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Gasification Technologies

Gasification Markets and Technologies — Present and Future

An Industry Perspective

A U.S. Department of Energy Report

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Disclaimer

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Preface

This report presents industry's views of technologies, market opportunities, and both long-term and short-term research needs deemed critical to improving the economics and performance of gasification technologies. The principal findings are the result of confidential interviews with "expert teams" from 22 prominent organizations across a wide span of the U.S. gasification industry, all of which are identified as having a direct influence on current and future technology trends. Internal deliberations by the U.S. Department of Energy's Office of Fossil Energy and the National Energy Technology Laboratory Gasification Technologies Product Team (GTPT) identified the need for the study. Subsequently, the GTPT decided upon the approach based upon input from the Gasification Technologies Council and its membership.

This report is intended to:

- Provide federal officials and managers with a clearer understanding of technology trends and research needs identified by a cross section of industry leaders.
- Assist decision makers in establishing federal funding priorities for gasification and related technologies research and development needs.
- Benefit industry decision makers through feedback of a broad spectrum of creative insights and forward-looking opinions from their colleagues' input.

Acknowledgments

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General Electric Company
Global Energy, Inc.
Praxair, Inc.
Shell Global Solutions
Siemens Westinghouse Power Corporation
Southern Company
Tampa Electric Company
Texaco Global Gas and Power
Tennessee Valley Authority
UOP LLC

It was readily apparent during the meetings that these organizations spent much time in preparation for the meetings, as well as allotting the time for the face-to-face discussions. In every case, the interviewers found the industry participants to be focused, thoughtful, insightful, and willing to engage in addressing the issues. The information provided will be extremely valuable to the DOE's Gasification Technology program planning process.

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Acronyms and Abbreviations

10^6 Btu	million British thermal units
ASU	air separation unit
ATS	Advanced Turbine Systems
BACT	Best Available Control Technology
Btu	British thermal unit
CCT	Clean Coal Technology
CFD	Computational Fluid Dynamics
CO	carbon monoxide
CO_2	carbon dioxide
COS	carbonyl sulfide
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
EPC	engineering, procurement, and construction
EPRI	Electric Power Research Institute
F-T	Fischer-Tropsch
GHG	greenhouse gas
GTC	Gasification Technology Council
GTPT	Gasification Technologies Product Team
H_2	hydrogen
H_2S	hydrogen sulfide
HAP	hazardous air pollutants
H/C	hydrogen-to-carbon
HCl	hydrochloric acid
Hg	mercury
HRSG	heat recovery steam generator
IGCC	integrated gasification combined-cycle
kW	kilowatt
LAER	Lowest Achievable Emission Rate
lb/10^6 Btu	pounds per million British thermal units
lb/MWh	pounds per megawatt-hour

LLC	Limited Liability Corporation
MACT	Maximum Achievable Control Technology
MSW	municipal solid waste
MTBF	mean time between failures
MTTR	mean time to repair
MW	megawatt
NETL	National Energy Technology Laboratory
NGCC	natural gas combined-cycle
NO_x	oxides of nitrogen
O&M	operation and maintenance
OPIC	Overseas Private Investment Corporation
PCB	polychlorinated biphenyls
petcoke	petroleum coke
pH	acidity
psia	pounds per square inch – absolute
psig	pounds per square inch – gauge
ppm	parts per million
R&D	research and development
RAM	reliability, availability, and maintainability
RCRA	Resource Conservation and Recovery Act
resid	residual heavy oil
SCR	selective catalytic reduction
SO_x	sulfur oxides
SO_2	sulfur dioxide
TCLP	Toxicity Characteristics Leaching Procedure
tpd	tons per day

Executive Summary

Task and Purpose

This report draws on the views of the gasification industry leaders and presents their perspective on markets and future market opportunities, environmental challenges, and opportunities and important technological research and development needs key to realizing the potential growth of gasification technologies. All of the opinions and major findings in this report are derived from confidential discussions with leading representatives from 22 stakeholder organizations.

The findings of this report are to be used to develop a more comprehensive technology roadmap for the U.S. Department of Energy's (DOE) Gasification Technologies Program and to support future budget requests. In addition, key findings are to be incorporated into the overall DOE portfolio planning and budgeting process.

Addressing Market Needs

Market Drivers

Economics. Product economics are identified as the most important determinant in gasification technology deployment potential. Gasification technologies must compete economically, regardless of intrinsic environmental benefits. The price differential between natural gas and the feedstocks available to a gasification plant site play a major role in determining the economic competitiveness for gasification technology. Capital costs and costs associated with protracted gasification technology engineering, procurement, and construction (EPC) schedules must be ameliorated.

Reliability, Availability, and Maintainability. Reliability, availability, and maintainability (RAM) must increase to reach acceptable industry thresholds and to eliminate redundancies contributing to high capital and EPC costs. RAM, together with investment costs, most affect the attractiveness of gasification because of its impact on the generation cost of electricity.

Environmental Considerations. The environmental superiority of gasification technologies for solid feedstocks has not as yet been leveraged into deployment, but can be leveraged in a future rewarding both environmental performance and fuel diversity. Navigating through the myriad of government regulations is a time-consuming and costly process, and the more complex the project technology, the longer and more costly the permitting process. The public perception of gasification being "dirty" because the feedstocks are perceived as "dirty" is impeding deployment by lengthening the permitting process. Even more significant is the risk associated with the uncertainty of future regulations.

Efficiency. Efficiency is a driver for technology deployment only if the efficiency gains relative to competing technologies lowers overall costs, or is at least cost neutral. The issue of efficiency is characterized in much the same way as environmental performance in that efficiency has not been a driver for deployment of the technology commercially, nor is it likely to be in the near term.

Feedstock/Product Flexibility. Feedstock and product flexibility alone cannot bring gasification technology into mainstream markets, but together with reduced capital and improved RAM, it is seen as the key to market entry. The most viable feedstocks appear to be coal, petroleum coke (petcoke), and residual heavy oil (resid), including hazardous oil-bearing secondary materials. Biomass is another option. In general, it is believed that in the United States the increased use of biomass feedstocks is driven more by environmental and regulatory factors than by free-market forces.

Energy Security. Gasification technology supports national energy security goals by producing power, clean fuels, and chemicals from our nation's most abundant energy resource, coal, as well as from readily available wastes.

Outreach. Better industry access to reliable gasification technology cost and performance data and improvement in communicating the technology's benefits are needed to accelerate deployment.

International. The range of feedstocks and products afforded by gasification technology makes the technology attractive to both developed and developing countries.

Markets

Clean Power Generation. Clean power generation is the primary market for gasification technology, with use of refinery bottoms providing market entry, coal-based generation following and dominating, and waste disposal and recycling applications emerging as major markets as well. Refinery applications offer economic advantages that make gasification competitive even at today's natural gas prices. The relatively low, stable cost of coal and its abundance domestically, and in key regions around the world, make coal gasification the ultimate dominant market for gasification technology. Gasification is environmentally superior to incineration for disposal of municipal and industrial wastes, and with some development work can emerge an economic "winner." Gasification offers an effective means to convert highly toxic substances, like polychlorinated biphenyls (PCB), into salable by-products. With improvements in RAM and capital costs, gasification will have significant market potential.

Clean Energy Conversion. Synthesis gas derived from gasification represents a fuel for fuel cells and a basis for producing clean fuels, with the clean fuels option believed to be the primary option through 2015. A near-term opportunity for gasification technologies is provided by the push for ultra-clean transportation fuels. The combination of gasification with Fischer-Tropsch (F-T) processes has potential in the U.S. liquid fuels market to meet a need for low-sulfur, high-quality diesel fuels. Future regulations are likely to put a high premium on F-T products for use as blending stock. Bottom-of-the-barrel resid and petcoke are excellent conversion feedstocks as well as being excellent candidates to produce power.

Many developed nations have access to low-cost refinery wastes to use as a feedstock for integrated gasification combined-cycle (IGCC). Developing Asia is experiencing the greatest energy growth in the world and is largely dependent upon its vast, relatively low-cost coal resources for electric power generation. Many of the coals, however, are high ash and can be a problem in IGCC plants.

Needs

Needs by industry in support of mainstream gasification technology commercialization include: (1) improving overall gasifier performance, especially RAM, (2) demonstrating the use of gasification as an economically and environmentally superior alternative to municipal and hazardous waste disposal, (3) improving investor confidence through the replication of commercial demonstrations, (4) streamlining the regulatory process, and (5) conducting a grassroots national public relations campaign on behalf of coal to eradicate coal's "dirty" image.

Environmental Considerations

Environmental Benefits of Gasification

Coal-Based Systems. IGCC is by far the cleanest coal-based power system available today, yet it is compared against natural gas combined-cycle (NGCC) in establishing permitted emission limits based on Best Available Control Technology (BACT) and Lowest Achievable Emission Rate (LAER). This comparison is deemed unfair because IGCC introduces benefits associated with feedstock diversity and energy security and provides an effective means of capturing carbon dioxide (CO_2), whereas NGCC does not.

Waste-based systems. The U.S. Environmental Protection Agency (EPA) recently recognized the superiority of gasification in processing refinery wastes and the associated waste source reduction and the recycling of wastes into usable by-products. Similar action on non-refinery-based toxic compounds, such as PCBs, is hoped for in the near future. It is considered that with some research and development (R&D) on municipal solid waste (MSW) processing and injection, MSW can also become a gasification feedstock subject to waste reduction and recycling, rather than continued treatment and disposal.

Environmental Issues and Needs

Misperceptions of Gasification. The public and regulator perceptions that coal and petcoke are dirty feedstocks, along with their perception that emissions from coal gasification plants are equivalent to those from other coal plants, unfairly limits the attractiveness of gasification. Needs include educating the public about the positive environmental and domestic energy implications of gasification, conducting more demonstrations to prove gasification is "clean," and forming gasification advocacy groups.

Permitting. Even in locations favorably inclined to gasification projects, the process is long and expensive. Needs include having the government step in and develop a structure to streamline the regulatory process, with a target of reducing the time to permit a gasification plant to six months.

Regulatory Uncertainty. The uncertainty over if, when, and how new environmental regulations and rules are to be implemented is a major impediment to the business development of the gasification industry. Needs include having regulators take care in how tightened regulations are written for nitrogen oxides (NO_x), greenhouse gases, trace contaminants (especially mercury), and solid wastes (ash and slag), so that gasification technology is not inadvertently halted before it has a chance to reach its operational and environmental performance potential.

NO_x Emissions. The uncertainty of regulatory requirements related to NO_x is very troublesome to the industry. Based on what appears to be a fundamental unwillingness to recognize the differences between IGCC and NGCC technologies, some regulators have been inclined to require NO_x emissions from IGCC plants to be controlled to the same levels as those from NGCC plants. Needs include conducting a study to determine whether selective catalytic reduction (SCR) for NO_x control is justified, and implementing R&D on alternative technologies that achieve ultra-low NO_x emissions, such as catalytic synthesis gas combustion and dry, low-NO_x conversion processes.

SO_x Emissions. Coal gasification-based power generation technologies emit far less sulfur oxides (SO_x) than other coal-based power systems, typically removing over 99 percent of the sulfur in the coal. However, nearly complete sulfur removal is required in support of reaching ever lower NO_x emissions levels and using synthesis gas for ultra-clean transportation fuels and fuel cells (sulfur compounds adversely impact NO_x processes and downstream equipment). Industry identified needs include pursuing sulfur capture options that offer nearly 100 percent sulfur removal at costs equal to, or lower than, today's state-of-the-art technology; and developing new markets for sulfur.

