures were utilized by GTI to minimize and account for contaminant losses and background contaminant levels. Ion Chromatography was successfully used to make HCl measurements down to 10 ppbv. Stage I sulfur species contents down to 1 ppmv were reliably measured by a gas chromatograph equipped with a flame photometric detector. The Stage II sulfur species were measured by a special gas chromatograph technique, but could only achieve a detection limit of 85 ppbv, compared to the target of 60 ppbv. This was considered acceptable for the Base Program laboratory screening and verification tests.

Application
Conceptual commercial process evaluations were performed in the Base Program to devise potentially viable schemes for a novel syngas cleaning process that utilizes the Ultra-Clean syngas polishing process. Comparison was made with the state-of-the-art, conventional syngas cleaning process, based on the Rectisol desulfurization technology. Two applications were addressed, a generalized chemical synthesis application, and a solid oxide fuel cell (SOFC) power generation application. An oxygen-blown, entrained, slagging gasifier was selected as the commercial raw syngas generator.

For the general chemical synthesis application, the syngas cleaning processes were designed to achieve total sulfur < 60 ppbv, total halides < 10 ppbv, and particulate < 0.1 ppmw. Some synthesis applications also must control ammonia and HCN contaminants (NH_3 < 10 ppmv, HCN < 10 ppbv), and options for these were considered. The SOFC syngas cleaning requirements are less stringent, with particulate < 0.1 ppmw, H_2S < 100 ppbv, HCl < 1 ppmv, and NH_3 < 5000 ppmv.

An overall, simplified process schematic for the conventional, state-of-the-art, syngas cleaning process is shown in Figure 4. Here, the conventional syngas cleaning process is separated into five major process sections: the syngas cooling section, the precleaning section, the desulfurization section, the sulfur recovery section, and the refrigeration system.

In the raw syngas cooling section, the raw syngas from the gasifier, at about 1371°C (2500°F), is cooled to an acceptable temperature for low-temperature cleanup of about 149°C (300°F) while generating high-pressure steam. In the precleaning section, recycled process water and condensate are used to scrub particulate from the cooled syngas. The char captured is recycled to the gasifier coal-slurry feed system. Next, raw water is used to scrub ammonia and halides from the syngas to meet the stringent syngas requirement. The waste water is processed in a water treatment plant.

The precleaned syngas then enters the desulfurization section where it is treated in a Rectisol process to remove H_2S and COS to very low content. The Rectisol process also removes a large portion of the syngas CO_2 content. The Rectisol process is a low-temperature (about -70°C), methanol absorption process, and is the typical choice for methanol synthesis plants (Biansca et al., 1987). The Eastman, Kingsport coal gasification plant applies the Rectisol desulfurization process for methanol synthesis (Tijm et al., 1999). Rectisol desulfurization is followed by syngas reheat and additional desulfurization in a zinc oxide guard bed system to satisfy the syngas sulfur content requirement.

The acid-gas from the Rectisol process, consisting of dilute H_2S mixed in primarily CO_2, is treated in the sulfur recovery section to remove sulfur in the form of elemental sulfur. The Rectisol process also requires a refrigeration system, which is treated as a separate process section because it is very expensive and consumes significant power.

The integration of the processing steps requires heat interchange between several process streams. Heat exchange equipment represents a dominant cost class in the conventional process. Steam generation and utilization throughout the conventional process must be carefully integrated.

The novel syngas cleaning process consists of four, integrated process sections: a raw syngas cooling section, a bulk desulfurization section, a sulfur recovery section, and the Ultra-Clean syngas polishing section, shown in Figure 5. The syngas cooling equipment reduces the raw syngas to the temperature of the bulk desulfurization section and generates high-pressure steam. Bulk desulfurization of the raw syngas using a regenerative, zinc-based, transport reactor process, operating at about 540°C, was applied. A process design configuration has been proposed in the evaluation for the bulk desulfurization section and the sulfur recovery section based on information available on both commercial and developing technologies. Sulfur recovery for this application is based on commercial configurations, but is a more complex process than is typical of sulfur recovery because the acid-gas is in the form of a low-concentration, SO_2 gas.

The Ultra-Clean syngas polishing section is the major conceptual section in the novel syngas cleaning process evaluated. A Base configuration and one alternative Ultra-Clean process configuration have been devised that require further, larger-scale testing to fully characterize and establish. These process schemes are illustrated in Figures 6 and 7.

The Base Ultra-Clean syngas polishing section, Figure 6, consists of two stages of barrier filter-reactors. They are separated by a syngas cooler for Stage II temperature control. The Stage I temperature is selected as the highest temperature for achieving total sulfur and HCl in the 1 ppmv concentration range using the selected Stage I sorbents. The Stage II temperature is reduced to an optimum for HCl and sulfur removal to the final cleaning requirement with the selected sorbents. The Stage II temperature selection requires a tradeoff between reaction kinetics and thermodynamic limitations.