Global Climate Change. One strong consensus about the greenhouse gas (GHG) issue that did emerge from the interviews is that nearly all the companies are giving it serious consideration as they make plans and position themselves for the future. Industry needs include: (1) placing priority on increasing efficiency by providing economic incentives for high efficiency, (2) developing technologies for either sequestering CO_2 or converting it into a marketable by-product, (3) conducting R&D on CO_2 sequestration as a hedge against future regulation, and (4) demonstrating the removal of CO_2 from synthesis gas as an early step in demonstrating carbon capture/sequestration.

Mercury and Other Trace Contaminants. New regulations are going to be enacted for trace metal emissions, notably mercury. Depending on the details, such regulations can become an obstacle to gasification and other solid-fuel technologies. Needs include: (1) conducting R&D to address disposal of the small volumes of captured mercury produced, (2) developing mercury and other vapor phase contaminant cleanup technologies that operate at 300–700 °F, (3) testing a carbon guard bed approach at an existing IGCC plant, (4) conducting R&D on the regeneration and disposal of guard bed material, (5) precisely characterizing how various trace contaminants partition in a gasification system, and (6) developing a better way to measure the mercury concentration in gasification process streams.

Solid Waste Disposal. Another source of regulatory uncertainty is the EPA's proposed rule on whether or not to classify as hazardous waste the synthesis gas and by-products (slag) produced by gasifiers that utilize a hazardous waste feedstock. Needs include supporting the Gasification Technology Council's action to have gasification recognized as the preferred technology (over incineration) for waste recycling of non-refinery wastes, developing new ways to economically utilize ash and slag, and conducting R&D on the co-disposal of fly ash with gasifier ash.

Water Consumption and Discharge. As the importance of water management issues continues to increase, the consumption and discharge of water represents an environmental hurdle for any new power plants, including gasification plants. New projects are likely to face zero water discharge requirements. Needs include implementing R&D for zero water discharge, developing dry feed systems, improving gas cleanup processes, and developing technologies to replace cooling towers to improve water management.

Reflecting the Effects of Efficiency on the Emissions of Energy Plants. Most emissions from energy plants (refineries, power plants, and chemical plants) are currently measured in terms of mass per unit energy input, *i.e.*, lb/10^6 Btu-input. This approach does not reflect the environmental benefits of high efficiency or the environmental costs of low efficiency. Needs include measuring emissions from electric power production in pounds per megawatt-hour (lb/MWh), and measuring emissions from synthesis gas or liquid fuel production in pounds per unit heat content of the fuel produced, such as lb/10^6 Btu-output.

Technology Needs

For gasification as a whole, process reliability is identified by nearly all participants as the single most important technical limitation to be overcome in order to achieve widespread deployment of the technology. The following discusses the individual processes that need improvement in the process sequence.

Feedstocks

Feedstock Preparation. Proper preparation of the feedstock for use in a gasifier is a key process step because of its potential for impacting process reliability and availability. It is believed that the preparation of the feedstock may have important ramifications on the life of the feed injectors in the gasifier, and thus plant availability. Needs include: (1) elucidating the effects of feedstock preparation on the life of the gasifier feed injectors, (2) developing new and/or improved approaches for dewatering and increasing the density of low-rank coals and alternative feedstocks, (3) establishing a fundamental understanding of the impact of new preparation technologies on the critical properties required for proper feeding, (4) developing low-cost briquetting techniques, and (5) eliminating lock-hoppers and associated storage equipment by developing a pressurized mill for coal-based systems.

Feed Systems. Operation and maintenance issues remain regarding erosion and corrosion of valves, pipes, and pumps. The development of new or improved feeding systems for high-pressure gasifiers remains fairly high on the list of priorities. Needs include: (1) developing co-feed systems for classes of feeds, (2) investigating co-feed systems having the flexibility to feed different solid feedstocks separately and together, (3) identifying and addressing mechanical and safety issues associated with preparing and feeding CO_2 slurries, (4) investigating the impact of high concentrations of CO_2 on gasifier performance, (5) developing low-cost surfactants to achieve a stable slurry with a 70 percent coal concentration, and (6) conducting R&D on dry feed systems that use synthesis gas or natural gas as the transport medium.

Instrumentation. Analytical instrumentation is an area in which most participants felt improvements or new developments are needed. Needs include developing and demonstrating instrumentation to measure the flow rate and density of the feedstock in slurry-based systems, and developing an affordable on-line analytical device that can provide the elemental composition of the gasifier feedstock.

Gasification

The gasification area of the plant received, by far, the most intense level of discussion. The gasification block constitutes about 15 percent of the capital cost of an IGCC plant.

Feed Injectors. Many participants feel that injector life is the weakest link in the reliability of gasification systems. Based on actual experience, the life of a typical injector nozzle is generally from two to six months. A minimum life of twelve months is desired in the near term, with an ultimate goal of two years. Needs include: (1) conducting a comprehensive study to define the factors that contribute to the failure of gasifier feed injectors, (2) developing new injector materials to further injector life and lower the manufacturing and refurbishing costs, (3) developing reliable, cost effective variable orifice injectors and multiple-fuel injectors that can adjust to load and feedstock changes, and (4) exploring the possibility of establishing an injector test facility.

Refractory Liners. Refractory liners in high-temperature slagging gasifiers are known to undergo significant deterioration over a relatively short period of time, 6 –18 months. Needs include: (1) developing new materials that have an expected useful life of three years or more at about 50 percent of the cost of current materials, (2) investigating new approaches to lining gasifiers, or eliminating the need for refractories, (3) conducting additional R&D on water-cooled refractories, and (4) establishing a small refractory material test facility at a commercial gasification site.

Ash/Slag Removal. An improved understanding of the properties and characteristics of the molten slag inside the gasifier is deemed beneficial by some organizations. Needs include: (1) establishing a better knowledge of flux (compounds used to lower ash fusion temperatures) effectiveness for solid feedstock units, (2) developing new fluxing agents that reduce the ash fusion temperature to 2,200 °F or less, and (3) establishing a database that contains coal properties of interest to gasification.

Instrumentation. The ability to reliably measure various process parameters, and the composition and properties of various process streams is considered a high priority based on the numerous responses received. Needs include: (1) developing means to measure temperatures inside the gasifier on a real-time basis; (2) developing on-line instrumentation to measure or analyze wear on the refractory liner, composition of hot product gas, and isokinetic particulate sampling; and (3) developing on-line instrumentation to measure ash fusion temperature, slag viscosity, and slag layer thickness.

New Gasification Concepts. Needs include: (1) investigating feedstock-flexible, higher efficiency gasifier concepts for applications that use low-energy-density feedstocks, such as high-ash coals and biomass; (2) performing a market survey to help define the applications and needs for smaller gasifiers; and (3) developing low-temperature, non-slagging gasifiers to reduce plant capital and operating costs.

Gas Cleaning

Synthesis gas cleaning and, in particular, the control of HAPs and trace metals, is an area of concern in light of future regulations of such emissions. The capital cost of removing particulate matter and chemical contaminants from the synthesis gas generally accounts for about 10–12 percent of the total capital cost of an IGCC plant.

Cold Gas Cleaning. Needs include: (1) developing cost-effective technologies that can remove heat-stable salts from existing processes, and new solvent systems with enhanced performance; (2) placing a priority on systems that can remove both carbonyl sulfide (COS) and hydrogen sulfide (H_2S) simultaneously, as well as chlorides; and (3) pursuing development of both wet and dry novel ambient temperature approaches.

Warm Gas Cleaning. The need is to develop a synthesis gas cleanup system operating between 300–700 °F to reduce sulfur to near-zero levels and to remove mercury, ammonia, and other trace contaminants.

Hot Gas Cleaning. The need is to develop synthesis gas cleanup systems in the long term that operate above 800 °F for gas turbine and fuel cell applications, addressing removal of tars, sulfur, alkalis, ash, hydrochloric acid (HCl), and mercury (Hg) to very low levels.

Particulate Filtration. Needs include: (1) developing more durable, reliable, and cost effective ceramic and metallic filter elements with a useful life of at least three years, (2) developing reliable safeguard devices to protect downstream processes in the event of filter failure, (3) involving manufacturers in filter and safeguard development, and (4) conducting R&D to resolve chloride cracking (stress corrosion) of pipes and valves in the gas flow path and the erosion of valves used for hot solids handling.

Heat Recovery

Synthesis Gas Cooling – Non-quench Operation. Needs include: (1) developing technologies that are capable of removing vapor phase trace metals from the hot raw synthesis gas stream before it enters the heat exchanger, and (2) investigating new heat recovery processes that minimize deposition and improved techniques for removing the deposits from the heat transfer surfaces.

Synthesis Gas Cooling – Quench Operation. Needs include: (1) pursuing process development to improve quench process efficiency for high-ash feedstocks in a commercial plant to address scale-up issues, and (2) investigating improved designs that quench effectively with less conversion of carbon monoxide (CO) to CO_2.

Heat Recovery Steam Generator. The need is to investigate replacing the heat recovery steam generator (HRSG) with a higher-temperature method of heat recovery, such as a hot oil or molten salt system to improve heat integration and efficiency.

Gas Separation

Air Separation. Membrane-based technologies have recently been reported to reduce capital costs of an IGCC plant by about $75–100/kW, improve plant efficiency 1–3 percentage points, and increase net power production by 7 percent. Needs include: (1) exploring air separation technologies that operate between -50 °F and 350 °F, (2) completing development of the current suite of membranes before pursuing the next generation of membrane materials, (3) developing an efficient and effective air extraction/return capability for the gas turbine, and (4) resolving the problem of accumulation of small carbonaceous particles on surfaces in the presence of high-purity oxygen.

Hydrogen/CO_2 Separation. If required today, existing technologies, such as Rectisol and Selexol, can be applied to capture CO_2; however, such applications are expensive and impose a severe energy penalty on the system. Needs include: (1) placing a high priority on development and demonstration of carbon sequestration and utilization technologies, (2) implementing fundamental research at universities and national laboratories on "outside-the-box" approaches to the separation of hydrogen and CO_2, (3) developing lower cost CO_2 capture technologies, and (4) placing emphasis on pressurizing the product streams and targeting separation technologies operating at 800 °F or less.

By-Products

Ash/Slag. Needs include: (1) developing new leaching test methods for each ash/slag application; (2) determining whether the specifications for certain markets can be relaxed to accommodate the high moisture and carbon content of the slag; (3) developing cost-effective means to reduce ash/slag carbon, moisture content, and product size; (4) developing means to reduce the cost of grinding and classifying the ash/slag; (5) exploring opportunities for recovery of components that either detract from ash/slag value or are in themselves valuable; and (6) characterizing the solids produced from gasification of waste materials and coal/waste blends to determine the marketability of the materials.

Sulfur. There is a growing concern that as more and more gasification facilities are constructed and operated, the production of high-grade sulfur by-product will eventually exceed demand. Needs include: (1) determining the level of IGCC capacity at which the market becomes saturated, and (2) developing new markets and ways to utilize sulfur.

Synthesis Gas Utilization

Gas Turbines. Needs include: (1) continuing the Advanced Turbine Systems (ATS) program, or other DOE programs, focusing on synthesis gas applications and encouraging gas turbine manufacturers to design turbines that can burn synthesis gas; (2) expanding the range of the fuel handling system and gas turbine nozzle performance to accommodate the use of multiple compositions of diluted fuels having a broad range of hydrogen content and time-varying heating values caused by swings in product output; (3) establishing a U.S.-based user test facility; (4) characterizing the deposition, corrosion, and erosion that results from feeding synthesis gas to a gas turbine; and (5) developing new low-NO_x gas turbine combustion systems, such as dry low-NO_x burners for low-Btu gas and catalytic synthesis gas combustion.

Fuel Cells. Needs include: (1) developing specifications for maximum allowable contaminant levels in the synthesis gas, (2) developing more poison-tolerant fuel cells, (3) investigating integration and optimization of the fuel cell in the overall plant configuration, and (4) supporting synthesis gas-based fuel cell system pilot-scale testing and demonstration projects.

Synthesis Gas Conversion. Needs include: (1) pursuing new approaches to improve the economics of synthesis gas conversion, (2) exploring new routes for the conversion of synthesis gas to chemicals and C_2 and C_3 alcohols, (3) directing near-term efforts at the development of synthesis gas conversion to F-T products, (4) developing process schemes for an integrated gasification/F-T plant, and (5) establishing a user facility to demonstrate new technologies.

Integration

Design Standardization and Modularization. Many believe that modularization of process units and standardization of designs stand to greatly benefit the commercialization of gasification. Needs include: (1) conducting a study addressing optimized design of a modular, standardized IGCC plant for a niche power market into which many such plants can be sold; (2) analyzing the market to determine the size of the standardized IGCC study plant; (3) developing a market growth strategy to repower 20–25 percent of existing power plant capacity with standardized plant designs; and (4) targeting a 20 percent reduction in footprint for the standardized plant.

Air Separation Unit/Gas Turbine Integration. Full versus partial integration between the air separation unit (ASU) and gas turbine is still an unresolved issue, and considering the higher pressure ratios of future gas turbines, integration is likely to continue to be problematic. Needs include conducting R&D to address the issue of integration of the gas turbine with the ASU.

Databases. Sources of information on gasification system design and performance appear to be, at best, very minimal. Numerous requests are made for the development of databases, which industry can utilize in the development of projects. It appears that there is considerable concern that designers are not aware of past mistakes and that important learning experience benefits are being lost.

CO_2 and Hydrogen Integration. Needs include: (1) defining the optimum configuration of a gasification system to accommodate CO_2 capture/sequestration and quantify the economics of the process; (2) conducting pilot and commercial-scale demonstrations of CO_2 capture and sequestration at a gasification facility; and (3) demonstrating hydrogen production resulting from CO_2 capture, with emphasis on storage and transport.

Instrumentation and Controls

There is clearly a need for the development of new and improved techniques for monitoring and controlling all processes and process streams within a gasification plant. Many believe that instrumentation and controls are key areas to further the advancement of gasification. Specific instrumentation needs are presented in the context of the components or subsystems previously discussed. Other needs include: (1) developing advanced, model predictive controls to regulate the total system, especially if load following is required; (2) demonstrating advanced logic supervisory/optimization systems; (3) developing simulators that can be used to train operators on new plants in a consistent manner; (4) developing tunable diode laser technology for gas measurements in high-temperature environments; (5) developing a reliable pH meter capable of operating under elevated pressures and temperatures up to 300 °F for scrubbing system applications; and (6) developing diagnostic procedures and tools to identify process improvements affecting plant reliability and performance.

Models

The need for more sophisticated advanced gasifier and other process models ranks very high. Needs include: (1) defining what models are clearly needed to benefit the entire industry before developing them; (2) focusing model development on dynamic models that can be used not only to predict the steady-state performance of a gasifier, but also to simulate transient events; and (3) validating the models with actual plant data rather than using theoretical diagnostics or dynamic modeling as substitutes for actual operational experience.

Government Role

Government-Sponsored Testing Facilities. Needs include: (1) increasing use of existing IGCC facilities, such as the Wabash River and Tampa Electric IGCC plants, to test and validate new technology, (2) expanding R&D at the government's component testing facilities at Wilsonville, Grand Forks, National Energy Technology Laboratory, and LaPorte, and (3) establishing a government-sponsored full-scale demonstration plant that includes slipstreams specifically designed for testing new technologies in a "plug and play" fashion.

Government Incentives for Gasification Projects. Needs include: (1) having the government provide insurance on the schedule, cost, and performance of initial commercial IGCC plants, (2) funding another wave of IGCC demonstrations that ties government cost-sharing to project performance, and replicating the most promising technologies to overcome technical risk, (3) providing tax credits or other financial incentives for initial commercial IGCC plants that are tied to performance targets, such as efficiency or CO_2 emissions, to encourage coal and biomass utilization.

Introduction

Task and Purpose

From the late fall of 2000 through the early spring of 2001, representatives of the Gasification Technology Product Team (GTPT) from the U.S. Department of Energy's (DOE) Office of Fossil Energy and the National Energy Technology Laboratory (NETL) conducted a series of interviews and information-gathering discussions with industrial teams from organizations representing a wide range of business lines in the U.S. gasification industry. The goals for this field research were to: (1) elicit the views of industry experts on their "vision" for the industry from the present to 2015 and (2) obtain opinions from leaders in the industry on what are likely to be critical technology research and development (R&D) needs in both the near term and long term. The results of this effort are intended to assist industry and government managers in the decision making process related to ensuring that existing systems can attain the best possible cost and performance in the near term and that future systems can achieve both the government's and industry's long-term visions.

Additionally, the findings of this report will be used to develop a more comprehensive technology roadmap for DOE's Gasification Technologies Program and to justify future budget requests. Key findings will be incorporated into the overall DOE portfolio planning and budgeting process.

Process

The GTPT met with representatives from 22 organizations across a broad spectrum of the gasification industry (refer to the Acknowledgments section for the list of participants). The GTPT arranged the interviews and discussions around a formal and consistent protocol and structure. The organizations and individuals acting as points-of-contact were selected based on their positions as industry leaders and their willingness and ability to discuss frankly and creatively the technology, market, and economic issues affecting the industry.

The GTPT developed the basic interview structure through an iterative process. The "tools" used in formulating this structure, which are included in the various appendices for reference purposes, included:

- A formal letter to the industry points-of-contact affirming the goals of the task and the interview date;
- An agenda setting forth the pattern and timing for the various presentations and discussions;
- A copy of a GTPT presentation providing each industry team with an overview of the DOE-sponsored R&D program with respect to content, management, and implementation; and
- A list of interview questions establishing the scope of the interview and addressing the specific themes of the study.

In line with the aim of promoting frank and open dialogue, the GTPT once again informed all organizations prior to the interview that the final report would not attribute any particular comments or views to specific individuals or companies. This protocol of "confidentiality" was key to achieving the frank and open discussion. The discussions covered a broad range of topics, including technology trends; market drivers; "hands-on" experience with a particular process, technology, or innovation; and detailed knowledge of technology operations. In each case, the individuals proved willing to engage in discussions of sensitive issues within the confines of the allotted time.

Scope

In an attempt to obtain the best possible sample, interview participants were drawn from the executive, technology research, application, and operational management ranks of the leading companies in the gasification industry. But it is recognized that the industry is so complex and diverse that the slate of issues and opinions within the domain of "gasification" is too exhaustive for all to be included in this report.

What has been compiled is a summary of the key findings and a synthesis of perspectives based on the sample of parties included in the study. While attempts were made to identify and represent convergent themes under the main topic headings, the report does not necessarily present a "consensus view." While most of the points covered have convergence, some have conflicting views. Moreover, despite a consistent interview structure for all interviews, the flow of each interview was unique. In most interviews, the interviewees devoted the greatest amount of time to issues that they viewed most critical or valuable, while minimizing or even disregarding certain issues or topics within the constraints of the scheduled time. This is another reason why trying to reach consensus on all the issues would be a fruitless task.

Presentation of Findings

The presentation of findings in this report is from industry's perspective, as interpreted from the interviews. Every effort has been made to present the material untainted by any views held by the interviewers or by government policies applicable to the subject discussed.

Addressing Market Needs

Introduction

The process of estimating future markets for gasification technologies, both domestically and internationally, is quite complicated. Even if an accurate model of the myriad of factors affecting markets and their interdependencies could be prescribed, forecasting uncertainties inherent in those factors adds another layer of complexity. The macro factors affecting new technology diffusion into any given market include: the future economic outlook, governing energy and environmental policies, regulatory reforms and outlook, resource availability and utilization issues, R&D funding availability and prioritization, partnering requirements, and the speed of innovation of competing technologies.

It is recognized that the complexities inherent in these macro factors and other issues significantly impact how markets ultimately evolve and mature. However, the interviews and subsequent discussions typically focused on more easily discernible micro-economic factors, as well as factors germane to the technology itself. Examples include price and availability of natural gas, feedstock type and availability, risk identification, key performance parameters, and issues affecting project development.

The market horizon chosen for discussion is from the present to 2015. The discussions address both domestic and international markets. The industry perspective on markets is presented in terms of market drivers, markets, and perceived needs.

Many of the markets presented in this report are likely to require some major technology advances during the next decade, as well as favorable economics, an environment that provides some coordinated efforts between technology development and regulatory development, and greater collaboration between technology suppliers, project developers and plant operators. Additionally, the continuation of the long-term government and industry commitment to collaborative research on advanced technology development is viewed as key to future successes.

A significant increase in market activity, both domestically and internationally, is envisaged beyond 2008. Industry needs for moving gasification technologies from niche opportunities to mainstream markets are provided at the end of this section.

Market Drivers

Economics

Gasification technology must compete economically, regardless of intrinsic environmental benefits.

Product economics are identified as the most important determinant in gasification technology deployment potential. In order to sell power in markets characterized as high demand, power plants have to compete economically, regardless of any tangible, or intangible, environmental or socio-economic benefits that may be intrinsic in a particular technology or process. Incremental improvement in the cost of plant operations is seen as necessary to enable integrated gasification combined-cycle (IGCC) technologies to be attractive to power producers.

Feedstock

The price differential between natural gas and the feedstocks available to a gasification plant site plays a major role in determining the economic competitiveness for gasification technologies.

Gasification technologies such as IGCC must compete against natural gas combined-cycle (NGCC) in the electricity generation market. Consequently, the price and supply outlook for natural gas is a major driver in technology decision making, as is the price and supply outlook for possible IGCC feedstocks, including coal and refinery wastes (petroleum coke and residual heavy oil), and other feedstock options (biomass, and industrial and municipal wastes).

Even at relatively low and stable natural gas prices ($2.50/$10^6$ Btu), the prospects for new IGCC facilities are considered favorable, in certain cases, as a hedge against future gas price volatility. These cases include situations: (1) having good access to coal and other solid fuel supplies; (2) offering a sound infrastructure (transmission, water, permits, product need, *etc*.); and (3) providing economic parity with the benchmark gas price through the use of low-cost feedstock, such as petroleum coke (petcoke) and residual heavy oil (resid). The use of biomass as a base-load feedstock is not considered viable in the short term, except in niche situations, such as pulp and paper industry applications. The impediments to biomass are technical in nature (tar production, feed preparation, and injection problems) and relate to feedstock availability and transportation logistics and cost. Also, the gasification of high ash coals, while technically feasible, is not considered to be economically attractive.

Investment Costs

Capital costs and costs associated with protracted gasification technology engineering, procurement, and construction schedules must be ameliorated.

Process complexity and the associated protracted engineering, procurement, and construction (EPC) schedules, and high capital costs have to be addressed.