There are three possibilities for dealing with the sorbent waste streams in this process: 1) they might be disposed of in a landfill, 2) they might be recycled to the gasifier to be incorporated into the plant slag, or 3) they might be regenerated for reuse in the process. The waste sorbents collected in Stage II can be disposed of in a landfill since they represent a very small mass flow of waste and their cost of purchase and disposal will be very small. They also can be recycled to the gasifier to be incorporated into the gasifier slag since their content of sulfur and HCl is so small as to have no impact on the raw syngas contaminant contents if the contaminants are released back into the syngas in the gasifier. Regeneration of the Stage II sorbents would not be appropriate.

Likewise, the Stage I sorbent waste can be disposed in a landfill, but recycling the waste to the gasifier would only be possible if the HCl sorbent could be separated from the sulfur sorbent, since the HCl sorbent would release a very large HCl content back into the raw syngas. The same is true of cycling the Stage I sorbent waste to the bulk desulfurization section regenerator for regeneration -- this can only be done if the HCl sorbent is first separated from the sulfur sorbent.

The alternative process, Figure 7, accomplishes both syngas moisture reduction and HCl removal by syngas cooling and water scrubbing of HCl following Stage I. In this alternative, no HCl particulate-sorbent is required in either stage, greatly simplifying the sorbent feeding equipment and providing the potential for simplified sulfur sorbent reuse. Here, the Stage I sulfur sorbent can be directly recycled to the bulk desulfurizer section's regenerator, or can be disposed of in the gasifier. The optimum Stage II temperature is expected to be the same as in the Base process. This alternative, of course, generates a particulate-free, waste water stream for treatment in the plant. In this alternative, other contaminants such as ammonia might also be effectively removed in the water scrubber with little additional cost, if it is designed for this duty. Both ammonia and HCN can also be catalytically decomposed at a hotter point in the synthesis plant.

It would be possible to include mercury control in Stage II by incorporating appropriate sorbent injection or a fixed bed system. The control of mercury and arsenic may be required in some synthesis applications, and these components might be subject to future emissions control regulations from all coal-fueled plants. In syngas, mercury will exist primarily as elemental mercury and arsenic may exist in several forms. Significant arsenic will be removed in the primary barrier filter, but mercury removal through char reactions in the primary barrier filter will be limited. Mercury might be controlled within the Ultra-Clean section using well known sorbents (activated carbon impregnated with sulfur, activated cokes, activated aluminas or

zeolites) injected into the Stage II syngas or using a packed bed reactor placed downstream of Stage II (Bingham, 1990). While only limited testing has been conducted in reducing gases, a variety of other sorbents, operable at higher temperatures, might also be used in Stage II of the Ultra-Clean section (Granite et al., 1998; Nelson, 2000). Activated coke is used commercially in waste-to-energy plants to remove mercury and other trace components, SO_2 and NOx at normal flue gas temperatures. Activated carbon beds, operating at 0°C (32°F) are in commercial use for removing H_2S and halogens from dried fuel gas, produced by waste-water biogas cleaning, to fuel a phosphoric-acid fuel cell power generation system (Theron, 2000). Such options should be much cheaper than controlling mercury, or arsenic at the plant stack because of the much higher partial-pressures of the contaminants in the high-pressure syngas. Some of these sorbent options will also provide additional Stage II sulfur and halogen removal.

Commercial process performance and economics have been estimated for the state-of-the-art, Rectisol-based, conventional syngas cleaning process and for the novel syngas cleaning process. Tables 1 and 2 list the major factors for comparison between the novel syngas cleaning process and the conventional process for the two applications. Each table lists key process factors, environmental factors and economic factors.

The total pressure drop across the syngas cleaning systems listed in Table 1 is 35% lower for the novel syngas cleaning Base process than for the conventional syngas cleaning process, and this may be a significant advantage for the novel syngas cleaning process for chemical synthesis. This reduced pressure drop may also provide some advantage for the SOFC power generation application (Table 2). The evaluation conducted in this report does not account for this potential cost reduction factor.

The final, cleaned syngas temperature listed in Tables 1 and 2 is comparable-to-lower for the novel syngas cleaning process relative to the conventional process. This temperature may influence downstream processing of the cleaned syngas, but does not produce a major cost differential between the novel and conventional processes.

The valuable components in the syngas for chemical synthesis (Table 1) are CO and H_2, and small amounts of these are lost in the conventional syngas cleaning operations (less than 0.1%) by absorption in the solvents and condensates. The novel syngas cleaning process, though, loses about 1.5% of the CO and H_2 for the reduction of the regenerator offgas to permit sulfur recovery. The hydrogen content and the heating value of the cleaned fuel gas for SOFC is indicated in Tables 1 and 2, and both are about 20% lower for the novel fuel gas cleaning than for the conventional fuel gas cleaning process. This is due primarily to the higher CO_2 content of the fuel gas in the novel fuel gas cleaning cases. The hydrogen content and heating value of the fuel gas may influence the design and behavior of the SOFC system, but is not considered to be a critical factor.

The novel syngas cleaning process, as indicated in Table 1 and 2, does not remove CO_2 from the syngas, while the conventional syngas cleaning process removes almost all of the CO_2 and water vapor from the syngas. In the novel syngas cleaning process alternative with HCl scrubbing, most of the water is removed from the syngas. This difference in behavior may be important to the specific synthesis application addressed in the plant. In SOFC power generation, it may be advantageous to overall power plant performance to maintain the CO_2 and water vapor in the fuel gas because these components moderate the combustion temperature of the fuel gas and add about 25 to 40% more mass flow through the power generation equipment.

The novel syngas cleaning process has some environmental advantages over the conventional syngas cleaning process with respect to the tail gas flow and its contaminants (SO_2 and CO_2) released, and the waste water processing required, as is indicated in Tables 1 and 2. The tail gas mass flow rate is 2 -3 times as much in the conventional process as it is in the novel syngas cleaning process, and the conventional process emits about four times as much SO_2 and eight times as much CO_2. The novel syngas cleaning process, though, generates solid waste streams, some of which can be combined with the gasifier ash/slag as an inert product. The total solid waste generated is less than 1% of the total coal ash rate in the plant. No cost for water treatment has been included in the economics, and this may be an important factor, especially for the SOFC power generation application where the typical plant may not have water treatment facilities.

Even with the conservative assumptions made, the capital investment for the novel syngas cleaning process is expected to be much less than that of the conventional syngas cleaning process. The novel syngas cleaning process generally uses less power and fuel than the conventional syngas cleaning process, so it has lower annual cost of operation. The Base Ultra-Clean section and the Ultra-Clean section with HCl scrubbing result in almost identical cost-of-syngas-cleaning. The cost-of-syngas-cleaning for the novel syngas cleaning process is very sensitive to the rate of the sorbent consumption in the process, and the prices of the sorbents. The bulk desulfurization sorbent and the Stage I sulfur sorbent are the key sorbents with respect to cost impact. The ranges in Total Capital Requirement and Cost of Syngas Cleaning listed in Tables 1 and 2 reflect the maximum and minimum expected sorbent feed rates and prices.

Criteria for the evaluation of sorbent testing, based on cost-of-syngas-cleaning having greater than 20% advantage over the conventional syngas cleaning processes, have been estimated for both the synthesis and the SOFC power generation applications. The guidelines are stated in terms of the maximum value of the sorbent-to-contaminant molar feed ratio (Ms/Mc), times the sorbent price in dollars per unit mass (Cs), that results in 20% cost advantage for the novel syngas cleaning process.

In the case of the bulk desulfurization sorbent, the Ms quantity is the total molar makeup feed rate of fresh sorbent to the bulk desulfurizer. Mc is the contaminant (total sulfur or HCl) molar flow rate to the Ultra-Clean Stage I section of the novel syngas cleaning process. For the Stage II sorbents, Ms is the sorbent molar feed rate to Stage II and Mc is the contaminant molar flow rate to Stage II. The sorbent prices should represent the commercially mature prices of these sorbents.

Table 3 lists the estimated maximum acceptable molar feed rate ratio (Ms/ Mc) times the sorbent price ($/mass) for each application. The most sensitive sorbent group is the bulk desulfurization sorbent plus the Stage I sulfur sorbent. These are combined because the bulk desulfurization sorbent will contribute to Stage I sulfur removal and the two sorbents will have similar prices.

The Stage I HCl sorbent is shown separately because it has the largest flow rate of the sorbents, but it has a relatively low cost. Finally, the Stage II HCl sorbent plus the Stage II sulfur sorbent are considered, being the least sensitive sorbents with respect to cost due to the relatively low sulfur and HCl flow rates in Stage II. If reasonable commercial prices for the sorbents can be established, then the maximum acceptable sorbent feed rates can be projected from Table 3. Based on this Table, it is expected that very large sorbent molar feed ratios, greater than 10:1, may be applied in Stage II of the Ultra-Clean process, and for the Stage I HCl sorbent. Even the

Stage I sulfur sorbent feed rate can be substantial if the bulk desulfurization sorbent losses can be limited.