As with most new technologies, gasification projects require a higher hurdle rate, or higher cost of capital, than projects using existing technology. That is, investors require a higher rate of return on their investment in a relatively new or untested technology to offset the risk in not knowing how the technology may perform in the marketplace. Unfortunately, gasification technology advantages with regard to reducing criteria pollutants, solid waste, and atmospheric mercury (compared to competing coal-based technologies) are non-monetized and do not provide any type of financial offset to the cost of gasification projects. This fact underscores the need for achieving DOE's mid-projection fully loaded EPC cost target of $1,000/kW by 2008. Cost targets are to be met through improvements derived from learning, economies of scale, plant standardization, reduction in major sub-system costs (such as turbines, gas cleaning, and oxygen plant), risk reduction, and other improvements germane to more mature technologies and plants.

Process complexity contributes to high capital cost and protracted EPC schedules. The complexity largely is the result of redundancies built into the not-yet-mature technology and lack of standardization and modularization of components and subsystems. And currently, the number of projects is too few and their capacities too large to encourage competition for development of standard, modular designs to reduce costs. The few large projects to date have used custom designs for the specific project.

Because of the high capital costs, most owners are looking for non-recourse financing with maximum leverage. This situation shifts the burden for performance onto EPC contractors, who often are unable to have performance warranties underwritten. This then shifts the risk of non-payment of debt onto financial institutions, who raise the risk premium and the cost of doing business.

Reliability, Availability, and Maintainability

Reliability, availability, and maintainability must increase to reach acceptable industry thresholds and to eliminate redundancies contributing to high capital and EPC costs.

Reliability, availability, and maintainability (RAM), together with investment costs, most affect the attractiveness of gasification because of the impact on the cost of electricity and other products. Gasification currently has a relatively poor RAM track record. The RAM must be improved to the extent that the use of multiple gasifier trains, presently necessary for RAM considerations, can be phased out in favor of single trains to improve plant economics. The goal of greater than 90 percent availability for a single train unit is viewed as a requirement for power generation. In applications such as refineries and chemical plants, where the units are fully integrated into upstream and downstream processes, there is a need for 100 percent availability — a particular challenge given current gasifier system complexity. However, the 100 percent availability goal is valid. Interruptions in product supply from the gasifier cannot be tolerated. For example, a brief 10-minute steam interruption can cause an uncontrolled shutdown of an entire refinery and a resultant 1- to 2-week outage.

Environmental Considerations

The environmental superiority of gasification technologies for solid feedstocks has not as yet been leveraged into deployment, but can be leveraged in a future rewarding both environmental performance and feedstock diversity.

Environmental considerations are discussed in detail in the following section because of the depth of information emerging from the interviews and the importance of the topic from a public interest perspective. An overview is provided here to place environmental considerations in the context of other factors identified by industry as driving gasification technology deployment.

There is a widely held opinion in the industry, much of which is supported by current demonstration projects, that the environmental performance of gasification is superior to other options when using solid carbonaceous feedstocks. However, these advantages have not significantly driven the deployment of gasification and are unlikely to do so in the near term. In the long term, gasification's superiority to combustion as a waste recycling and disposal technology is likely to be leveraged into a significant market.

While regulations on the greenhouse gas (GHG) carbon dioxide (CO_2) would be an immediate hurdle to deployment of coal plants, gasification plants are in the best position compared to other coal-based alternatives to capture CO_2. Given the uncertainty of CO_2 regulation, there is industry reluctance to make large investments in projects with high CO_2 emissions, since a cost-effective solution for reducing such emissions is not yet available. Nevertheless, the GHG issue can be an enhancing factor for gasification in the long run because the CO_2 occurs in concentrated form, making it more amenable to capture.

The industry is unanimous in the opinion that anything that can improve the plant permitting process is helpful. Navigating through the myriad of government regulations is a time-consuming and costly process; and the more complex the project technology, the longer and more costly the process usually is. Even more significant is the risk associated with the uncertainty of future regulations. Further, there is still a public perception that because coal and petcoke are "dirty" feedstocks, any process that uses them must also be "dirty." This perception further lengthens the permitting process. Obtaining a plant site is a long and difficult process, especially with regard to transmission line access or the siting of new lines. Therefore, features that are attractive relative to siting are important. IGCC has the advantage of offering far higher efficiency, lower pollutant emissions, and lower water consumption than other coal-fueled technologies.

Efficiency

Efficiency gain is only a driver for technology deployment if the gain relative to competing technologies improves plant economics (or is at least cost-neutral).

The issue of efficiency is characterized in much the same way as environmental performance in that it has not been a driver for deployment of the technology commercially, nor is it likely to be in the near term. Also, in the long term, efficiency is likely to be much less important than improvements in cost and RAM. Efficiency is only a driver to the extent that any gain also improves cost performance, or is at least cost-neutral. Otherwise, some form of government incentive is deemed necessary to obtain dramatic improvements in efficiency. It was forecast by some of the respondents that natural gas has to approach $12/10^6 Btu to justify capital projects that focus on significant increases in efficiency and improve the bottom line. Higher efficiency is viewed as "nice to have," primarily from an emissions reduction standpoint, which includes CO_2. The industry view is that the current efficiencies available (41–45 percent) appear adequate.

Feedstock/Product Flexibility

Feedstock and product flexibility alone cannot bring gasification technology into mainstream markets, but together with reduced capital and improved RAM, it is seen as the key to market entry.

Although both feedstock and product flexibility add to the attractiveness of gasification technologies, these features alone do not justify the selection of the technology at today's relatively high capital cost coupled with the perceptions of higher risk. However, a constant theme from the industry experts is that gasification will continue to be attractive in the long term because of its capability to process multiple feedstocks and to produce multiple products.

The most viable feedstocks appear to be coal, petcoke, and resid, including hazardous secondary oil-bearing materials. The primary driver for feedstock selection is cost. "The cheaper the better," is how one respondent characterized feedstock selection criteria. Other feedstocks considered include gob, pond fines, biomass, animal wastes, and municipal and industrial wastes.

With respect to biomass, there are widely conflicting views about its overall potential for use as a feedstock. One school of opinion places biomass applications in the niche category at best, suggesting that the pulp and paper industry represents the best opportunity. Of those harboring the view that biomass is not going to transition to becoming a significant feedstock, many cite the high costs associated with harvesting and dewatering the biomass as a major factor, limiting application to those regions that have an indigenous uniform supply of suitable biomass feedstock, such as the pulp and paper industry.

Beyond the issue of biomass availability, including the seasonal factors associated with many of the biomass feedstocks, another major concern is that more energy is expended in the collection and preparation stages than is generated through processing the biomass. Also, as discussed in the Technology Needs section, technical hurdles to biomass use remain. In general, it is believed in the United States that increased use of biomass feedstocks is driven more by environmental and regulatory factors, if anything, than by free-market forces. Without tax credits or similar incentives, biomass is unlikely to be used as a baseload feedstock and market entry is likely to be as a feedstock blend.

Energy Security

Gasification technology supports national energy security goals by producing power, clean fuels, and chemicals from our nation's most abundant energy resource — coal — as well as from readily available wastes.

For the United States, there is a likelihood of market pull from a national security perspective, using the country's abundant coal resources and readily available wastes. Long-term opportunities exist for conversion of coal, petcoke, and resid to electricity, fuels, and chemicals.

Outreach

Better industry access to reliable gasification technology cost and performance data and improvement in communicating the technology's benefits are needed to accelerate deployment.

Many of the industry representatives cite the lack of reliable information about costs, performance benefits, and other outcomes of technology investment as one of the reasons for the slow pace of gasification technology diffusion into the market place. It is generally believed that better access to reliable data and improvements in communicating technology benefits would better support R&D investment decisions and provide an important impetus for commercialization efforts.

International

The range of feedstocks and products afforded by gasification technology makes the technology attractive to both developed and developing countries.

Many developed nations have access to low-cost refinery wastes to use as a feedstock for IGCC. Developing Asia is experiencing the greatest energy growth in the world and is largely dependent upon its vast, relatively low-cost coal resources for electric power generation. Many of the coals, however, are high ash coals and can be a problem in IGCC plants.

Markets

The evolution of markets is very much about the history of competitors coming out with new benefits and new products to offer to buyers. Market evolution in the gasification industry has been driven primarily by the forces of innovation and competition stimulated by problem recognition and problem solving. The private sector has conducted crosscutting research and development to underwrite the very significant technical and economic risks involved in deploying these technologies. Market segmentation and product enhancement through 2015 is projected to be very dependant upon a similar interplay of these dynamic forces continuing in the future.

By and large, the industry panels believe that two primary domestic markets — clean power generation and clean energy conversion — will grow considerably by 2015. Of these two, the clean power generation market is projected to be predominant.

Clean Power Generation

Clean power generation is the primary market for gasification technology, with use of refinery bottoms providing market entry, coal-based generation following and dominating, and waste disposal and recycling applications emerging as major markets as well.

The clean power generation market from refinery bottoms is viewed to have great potential for growth, in particular where projects may take advantage of the synergies associated with polygeneration (steam, hydrogen, and power production) and in cases where projects are sized large enough to attract companies with both fuels and chemicals interests into risk-sharing partnerships. But, coal gasification is projected to become the dominant application in the power generation market during the next 12–15 years in the United States and in overseas markets. Petcoke-to-electricity opportunities are viewed as limited ultimately by the eventual dwindling of petcoke resources.

Refinery Applications. Refinery applications offer economic advantages that make them competitive even at today's natural gas prices, but some view this market as limited on a worldwide basis. In the United States, the best fit for gasification is in refinery applications, using the readily available, low-cost refinery bottoms, primarily petcoke. In Europe, the opportunities in this application are fairly similar, the difference being that European refineries, which rarely have cokers, gasify resid rather than petcoke. However, there is some skepticism in the industry about whether the availability and reliability of gasification is sufficient for refinery applications in the near term.

Even at today's natural gas prices, there are many domestic petcoke-based and resid-based gasification projects that are economically viable. Although, at low natural gas prices (less than $2.50/10^6 Btu), the co-production benefit of producing hydrogen is lost to a refiner through the selection of more economic methods, such as combustion of petcoke with steam methane reforming for hydrogen production. The future supply and cost of petcoke is viewed as more uncertain than for coal. It is estimated by one of the industry representatives that because of resource availability constraints, the ultimate potential for petcoke-based power generation projects is about 50,000 megawatts (MW) on a worldwide basis and, therefore, the future for power generation is dependent on coal gasification.

While the price and supply outlook for refinery bottoms is deemed less certain, the market for fuel oil both in Europe and the United States is shrinking and petcoke in most U.S. locations brings a relatively low net back price. Many refiners consider petcoke as an "opportunity fuel" — a fuel given to a party willing to incur the costs of transportation. Although the price of petcoke is likely to increase as demand picks up, it is forecast to remain relatively cheap on a $/10^6 Btu basis because of its high sulfur content, which lowers the price below that of even high-sulfur coals. Furthermore, the increased size of the sulfur "sink" may depress petcoke prices in the future even as the demand for petcoke increases. The tightening of sulfur specifications for fuel oil and diesel fuel, and the added cost penalty of upgrading through hydrotreating, is likely to result in a steady market decline in demand for these fuels in the future, making them excellent candidates for gasification feedstocks within the infrastructure of refineries.

Coal Gasification. The relatively low, stable cost of coal and its abundance domestically, and in key regions around the world, make coal gasification the ultimate dominant market for gasification technology. Many of the industry representatives view gasification as the most viable technology to eventually displace the existing coal-fired power generation fleet through the improvement of efficiency, reduction of emissions (close to zero), and the enhancement of power generation at existing sites. Existing plants that have the necessary infrastructure (transmission, water, fuel supply, operating permits) are obvious candidates for both repowering and replacement.