The novel syngas cleaning process, using the Ultra-Clean syngas polishing technology, shows extremely promising performance potential, environmental advantages, and economic potential compared to the conventional technology. The "dry" syngas cleaning characteristic of the novel syngas cleaning process minimizes waste water and condensate treatment requirements inherent with the conventional syngas cleaning process. The capital investment for the novel syngas cleaning process is estimated to be at least 30% lower than that of the conventional syngas cleaning process. The total cost-of-syngas-cleaning, in dollars per unit mass of syngas cleaned, is estimated to be at least 20% less than that of the conventional syngas cleaning process.

The rates of sorbent consumption for the bulk desulfurization sorbent and the Ultra-Clean syngas polishing sorbents, and the delivered prices of these sorbents, are the key parameters that influence the commercial cost feasibility of the novel syngas cleaning process. These parameters are uncertain at this time, requiring further, larger-scale testing to establish, but the laboratory testing and other available data provide preliminary estimates for consumption rates and prices. Sorbent maximum acceptable consumption-and-price criteria, based on a 20% cost reduction relative to conventional technology, have been estimated and appear to be easily satisfied.

Future Activities

The design of the bench-scale test facility and the scoping of the test program have been initiated in the Optional Program. A schematic of the plant, to be constructed at a GTI facility, is illustrated on Figure 8. The plant consists of a GTI fluid bed coal gasifier (10 tons per day), a syngas conditioning section that controls the syngas sulfur and HCl content, and temperature, a Ultra-Clean process test section, and a stack gas treatment section. The unique test facility allows independent and closely controlled testing of the barrier filter-reactor and sorbents at both Stage I and Stage II conditions.

References

Abbasian, J., R. B. Slimane, F. S. Lau, J. R. Wangerow, and M. K. Zarnegar, GTI, "Development of High Temperature Coal Gas Desulfurization Systems - An Overview," Proceedings of the 14th Annual Pittsburgh Coal Conference, 1997.

Biansca et al., "Process Screening Study of Alternative gas Treating and Sulfur Removal Systems for IGCC Power Plant Applications," EPRI Report, EPRI AP-5505, December 1987.

Bingham, M. D., "Field Detection and Implications of Mercury in Natural Gas," Soc. Petroleum Engrs., Production Engineering, 120, May 1990.

Granite, E. J., H. W. Pennline, and R. A. Hargis, "Sorbents for Mercury Removal for Flue Gas," DOE/FETC/TR--98-01, January 1998.

Nelson, S., "High-temperature Sorbents to Lower Mercury Control Costs," Proceedings of the Seventeenth Annual Int. Pittsburgh Coal Conf., Pittsburgh PA, September 2000.

Newby, R. A., M. A. Alvin, D. M. Bachovchin, E. E. Smeltzer, T. E. Lippert, "Integrated Low Emissions Cleanup System for Coal-Fuels Turbines, Phase III Topical Report -- Bench-Scale Testing and Evaluation," Final Report to DOE/ METC under Contract No. DE-AC21-87MC24257, Aug. 1995 (DOE/MC/24257—5059).

Parsons Power Group, Inc, M. G. Klett et al., "Assessment of Hot Gas Cleanup Systems for IGCC and PFBC Advanced Power Systems, " Parsons Report No. 9609, DOE Contract Number DE-AC01-94FE62747, Jan. 1997.

Slimane, R. B., O. M. Akpolat, F. S. Lau, R. A. Newby, T. E. Lippert, K. Pandya, J. Abbasian, and S. C. Jain, "Experimental Studies In Support of the Ultra-Clean Gas Cleanup Process Development," 18th Annual International Pittsburgh Coal Conference, Dec. 4-7, 2001, Newcastle, New South Wales, Australia.

Theron, J., "Fuel Cells Thrive on Clean Gas," Chemical Engineering, p. 41, July 2000.

Tijm et al., 1999, "Liquid Phase Methanol Project: Operating Experience Update," 1999 Gasification Technologies Conference, San Francisco.
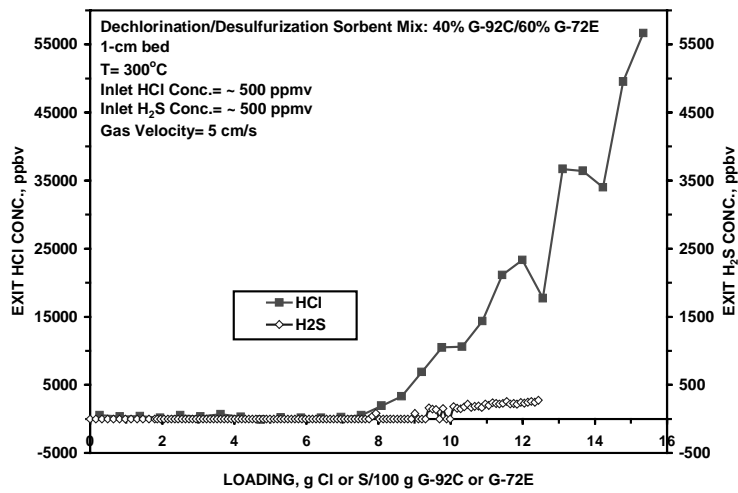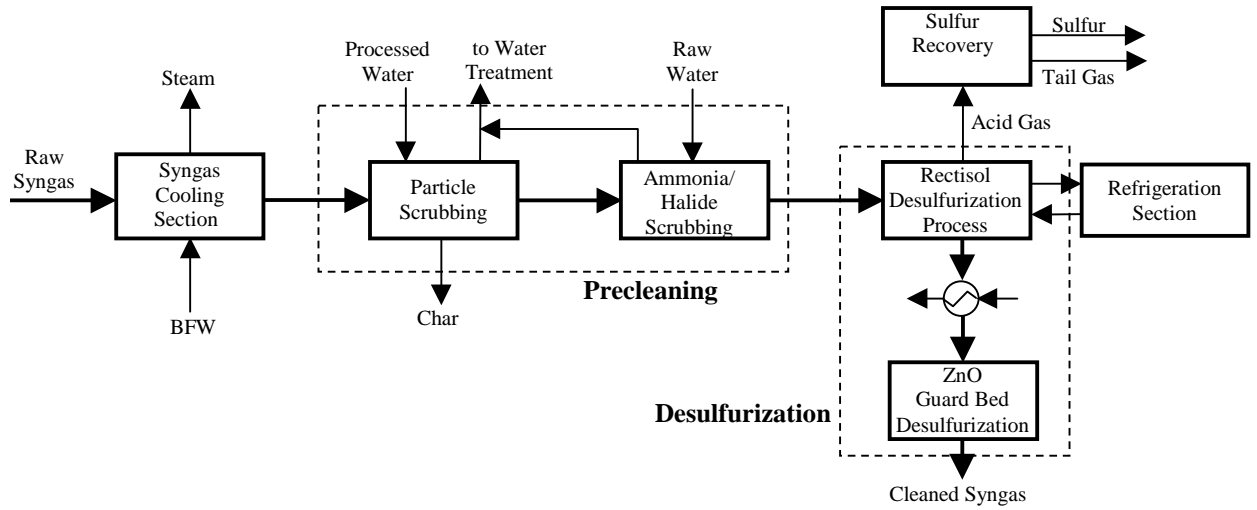
Figures and Tables
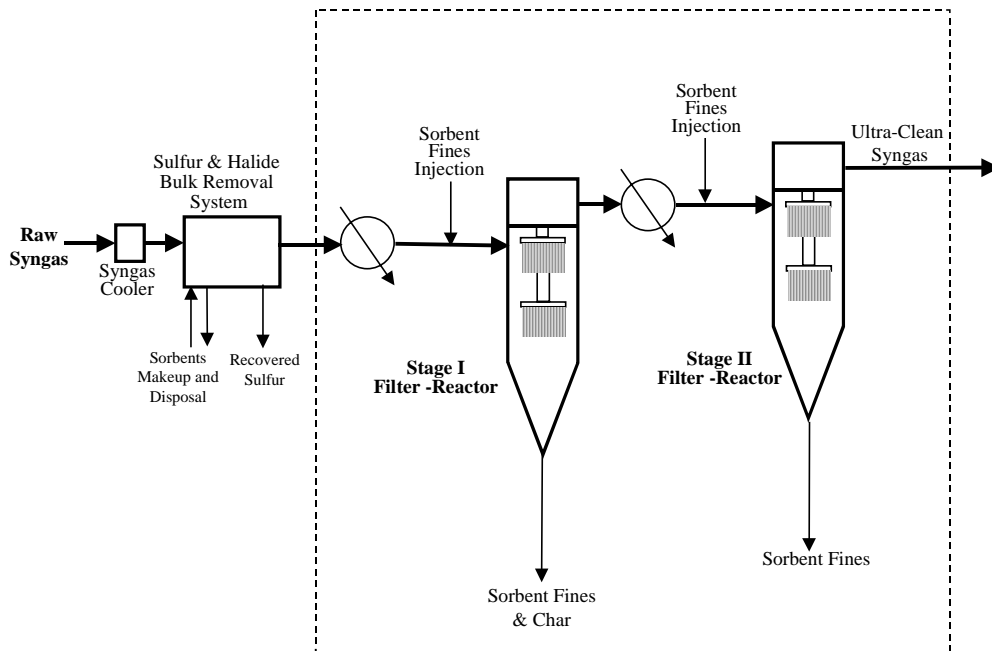
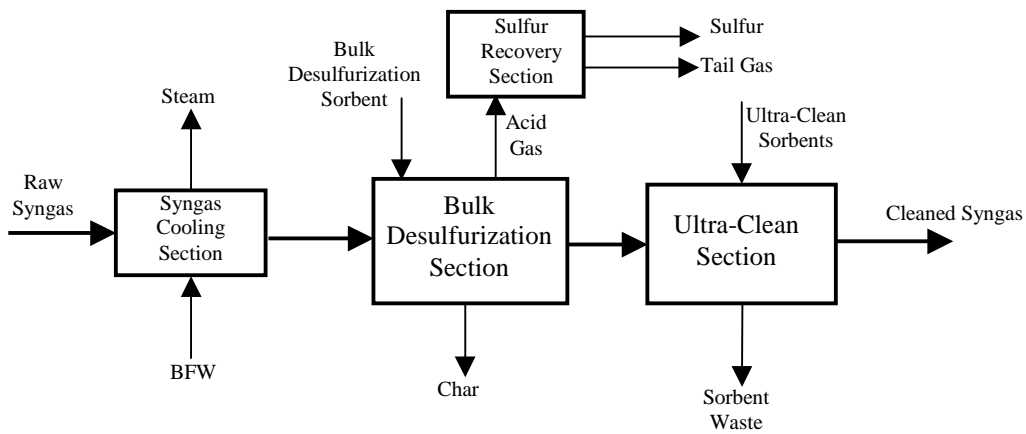**Figure 1 - Ultra-Clean Syngas Polishing Concept**
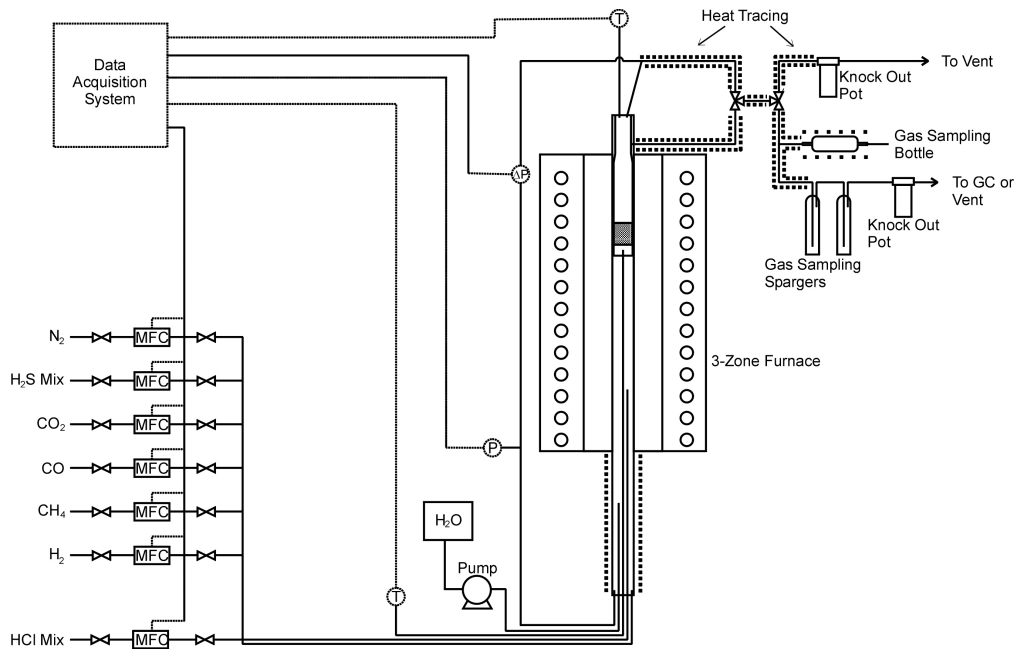
Figure 2 – Schematic Diagram of the GTI Packed-Bed Reactor Unit
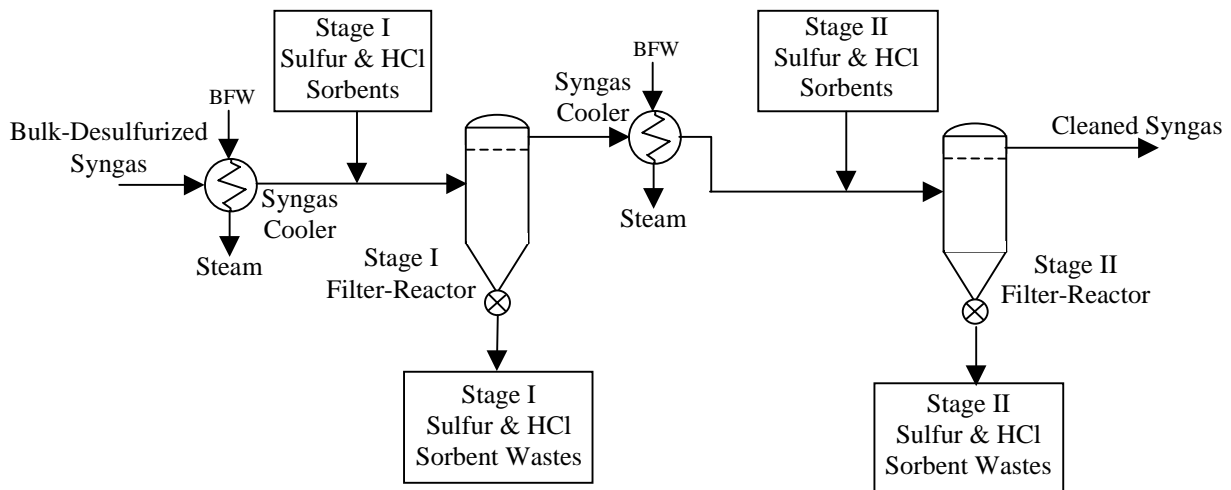