Coal-based projects become feasible at a coal cost of about $1/10^6 Btu. While current coal prices are averaging about $1.40/10^6 Btu domestically, gasification's ability to easily remove and handle sulfur can make use of low-cost, low-grade, high-sulfur coals viable. The amount of ash in the coal becomes a concern at high levels from a cost standpoint, rather than a technical concern. Most of the major technology developers consider that the gasifiers can handle feedstocks with over 20 percent ash content, but that such feedstocks are not economic because so much oxygen is needed just to melt the minerals. Moreover, there is the added thermodynamic penalty in that the heat in the ash, which exits the reactor at about 2,000 °F, cannot be recovered.

Proposed new sites, where NGCC is the present economic choice, but which also have access to coal and other solid feedstock supplies, provide the opportunity during pre-planning for a phased gasification development as a hedge against volatile prices of natural gas.

Waste Disposal. Gasification is environmentally superior to incineration for disposal of municipal and industrial wastes, and with some development work can emerge an economic "winner." The industry considers gasification preferable to combustion for the destruction of municipal and industrial wastes, mainly because gasification does not emit dioxins or furans like incineration processes do. In terms of feedstock/device matching, the feeding of raw municipal solid waste (MSW) is better suited for atmospheric pressure gasifiers due to the heterogeneity of the feed. Pre-treatment of the MSW renders the feed usable for pressurized units, but pre-treatment adversely affects project economics. Feedstock diversity — the ability to obtain and process low-cost feeds on a spot basis — is an inherently significant benefit to a project. But, such flexible feed gasifiers still require a lot of development work that will likely not proceed without public sector support or some strong market incentives. Ultimately, the market for gasifying bio-wastes may be more lucrative in Europe and Japan, where the fees for landfilling continue to rise and the regulations governing waste landfills become more restrictive.

Waste Recycling. Gasification offers an effective means to convert highly toxic substances, like polychlorinated biphenyls (PCB), into salable by-products; and, with RAM and capital cost improvements, has significant market potential in this recycle arena. Gasification as a waste recycling option (compared to energy conversion only) to recover valuable, usable products is currently in the market niche category, but has the potential to grow into a solid commercial performer over the long term. For example, the use of chlorinated hydrocarbon liquids and other organic waste streams provides an opportunity for gasification to be a cost-effective environmental cleanup technology by effectively converting the chlorine, carbon, and hydrogen constituents into valuable products. This approach offers a solution to the PCB problem and an alternative to thermally treating chlorinated organic by-products. Not only does gasification move the waste conversion in the desired direction in the waste hierarchy by recycling rather than simply processing, but it increases the energy efficiency of the operation. Because the fit for this sort of deployment is in integrated applications, such as chemical plants, the significant hurdles of low RAM and high investment costs still have to be overcome to realize the full market potential by 2015.

Gasification applied to the pulp and paper industry fits the scenario of providing a recycle function and having an indigenous uniform supply of suitable biomass feedstock. But, the window of opportunity to replace existing black liquor boilers with gasifiers, which would afford major increases in both thermal and resource efficiencies, is likely to close unless action is taken before 2015. So far, there has been much talk, but little action, to deploy gasification technologies in pulp and paper applications. The overall reluctance may be mainly driven by cultural preference — the preference for something tried and tested over an option that potentially shows significant cost and performance benefits, but has perceived high risk. The risk is associated with deploying technologies in first-of-a-kind applications without some monetized risk sharing mechanism to offset potential cost or operation shortfalls. Also, retraining the workforce to operate entirely “new” processes is considered to be a major impediment to the deployment of gasification not only in the pulp and paper industries, but in many of the other non petro-chemical market segments identified.

Clean Energy Conversion

Synthesis gas derived from gasification represents a fuel for fuel cells and a basis for producing clean fuels, with the clean fuels option believed to be the primary option through 2015.

The clean energy conversion market requires looking at things from a product differentiation perspective. Many non-power related synthesis gas markets require that the gas is delivered at high-pressure, making high-pressure gasification the optimum economic option for potential customers. Pressurizing synthesis gas is costly. If and when fuel cells become commercially available, they may offer a more lucrative use of the synthesis gas than conversion to fuels. However, within the time frame considered here, fuels are considered the primary conversion commodities.

A near-term opportunity for gasification technologies is provided by the push for ultra-clean transportation fuels. But, this market driver may be eliminated if the sulfur levels for finished products are pushed so low in the near term that refiners find it necessary to install desulfurization technology or other advanced approaches to meet the stringent specifications. Installation of desulfurization precludes the gasification route to sulfur removal and reduces the availability of low-cost refinery feedstock for IGCC.

The combination of gasification with Fischer-Tropsch (F-T) processes has potential in the U.S. liquid fuels market to meet a need for low-sulfur, high-quality diesel fuels. Future regulations are likely to put a high premium on F-T products for use as blending stock. Bottom-of-the-barrel resid and petcoke are excellent conversion feedstocks as well as being excellent candidates to produce power. Although premium prices are likely for F-T fuels, the market for such fuels needs to be better defined and developed to take full advantage of the window of opportunity.

The synergies between chemical plants and gasification plants also provide market opportunities. There are, at present, market opportunities for gasification in the chemical industry through the use of synthesis gas as a chemical feedstock. Additionally, chemical plants can utilize the low-pressure steam (50–100 pounds per square inch – absolute (psia)) generated from gasification plant waste heat.

International Markets

There is a limited market for gasification-derived power, ammonia, and other chemicals for China and India.

In terms of the prospects for new international markets for gasification, there may be a limited market for coal gasification to produce power, ammonia, and other chemicals in China and India. However, many of China's and India's coals have high ash contents. And, the gasification of high-ash coals, while technically doable, is not economically attractive. Also, while gasification has positive environmental benefits, these benefits do not translate to economic benefits, because there is no monetized incentive for improved environmental performance in these countries.

Summary

Needs defined by industry to support mainstream gasification technology commercialization are as follows:

Needs

- **Improve overall gasifier performance, especially RAM.**
- **Demonstrate the use of gasification as an economically and environmentally superior alternative to municipal and hazardous waste disposal, including development and demonstration of a robust and tolerant gas purification block for handling variations in feedstocks.**
- **Improve investor confidence through the replication of commercial demonstrations, showing significant improvements over precursor facilities, such as improved asset development and management, reduced costs and schedules, better plant operator training, and enhanced plant performance, particularly on-time availability.**
- **Streamline the regulatory process to entice other partners into the development of gasification projects. (The recent rulemaking change to exempt synthesis gas produced from hazardous refinery wastes from being classified as hazardous under the Resource Conservation and Recovery Act (RCRA) is cited as the type of improvement both needed and possible through a sustained coordination effort between government and industry).**
- **Address risk and financing problems either through stronger project teaming arrangements and loan guarantees, or demonstrating a proven hedge against certain risks through the feedstock flexibility and co-production capabilities afforded by gasification technology.**

- **Conduct a grassroots national public relations campaign on behalf of coal to eradicate coal's "dirty" image and replace it with one showing that technology such as gasification is an environmental cleanup technology.**
- **As a prerequisite to attempting to resolve problems associated with commercialization of biomass-based gasification, examine the entire carbon cycle for the whole suite of candidate feedstocks and conduct a more thorough assessment of the technical and environmental pros and cons.**

Environmental Considerations

Environmental Benefits of Gasification

Coal-Based Systems

IGCC is by far the cleanest coal-based power system available today, yet it is compared against NGCC in establishing permitted emission limits based on Best Available Control Technology (BACT) and Lowest Achievable Emission Rate (LAER) requirements. A comparison on this basis is deemed incomplete because IGCC combines benefits associated with fuel diversity, energy security, and CO_2 capture that are not associated with NGCC.

Ultra-Clean Energy from Coal. Gasification is the most environmentally attractive alternative for producing power, fuels, and chemicals from solid feedstocks. Compared to other coal-based generation technologies, IGCC has an advantage with regard to atmospheric emissions of mercury, sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter, as well as solid waste. IGCC achieves over 99 percent sulfur removal, NO_x emissions are in the single digits on a parts per million (ppm) basis, and airborne particulate emissions are negligible. Gasification also has a notable advantage in overcoming another significant environmental hurdle to utilizing solid carbonaceous fuels — controlling CO_2 emissions. If CO_2 sequestration becomes viable, gasification becomes more attractive because it provides an effective means of capturing CO_2 by shifting carbon to a concentrated CO_2 stream prior to combustion. In addition, IGCC's high efficiency results in less CO_2 being emitted per unit of electric power produced.

Not only does the environmental superiority of gasification systems go unrewarded economically as previously discussed, IGCC plants are penalized because IGCC is held to a higher environmental standard than other coal-based power plants. Holding IGCC to NGCC performance standards is deemed "unfair" by many in industry because it ignores the fuel diversity and energy security benefits derived from indigenous solid feedstock use. Gasification is seen as a solution to some of the Maximum Achievable Control Technology (MACT) regulations that will take effect in 2005 in the pulp and paper industry for recovery boilers and at sometime in the future for the power generation industry.

Waste-Based Systems

The U.S. Environmental Protection Agency (EPA) recently recognized the superiority of gasification in processing refinery wastes and the associated waste source reduction and recycling of the wastes into usable by-products. Similar action on non-refinery-based toxic compounds is hoped for in the near future. And, many believe that with some R&D on MSW processing and injection, MSW too can become a gasification feedstock subject to waste reduction and recycling, rather than continued treatment and disposal.

Reducing and Recycling Wastes. Gasification is proving to be the most effective and efficient means for dealing with various carbonaceous wastes, such as refinery bottoms and hazardous organic wastes. Gasification can convert these wastes into commercially valuable products, such as electricity, fuels, synthesis gas, and hydrochloric acid. By doing so, gasification serves as a means of source reduction and of recycling, both of which are preferred to either waste treatment or disposal. With some R&D in enhancing the methods of processing and injecting organic sludge, MSW can become a candidate for gasification-based source reduction and recycle in lieu of landfill disposal.

The EPA has issued a proposed rule exempting wastes generated at petroleum processing facilities from federal hazardous waste rules under the RCRA if the wastes are converted into a synthesis gas via gasification. It is hoped that gasification's superiority to incineration in dealing with non-refinery-based toxic compounds will lead to similar action. Currently, difficult institutional barriers must be overcome in permitting gasifiers for processing non-refinery-based toxic compounds, such as the manner in which PCB provisions are written in the Toxic Substances Control Act.

Environmental Issues and Recommendations

Misperceptions of Gasification

The perception that gasification plants are "dirty" because the feedstocks are seen as "dirty" is impeding deployment by lengthening the permitting process. Public visions of dust, smoke, unclean water discharges, and solid waste disposal make siting a gasification plant very difficult. Furthermore, IGCC plants are having to undergo a hazardous operations design review that addresses emergency releases, which has a negative influence on public perception.

Misperceptions are also held by environmental regulators, both EPA, and state and local officials. In waste processing applications, regulators are viewing gasification not as an environmentally friendly process, but rather as an incinerator. In power generation, IGCC environmental performance is held to NGCC standards.

Needs

- **Conduct a grass-roots national public relations campaign to change coal's image as previously mentioned, educating the public about the positive environmental and domestic energy implications of gasification.**
- **Fund more gasification demonstration projects.**
- **Conduct closed-loop measurements of IGCC emissions to provide data and verify that IGCC is cleaner than any other coal-based power plant option.**
- **Through government and industry partnerships, facilitate formation of advocacy groups that certify that the products from certain gasification technology feedstocks are "green."**
- **Convince EPA to actively support gasification, which is key to DOE's Vision 21 program.**

Permitting

Even in locations favorably inclined to gasification projects, the process is multi-year and expensive.