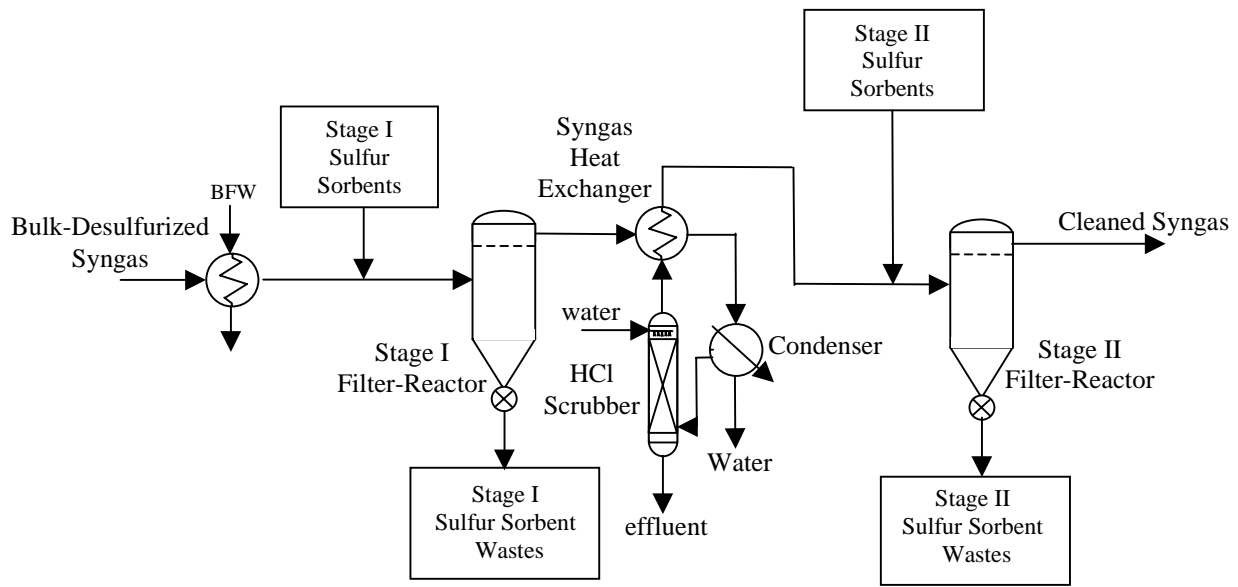**Figure 3 - HCl and H$_2$S Breakthrough Curves**

Figure 4 – Conventional Syngas Cleaning Schematic
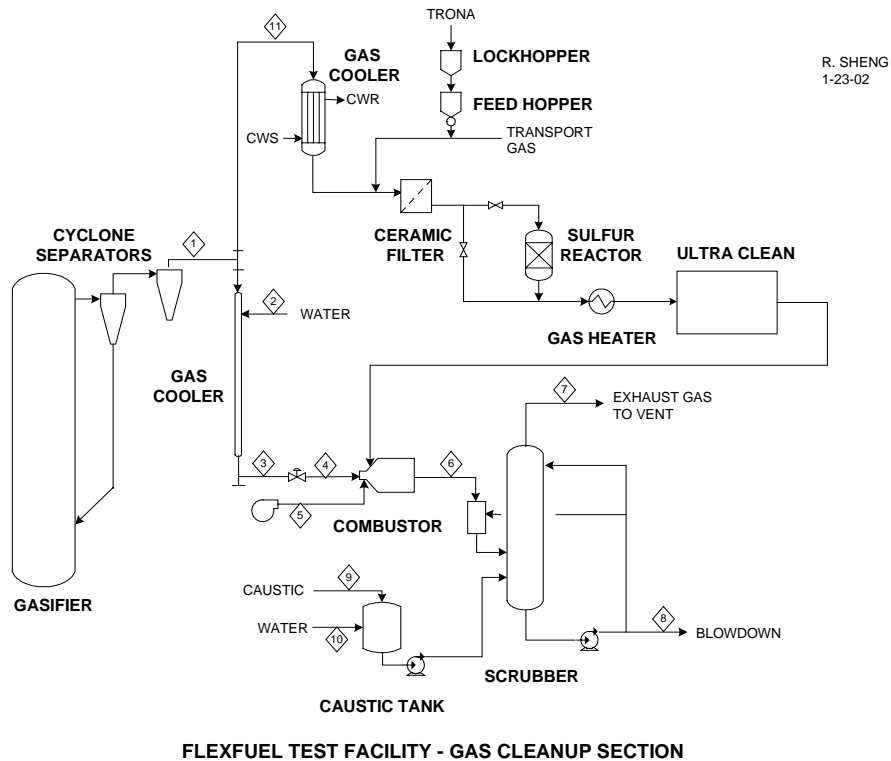