Needs

- **Have the government step in and develop a structure to streamline the regulatory process, with a target of reducing the time to permit a gasification plant to six months.**

Regulatory Uncertainty

The uncertainty over if, when, and how new environmental regulations and rules are to be implemented is a major impediment to the business development of the gasification industry. Both the issuance of completely new regulations, such as potential CO_2 controls, and the tightening of existing regulations, such as lower and lower BACT and LAER requirements, are seen as hampering efforts to develop gasification over the next decade, perhaps before the technology can prove itself commercially. (BACT is required on major new or modified sources in clean areas, *i.e.*, attainment areas. LAER is required on major new or modified sources in non-attainment areas.)

Needs

- **Establish a process to effectively harness industry input before more stringent regulations are written for NO_x, greenhouse gases, trace contaminants (especially mercury) and solid wastes (ash and slag). Otherwise,**

gasification technology may be inadvertently halted before it has a chance to reach its operational and environmental performance potential.

NO_x Emissions

The uncertainty of regulatory requirements related to NO_x is very troublesome to the industry. Based on what appears to be a fundamental unwillingness to recognize the differences between IGCC and NGCC technologies, some regulators have been inclined to require NO_x emissions from IGCC plants to be controlled to the same levels as those from NGCC plants. Gasification systems can already meet a 9 ppm NO_x emission standard by using state-of-the-art gas turbines. Applying the NGCC standard requires NO_x emissions to be reduced to 3 ppm, potentially causing major process problems.

To achieve the 3 ppm level today, expensive selective catalytic reduction (SCR) NO_x control units have to be added to IGCC systems. Furthermore, the sulfur levels in the synthesis gas have to be significantly reduced first, to less than 5 ppm. This emission level is probably achievable only with Rectisol or an equivalent physical absorption process, a very expensive process. In the opinion of most experts, no more than a few ppm of sulfur dioxide (SO_2) in the gas turbine exhaust is allowed if the SCR is to function without fouling the downstream heat recovery steam generator (HRSG) tubes with ammonium salts. The use of an SCR raises the flue gas exit temperature and increases the pressure drop, thereby reducing the power output of the steam turbine. The addition of SCR and Rectisol units significantly increases the capital cost of IGCC plants and adversely impacts their RAM. Forcing IGCC plants to adopt SCR by imposing near-term NO_x requirements may eliminate the incentive for private industry to continue developing other NO_x control technologies, such as improved synthesis gas combustors. Adding controls simply increases cost, adversely affects RAM, and hinders deployment opportunities.

Needs

- **Conduct a study to determine whether SCR for NO_x control can be justified, carefully weighing cost and performance penalties against potential benefits.**
- **With DOE funding support, implement R&D on alternative technologies that achieve ultra-low-NO_x emissions, such as catalytic synthesis gas combustion and dry, low-NO_x conversion processes.**

SO_x Emissions

Although coal gasification-based power generation technologies emit far less SO_x than other coal-based power systems, typically removing over 99 percent of the sulfur in the coal, even greater sulfur control is needed. Nearly complete sulfur removal is required in support of synthesis gas as a “building block” for ultra-clean transportation fuels and as a fuel for fuel cells. More extreme sulfur removal methods exist, but are economically prohibitive.

In the long term, captured sulfur can adversely affect gasification plant economics. A 300 megawatt (MW) IGCC plant produces approximately 25,000 tons of sulfur annually. As the number of gasification plants increases, the supply of by-product sulfur may exceed demand, becoming a disposal cost rather than a revenue source.

Needs

- **Pursue sulfur removal options that offer nearly 100 percent sulfur removal at costs equal to, or lower than, today’s state-of-the-art technology.**
- **Develop new markets for sulfur, following the examples of U.S. Department of Transportation development of roadbed materials containing sulfur and use of sulfur in concrete for highly corrosive environments.**

Global Climate Change

The great uncertainty associated with global climate change issues led more than one of the interviewed companies to describe the potential for U.S. GHG regulations as a "wild card." Not surprisingly, there is no strong consensus regarding if, when, or how such regulations may be implemented.

Some of the interviewed companies think it is likely that GHG emissions will be regulated by the United States within the next five to ten years. These companies believe that the significant global political momentum and strong public emotions behind the drive to address global climate change are going to force the United States to act in the near term. Other companies interpret the current political climate differently, thinking that it precludes any near-term action. These companies believe that the Kyoto Treaty is flawed because developing countries are not included and that U.S. taxpayers are not willing to accept the huge costs associated with GHG controls. Instead of requiring industry to capture and sequester CO_2, these companies believe that the climate change issue will be addressed in the near term with more practical measures, such as increasing the thermal efficiencies of power plants and enhancing the natural sequestration of atmospheric CO_2; for example, by planting trees. However, some of the companies that doubt near-term action will occur also believe that GHG emissions will eventually be regulated by the United States in the long term, sometime after 2015.

One common thread about the GHG issue that did emerge from the interviews is that nearly all the companies are giving it serious consideration as they make plans and position themselves for the future. The market has already reacted to the possibility of GHG regulations by moving away from high-carbon fuels toward natural gas. During negotiations for new projects, customers are starting to request the rights to any associated GHG emissions reduction credits. Some companies are somewhat hesitant to make large investments in projects with significant CO_2 emissions and are screening proposed projects based on their potential liability for GHG emissions. At the same time, industry is also highly reluctant to expend significant capital to mitigate GHG emissions that may or may not prove to be a future liability; although, many companies think that spending some capital on efficiency improvements to existing infrastructure may be prudent.

If GHG regulations are promulgated in the United States, the extremely high cost of CO_2 removal and sequestration strongly favors hydrocarbon feedstocks that have higher hydrogen-to-carbon (H/C) ratios than petcoke or coal. Consequently, if the timing and structure of GHG regulations is poorly conceived, many companies believe that industry would aggressively switch their feedstocks to natural gas, thus devastating the coal industry.

While it is clear that the economics of CO_2 recovery are poor in all cases, some companies believe that they are less so for gasification than for other alternatives. Since gasification systems can convert (shift) carbon to CO_2 and remove it prior to combustion, it is less expensive to capture CO_2 from IGCC plants than from any other coal-based plant or NGCC plant. Furthermore, gasification is the most efficient of the coal-based technologies. Gasification plants also offer the option to offset CO_2 emissions by gasifying biomass.

Needs

- **Place priority on increasing efficiency by providing economic incentives for high efficiency because increasing efficiency is the most practical way to reduce GHG emissions in the near term.**
- **Develop new technologies for either sequestering CO_2 or converting it into a marketable by-product.**
- **Conduct R&D on CO_2 sequestration as a hedge against possible future regulation.**

- **Demonstrate the removal of CO_2 from synthesis gas as an early step in demonstrating carbon capture/sequestration.**

Mercury and Other Trace Contaminants

New regulations are going to be enacted for trace metal emissions, notably mercury. Depending on the details, such regulations can become an obstacle to gasification and other solid-fuel technologies. Although technologies may be available to comply with trace metal regulations, compliance increases plant costs.

Most of the companies interviewed expect mercury regulations to be issued in the near term. When mercury regulations are introduced, gasification plants have to capture mercury upstream of the combined-cycle plant. Although relatively small in volume, the sorbent used to capture the mercury may be classified as a hazardous waste.

The need to control mercury and other trace metals affects which gas cleanup system is ultimately utilized in gasification plants. It has been reported in some cases that elemental mercury (Hg) passes through the entire gasification plant, including the cold gas cleanup system, to the atmosphere.

Gasification's advantage in limiting trace contaminants is under-appreciated. This specific advantage needs to be demonstrated and an assessment made as to the need for trace contaminant emission regulation. Installing a carbon guard bed prior to the stack is a recognized approach to controlling mercury, as well as arsenic and carbonyl emissions. Carbonyl emissions are highly toxic and are believed to represent a potential major environmental hurdle to gasification. While carbon guard beds represent a potential cost-effective approach for control of mercury and carbonyl emissions exists, plants may be reluctant to participate in a project to install a carbon guard bed for fear that it would reveal some problems or lead to more stringent regulations.

It is noteworthy that most of the EPA-sanctioned mercury measurement techniques are for oxidizing environments. For reducing environments, which is the environment for gasification, there are no reliable mercury measurement techniques.

Needs

- **Conduct R&D to address disposal of the small volumes of captured mercury.**
- **Develop warm-temperature gas stream clean-up technologies for capturing mercury, alkali, other trace metals, and other vapor phase contaminants, focusing on 300–700 °F.**
- **Investigate and validate a carbon guard bed approach to mercury capture by installing one on an existing IGCC plant.**
- **Conduct R&D on the regeneration and disposal of the guard bed material used to remove mercury and carbonyls.**
- **Carry out a demonstration to precisely characterize the various trace contaminants in a gasification system, such as the partitioning of mercury.**
- **Develop acceptable methods and instrumentation hardware to measure the mercury concentration in gasification process streams.**

Solid Waste Disposal

Another source of regulatory uncertainty is the EPA's proposed rule on whether or not to classify as hazardous waste the synthesis gas and by-products (slag) produced by gasifiers that use a hazardous waste feedstock. The proposed rule provides that carbon-containing hazardous wastes from petroleum refining operations be exempt from the RCRA jurisdiction. But, in the long term, not being able to secure permits to gasify wastes other than refinery wastes can potentially become an obstacle to gasification. The Gasification Technology Council (GTC) is currently working to have gasification recognized as the preferred technology for recycling of other wastes in lieu of incineration.

The RCRA has been a major environmental hurdle due to the requirement that synthesis gas produced from secondary oil-bearing wastes from refineries are classified as waste-derived fuels regulated under RCRA. This has greatly inhibited some companies from being involved with gasification because they simply do not want to deal with hazardous material either as a feedstock or waste stream.

Although water/solids separation is required for IGCC's bottom ash and quench waste streams, disposal of the bottom ash in a landfill is currently permitted. But, landfill disposal may become an economic and logistics issue in the long term.

Needs

- **Continue government support of the GTC's action to have gasification recognized as the preferred technology for waste recycling of other wastes.**
- **When gasifying waste materials, improve characterization of the composition of the slag (which may require special treatment).**
- **Develop new ways to economically utilize ash and slag because landfill disposal and cost is expected to become an issue in the long term.**
- **Conduct R&D on the co-disposal of fly ash and gasifier ash.**

Water Consumption and Discharge

As the importance of water management issues continue to increase, the consumption and discharge of water represents an environmental hurdle for any new power plant, including gasification plants. New projects are likely to face zero water discharge requirements in certain regions. Some companies have had difficulty getting water permits for gasification projects because the allowable levels of trace metals are established arbitrarily and are many times below detectable limits. Since IGCC power plants consume less water than conventional pulverized coal-fired power plants, the industry needs to place more emphasis on this significant advantage of gasification when promoting the technology.

Needs

- **Implement R&D to reduce the volume of water that is consumed, treated, and discharged by gasification systems, with zero discharge being the ultimate goal.**
- **Develop dry feed systems, improved gas cleanup processes, and a technology to replace cooling towers, all to improve water management.**

Reflecting the Effects of Efficiency on the Emissions of Energy Plants

Most emissions from energy plants (refineries, power plants, and chemical plants) are currently measured in terms of mass per unit energy input, such as lb/10^6 Btu-input. This approach does not reflect the environmental benefits of high efficiency nor the environmental costs of low efficiency. A large majority of the companies that commented on this issue agreed that emissions need to be measured on a basis that includes the effect of efficiency.