Figure 5 – Novel Syngas Cleaning Process Overall Configuration

Figure 6 – Base Ultra-Clean Section for Syngas Polishing

Figure 7 – Ultra-Clean Section with HCl Scrubbing for Syngas Polishing

Figure 8 - Ultra-Clean Syngas Polishing Process Test Facility

Table 1 - Synthesis Syngas Cleaning Process Comparisons
Raw syngas rate 81,140 kg/hr (178,880 lb/hr), inlet pressure 4,137 kPa (600 psia)

	Conventional (Rectisol)	Novel Base case
Process Factors		
Total syngas pressure drop (% of inlet)	20.8	15.4
Clean syngas temperature °C (°F)	371 (700)	288 (550)
Raw syngas molar $CO+H_2$ flow loss (%)	0.088	1.50
Cleaned syngas H_2O mole%	3.2×10^{-5}	11.49
Cleaned syngas CO_2 mole%	7.3×10^{-4}	7.54
Environmental Factors		
Tail gas/Raw syngas mass ratio (%)	41.4	12.5
Tail gas SO_2 release, kg/hr (lb/hr)	6.8 (15.0)	1.5 (3.4)
Tail gas CO_2 release, kg/hr (lb/hr)	16,421 (36,202)	1,965 (4,333)
Maximum solid waste, kg/hr (lb/hr)	0	545 (1,201)
Waste water, kg/hr (lb/hr)	10,843 (23,904)	776 (1,710)
Economic Factors		
Total Capital Requirement (k$)	37,000	23.000-24,000
Cost of Syngas Cleaning (constant $), ($ / 1000 kg raw syngas)	16.0	7.4 - 14.5

Table 2 - SOFC Fuel Gas Cleaning Process Comparisons
Raw fuel gas rate 81,140 kg/hr (178,880 lb/hr), inlet pressure 4,137 kPa (600 psia)

	Conventional (Rectisol)	Novel Base Case
Process Factors		
Total fuel gas pressure drop (% of inlet)	20.8	15.4
Clean fuel gas heating value, GJ/kg-mole (Btu/lb-mole)	262,095 (112,700)	200,002 (86,000)
Clean-to-Raw fuel gas mass ratio (%)	71.0	101.8
Clean fuel gas temperature, °C (°F)	195 (383)	176 (348)
Clean fuel gas H_2 mole%	41.24	32.30
Environmental Factors		
Tail gas/Raw fuel gas mass ratio (%)	41.4	12.5
Tail gas SO_2 release, kg/hr (lb/hr)	6.8 (15.0)	1.5 (3.4)
Tail gas CO_2 release, kg/hr (lb/hr)	16,421 (36,202)	1,965 (4,333)
Maximum solid waste, kg/hr (lb/hr)	0	622 (1,371)
Waste water, kg/hr (lb/hr)	10,843 (23,904)	776 (1,710)
Economic Factors		
Total Capital Requirement (k$)	39,000	26,000 - 27,000
Cost of Fuel Gas Cleaning, ($ / 1000 kg raw fuel gas)	14.0	4.8 - 11.6

Table 3 – Maximum Sorbent Feed Rate Criteria for 20% Cost Advantage over Conventional Syngas Cleaning

	Bulk Desulfurization Sorbent + Stage I Sulfur Sorbent (Ms/Mc) x $/kg	Stage I HCl Sorbent (Trona) (Ms/Mc) x $/kg	Stage II Sulfur Sorbent + Stage II HCl Sorbent (Ms/Mc) x $/kg
Chemical Synthesis Application			
Ultra-Clean Base	38.1	0.7	110
Ultra-Clean with HCl Scrubbing	38.0	----	220
SOFC Power Generation Application			
Ultra-Clean Base	44.7	0.7	110