While this is straightforward for those plants that produce only a single product, such as power, establishing such a basis is much more complex for plants that produce multiple products, such as those that co-produce synthesis gas and steam, or combined heat and power. No recommendations are given on how efficiency is fairly dealt with in this situation. In fact, one company suggested that the only practical and equitable approach for polygeneration energy plants is to calculate emissions the conventional way — based on feedstock energy input.

Needs

- **In order to account for the effect of efficiency (and to be consistent with the real purpose of producing usable energy, not consuming it in the conversion process), measure emissions in terms of mass per unit of energy produced. For example, measure emissions from electric power production in pounds per megawatt-hour (lb/MWh); and measure emissions from synthesis gas or liquid fuel production in pounds per unit heat content of the fuel produced, such as lb/10^6 Btu-output.**
- **Implement a government policy initiative to develop the best solution for establishing a baseline and measuring emissions data; and using the results of the initiative, have the government mandate the basis that best serves the public interest.**

Technology Needs

Introduction

One of the main objectives of the meetings was to discuss gasification technology issues and to identify R&D needs in the near term, mid term, and long term. The topics of discussion included: (1) Feedstocks, (2) Gasification, (3) Gas Cleaning, (4) Heat Recovery, (5) Gas Separation, (6) By-Products, (7) Synthesis Gas Utilization, (8) Integration, (9) System Analysis, (10) Instrumentation and Controls, and (11) Models.

For gasification as a whole, process reliability is identified by nearly all participants as the single most important technical limitation to be overcome in order to achieve widespread deployment of the technology.

The failure of plants to meet performance milestones on which project economics are based has had significant impact on how projects are being developed and financed. EPC companies are often required to shoulder all risk for liquidated damages for not achieving performance guarantees, and some are now unwilling to assume the risks associated with guaranteeing the performance of many integrated process units. Gasification plants must be constructed according to the planned schedule and reach design performance within a short period of time. The long time taken by DOE's Clean Coal Technology (CCT) IGCC demonstration projects to achieve design performance cannot be tolerated by privately financed commercial projects.

Although single gasifier system reliabilities for the CCT IGCC projects have now achieved their design performance, concerns still exist regarding the performance of future plants. Because financial institutions are generally risk averse, they typically require major gasification projects to have multiple gasifiers (trains) or sparing to ensure reliability targets are achieved. But the cost is significant. The use of multiple trains must be phased out to improve the economic competitiveness of gasification. The general belief is that the reliability for single-train plants must be at least 90 percent for utility applications. For refinery applications, availabilities must be close to 100 percent. To improve the performance of gasification-based plants, many believe that R&D needs to focus on standardizing and modularizing the overall process rather than designing new systems for each project. Such an approach not only allows for lower EPC costs and shorter schedules, but should also prove valuable in improving reliability.

Although first-generation IGCC plants had high capital costs, the EPC cost of similar plants today is believed to be around $1,200/kW. At this cost, IGCC plants are competitive in niche applications where feedstock costs are low. A total installed cost of $900–1,000/kW for coal- or refinery waste-based IGCC is competitive with NGCC at a natural gas price of $\$2.00/10^6$ Btu. For biomass applications, the cost of natural gas would have to be about $\$6.00/10^6$ Btu for IGCC to compete with NGCC. The lowest cost believed achievable through step changes in the technology is about $800/kW. Fulfilling the technology needs identified in the following discussions offers promise for achieving this target cost.

Priority Ranking of Needs

Most Frequently Identified R&D Needs by Gasification Industry Stakeholders

A total of 95 different R&D needs were identified by the twenty-two gasification industry stakeholders that were interviewed. (Similar R&D needs identified by different companies were combined.) Of these, 40 R&D needs were identified by more than one company. When the R&D needs were ranked by the frequency of identification, the following "top twenty" results were obtained. It should not be inferred that government-sponsored R&D would be suitable or effective for addressing all of these needs.

Top Twenty R&D Needs, Ranked by Frequency of Identification

1. Development/improvement of refractory systems
2. Development of technologies to measure and control hazardous air pollutants (HAPs) and trace metals (mercury, selenium, arsenic)
3. Improvement of gasifier instrumentation for measurement and control
4. Development/improvement of systems for feeding multiple solid feedstocks, including coal and biomass feedstocks (in slurry or dry form), to high-pressure and other gasifiers
5. Development of feed injectors that extend life, reduce cost, provide fuel flexibility, and offer effective load following
6. Development of technologies for the continuous on-line analysis of flow rate, composition and/or other characteristics of various gasifier feedstocks
7. Development of warm-gas (300–700 °F) cleanup technologies for control of sulfur, ammonia, chlorides, *etc*.
8. Development of gasifier models
9. Development/improvement of preparation systems for solid feedstocks, including briquetting
10. Characterization and beneficiation of ash and slag
11. Improvement of air separation systems in terms of cost, efficiency, and better integration with gas turbines
12. Development of advanced, high-temperature, low-NO_x combustion turbines for synthesis gas applications
13. Development of an industry-wide knowledge management system to improve the operation of gasification systems
14. Assessment/development of novel gasifiers, such as hybrid, high-efficiency, small-scale or low-temperature gasifiers
15. Development of improved particulate control technologies
16. Research, development, and demonstration of CO_2 capture/sequestration technologies
17. Development of various hydrogen separation technologies
18. Development of modularized and/or standardized systems to reduce costs for greenfield and repowering applications
19. Assessment and development of markets for sulfur, CO_2, and ammonia by-products
20. Development of a database for gasification properties versus temperature and pressure for various coal and coal blends (such as ash fusion temperatures, gasification reactivity, and slag viscosity)

Feedstocks

For the next fifteen years, coal and petroleum-based materials, such as petcoke, resid, and high-sulfur fuel oil, are generally accepted as the feedstocks of choice for gasification projects. Emphasis in the near term needs to be directed at improving the cost and reliability of feed systems for these feedstocks, especially the solid coal and petcoke feedstocks. For other feedstocks to be considered in the near term, their use should not depend on site-specific parameters, but rather be broadly applicable and have significant market potential.

Feedstock Preparation

Feedstock preparation and handling systems for coal and petcoke are considered to be fairly reliable. However, proper preparation of the feedstock for use in a gasifier is a key process step because of its potential for impacting process reliability and availability. It is believed that the preparation of the feedstock may have important ramifications on the life of the feed injectors in the gasifier, and thus plant availability. Work is needed to elucidate such effects.

Feedstock preparation issues in gasification focus mainly on the use of low-rank coals and alternative feedstocks such as MSW, sewage sludge, and biomass. Such feedstocks suffer from low energy density and high moisture content, making them uneconomical for transport over large distances. In addition, physically handling and preparing many of these materials for use in gasifiers are impediments to their use. Even after dewatering some materials, problems with feeding have been experienced, especially for fibrous materials such as biomass.

For processing alternative feedstocks, the use of briquettes produced from these feedstocks may be an option; however, the number of gasifier technologies that can process briquettes is limited. For use in a gasifier, the briquettes must possess sufficient mechanical integrity to withstand feeding and injection into the gasifier. There is concern that without such inherent strength in the briquettes, the briquettes may "explode" upon contact with the hot gaseous product in the gasifier, thereby exacerbating the problem with carryover of particulate matter into downstream process units. Although the use of binders for improving the strength of the briquettes is not a desirable option, it is highly likely that such additives may be required. Whether the briquettes are manufactured at the gasification plant or off-site is an issue that must be addressed. A study to address the feasibility of off-site briquetting plants, incorporating an assessment of the infrastructure and cost to transport the briquettes to the gasification site, may be warranted.

Work is needed on coal-based systems as well. Lock-hopper (pressure-cycled chambers used to pressurize dry feedstock) operations have been the cause of considerable downtime and require coal storage equipment between the mill and the gasifier because of the batch-type operation of lock-hoppers.

Needs

- **Elucidate the effects of feedstock preparation on the life of the gasifier feed injectors, and thus plant availability.**
- **Develop new and/or improved approaches for dewatering and increasing the energy density of low-rank coals and alternative feedstocks, such as MSW, sewage sludge, and biomass.**
- **In parallel with improving dewatering and energy density, establish a fundamental understanding of the impact of new preparation technologies on the critical properties required for proper feeding in both dry and wet feed systems.**
- **Develop low-cost briquetting techniques, including use of low-cost binders.**

- **Address the issue of on-site versus off-site briquette manufacturing, incorporating an assessment of the infrastructure and cost to transport the briquettes to the gasification site.**
- **Eliminate lock-hoppers and associated storage equipment by developing a pressurized mill for coal-based systems that is capable of feeding coal directly into a high-pressure gasifier and combining the pulverizing and drying steps into one operation.**

Feed Systems

As mentioned above, current feed systems, both dry and slurry-based systems, used for coal and petcoke are reported to perform satisfactorily, providing reasonably good system reliability. But operation and maintenance (O&M) issues remain regarding erosion and corrosion of valves, pipes, and pumps. The development of new or improved feeding systems for high-pressure gasifiers remains fairly high on the list of priorities. For plants processing opportunity feedstocks, the feed system is typically the cause of reliability problems and developments are needed to improve performance with such feedstocks in high-pressure gasifiers. In addition, the long-term effects of system contamination from such feedstocks are of concern. Systems that are versatile, simple, and inexpensive are desired.

A capability to co-feed waste feedstock with coal in both large and small gasifiers is needed. Designs need to recognize that while small gasifiers may co-feed up to 40 percent waste to satisfy a niche market need, larger gasifiers are likely to only require up to 10 percent co-feed capability. Also, recognizing that feedstocks fall into different classes from a processing characteristics standpoint, co-feed systems need to be designed for classes of feeds rather than being flexible for all feedstocks.

Slurry-Based Feed Systems. Systems that transport the feedstock into the gasifier via a liquid medium have a thermodynamic penalty because of the energy required to vaporize the liquid. This is especially true when water is the slurry medium. Liquid carbon dioxide has been suggested many times as a potential candidate for the slurry medium; however, little has been done to advance this idea.

For slurry-based systems using water, the concentration of coal in the slurry is typically 61–62 percent. Increasing this concentration to 70 percent or more is desirable while maintaining the viscosity of the slurry sufficiently low for pumping. Operating with such high coal concentrations in the feed may result in less expensive feed systems than dry feed systems that incur high costs for removing moisture from the feedstock.

There is an expressed need for improved industry outreach to address generic O&M problems that are common to the gasification industry. One example is the need for a “slurry handling design manual” that could be used by the entire gasification industry to help prevent future plant designers from repeating past mistakes. Any material that has to be pumped is potentially problematic. There is a need to more fully understand: (1) the effect of coal slurry composition on erosion and corrosion of pipes and valves and (2) the optimal acidity (pH) of a slurry to minimize or prevent pipe erosion and corrosion. In general, more reliable technologies for slurry transport are required, as well as R&D on seals for rotating equipment, especially for high-pressure operations.

Dry Feed Systems. Because of the thermodynamic penalty inherent in slurry-based systems, many prefer reliable, cost-effective dry feed systems. Currently, only lock-hopper technology is employed to pressurize dry feedstocks. Some believe that work is needed to improve these systems, including the feeding of very fine coal, less than 150 microns, as well as developing new approaches.

The solids-to-gas ratio in such systems must be kept as high as possible.

Needs

- **Develop co-feed systems for classes of feeds.**
- **Investigate co-feed systems having the flexibility to feed different solid feedstocks separately and together.**
- **Identify and address mechanical and safety issues associated with preparing and feeding CO_2 slurries.**
- **Investigate the impact of high concentrations of CO_2 on the performance of gasifiers and on the gasification reactions themselves.**
- **Develop low-cost surfactants to achieve a stable slurry with 70 percent coal concentrations and more durable slurry valves.**
- **Develop a "slurry handling design manual" to help prevent future plant designers from repeating past mistakes.**
- **Determine the effect of coal slurry composition on erosion and corrosion of pipes and valves, and the optimal pH of a slurry to minimize or prevent pipe erosion and corrosion.**
- **Develop more reliable technologies for slurry transport and high-pressure seals for rotating equipment.**
- **Examine prior work conducted by the U.S. Bureau of Mines on alternative feed systems.**
- **Conduct R&D on dry feed systems that use synthesis gas or natural gas as the transport medium.**

Instrumentation

Analytical instrumentation is an area that most felt improvements or new developments are needed. Such instrumentation is required to better control and meter the feedstock into the gasifier, especially for some opportunity feedstocks, such as biomass. Those operating slurry-fed gasifiers prefer analyses of slurry feedstock elemental composition (carbon, hydrogen, sulfur, and inorganics), but defer to results obtained prior to forming the slurry. Feedstock composition information impacts on how processes in the plant are operated, such as the gasifier.

Needs

- **Develop and demonstrate instrumentation to measure the flow rate and density of the feedstock in slurry-based systems.**
- **Develop an affordable on-line analytical device that can provide the elemental composition of the gasifier feedstock for those situations where the composition is constantly varying, as with the heterogeneous MSW feedstock, or co-feed applications.**

Gasification

The gasification block of the plant probably received the most intense level of discussion. The gasification block constitutes about 15 percent of the capital cost of an IGCC plant. There is general agreement that the priority for gasification is to reduce the capital cost and increase the reliability of gasifiers. Numerous technology needs are identified to accomplish this. Nearly all of the participants identify the feed injectors and refractory liners used in gasifiers as the weakest links in the process for achieving high on-stream availability factors. The need for new process monitoring and control instrumentation for these weak links is of paramount importance.

Feed Injectors

The feed injectors in a gasifier must feed steam, oxygen, and the feedstock into a very harsh, high-temperature, reducing environment. Many feel that feed injector life is the weakest link in the reliability of gasification systems. Based on actual experience, the life of a typical injector nozzle is generally between two and six months. A minimum life of twelve months is desired in the near term, with a long-term goal of two years. Some gasification operators expend considerable effort to improve feed injector life.

In order to extend the life of the feed injector, a more thorough understanding of all of the parameters affecting injector life and the fluid dynamics in the vicinity of the nozzle is needed. This information may help to design feed injectors that are scalable. This information can be used by the various manufacturers to improve proprietary designs. The application of Computational Fluid Dynamics (CFD) modeling around the injector may be helpful in elucidating some of the parameters affecting life. CFD modeling may be useful in understanding issues such as changes in heat flux, injector heat load, and fluid recirculation patterns that are affected during scale-up of the gasifier to larger and larger sizes.

Materials used in the manufacture of the injectors are cited most often as an important parameter. New materials or coatings for existing materials are needed to provide protection from sulfidation and corrosion at high reactor temperatures. Also, better gaskets are needed for equipment feeding hot oxygen into the injector.

Injector life is also believed to be highly dependent on whether a dry or wet feed system is used. As mentioned previously in the report, feedstock preparation is also believed to play an important role in feed injector life. Although the dry feed system may be more difficult to operate at higher pressures, injector life may be longer due to the absence of large amounts of evaporating water. Again, CFD modeling can play a role in understanding the physics and chemistry occurring at the injector tip.

Variable orifice injectors are needed to allow the plant operators to more rapidly respond to load and feedstock changes without adversely affecting the operation. An injector that is designed to operate with more than one feedstock also is advantageous, because the plant does not have to shut down to switch feed injectors whenever the conditions require a change in feedstocks. A multiple-feed injector has to be capable of handling the transition from one feedstock to another without any operational problems. In the past, some injectors have experienced vibration problems during the transition period.

There is an expressed need for a facility to test new injector designs because injector manufacturers do not have such facilities. However, feed injector technology is closely guarded by the industry and this is a detriment to the establishment of an industry-shared facility. Also, pilot plant testing of feed injectors is not scalable, which means that testing is still required in commercial facilities.

Needs

- **Conduct a comprehensive study to define the factors that contribute to the failure of feed injectors, including application of CFD modeling around the injector to elucidate some of the parameters affecting life.**
- **Develop new injector materials to further injector life and lower the manufacturing and refurbishing costs.**
- **Develop reliable, cost-effective, variable-orifice injectors and multiple-fuel injectors that can adjust to load and feedstock changes without adversely affecting operation.**
- **Explore the possibility of establishing an industry-shared injector test facility.**

Refractory Liners

Refractory liners in high-temperature slagging gasifiers are known to undergo significant deterioration over a relatively short period of time and require considerable maintenance, resulting in a significant amount of downtime. Depending upon the operating temperature of the gasifier and the feedstock, refractory liners are reported to last on the order of 6–18 months. The upper end of this is usually achieved by operating the gasifier at lower than desired temperatures. Unfortunately, doing so limits carbon conversion to about 95 percent, reduces overall process efficiency, and simultaneously increases the carbon level of the slag, rendering it unmarketable without further processing. The feedstock being processed also has an impact on refractory life. Increased wear has been observed at higher temperatures using petcoke. In addition, feedstocks such as black liquor from pulp mills are notoriously corrosive because of the high sodium content.

The costs associated with rebricking a gasifier include about $1 million for materials and three weeks of downtime. This downtime, if it occurs more than once per year, establishes an upper bound on plant availability. Plant operator preference is to replace the lining during their regular scheduled outage.

Although refractory materials containing chromium can pose an environmental and health problem, the use of such materials did not appear to be of major concern, either during gasifier operation or upon disposal of the spent refractory. In the long run, it is still best to develop approaches or materials that do not utilize potentially hazardous materials.

At present, new materials are screened by attempting to simulate the environment inside the gasifier; however, such simulations may not be truly representative of the actual environment. It is also viewed as risky to replace existing material in a commercial gasifier with test samples for fear of unnecessary downtime. Operators doing this must have considerable assurance, or confidence based on simulated testing, that the material performs at least as well as that currently used in the gasifier.

Needs

- **Enhance refractory performance by developing new materials that are less prone to degradation and have an expected useful life of three years or more, preferably at about 50 percent of the cost of currently used materials.**
- **Investigate new approaches to line gasifiers, including concepts that completely eliminate the use of refractories, especially for applications using highly corrosive feedstocks.**
- **Conduct additional R&D on water-cooled refractory.**
- **Establish a small test facility, such as a small gasifier located at the site of a commercial gasification facility, to screen new refractory material.**

Ash/Slag Removal

Depressurization and removal of the slag from high-temperature gasifiers is an area that generated mixed responses from the participants. The divergent views may be attributed to different technologies being employed by the various gasifier licensors. Slag removal, in general, is not considered to be a high priority area.

There is expressed interest in developing an improved understanding of the properties of slag flow and the effectiveness of slag modifiers. The silica and alumina content of certain coals result in high ash fusion temperatures, whereas iron oxide and calcium tend to lower ash fusion temperatures. For example, when mixing different types of coals, the resulting slag viscosity can be very unpredictable. Databases such as those maintained by the U.S. Geological Survey contain compositional analyses of coals but need to be expanded to include additional properties.

As discussed previously, on-line feed analyzers are needed to allow better control and optimized operation of the gasifier as the properties of the feedstock changes. Currently, most analyses are based on periodic sampling and therefore cannot be used to help control the operation of the gasifier. Turnaround for such analyses can be as much as two days. Ash fusion temperature and slag viscosity measurements are of particular interest. To guard against unforeseen changes in slag viscosity due to variations in the feed properties, some plant operators run the gasifier at lower than optimum temperatures to protect component life. Other operators assume the risks associated with operating at higher than optimum temperatures to ensure stable operation, thereby decreasing component life. Feedstock analyses help to guard against unforeseen changes in the viscosity of the slag, thereby helping to prevent bridging at the discharge of the gasifier. Also, feedstock analyses allow operation at the optimum gasification temperature to maximize carbon conversion. In addition, development of on-line instrumentation capable of measuring the thickness of the slag layer on the refractory is warranted to improve slag removal because slag viscosity can be related to the thickness of the slag layer on the refractory.

The only equipment-related issues identified deal with the performance of valves used to handle soot and slag. Currently, ball valves are used in most applications. These valves need to have improved lifetimes and to be made less costly. Better yet, novel methods for removing soot and slag from the gasifier ought to be developed that eliminate the need for such valves.

Needs

- **Establish a better knowledge of flux (compounds used to lower ash fusion temperatures) effectiveness for solid feedstock units.**
- **Develop new fluxing agents that reduce the ash fusion temperature to 2,200 °F or less.**
- **Establish a database that contains coal properties of interest to gasification, such as ash fusion temperature under reducing conditions and gasification reactivity versus temperature, for various coals and various solid feedstock blends.**
- **Develop on-line instrumentation to measure ash fusion temperature, slag viscosity, and slag layer thickness.**
- **Develop improved ball valves or new methods for handling soot and slag.**

Instrumentation

The capability to reliably measure various process parameters and the composition and properties of various process streams is considered a high priority based on the numerous responses received. Accurate and reliable measurements of the temperature inside the gasifier for extended periods is a major area of concern. Thermocouples used to measure the temperature inside the gasification zone are reported to last about 30–45 days. The high frequency of failures of the thermocouples is mainly due to corrosion resulting from slag penetration into the refractory and stresses caused by temperature cycles. These devices are also reported to drift. No life target is proposed, but something approaching that of the refractory lining is deemed to be worthwhile from a maintenance perspective. Real-time analysis of a number of other key operating parameters and the condition of critical components is needed as well to optimize performance and extend component life.

Needs

- **Develop means to measure temperatures inside the gasifier on a real-time basis.**
- **Develop other on-line instrumentation to: (1) measure wear on the refractory liner to plan outages for replacement; (2) analyze composition of hot product gas from the gasifier, including trace components such as hydrogen sulfide (H_2S) and hydrogen chloride (HCl); (3) obtain isokinetic sampling of particulate for process design and design verification (either inside the gasifier,**

which is preferable, or in the cool, raw synthesis gas); and (4) achieve realtime analysis of feedstocks and products with computer controls and models for on-line heat and material balance calculations and improved gasifier control.

Feedstock Flexibility

Feedstock flexibility, the capability of the gasifier to process different feedstocks, is considered to be a desirable attribute by many, especially the ability to process all ranks of coal. It is believed that to achieve such flexibility, a multiple-injector gasifier is necessary rather than co-feeding though one nozzle. Some of the industry panels believe that it would not be practical to design one gasifier to handle all feedstocks. Others appear to be satisfied with the existing fleet of gasifiers and what they can process, especially the dry feed gasifiers.

Needs

- **Investigate new, feedstock flexible, higher efficiency gasifier concepts for applications that use low-energy-density feedstocks, such as high-ash coals and biomass.**
- **Investigate use of multiple feed injectors to expand fuel flexibility of existing gasifiers.**

New Gasification Concepts

There are mixed opinions on whether or not there is a need to develop new gasification concepts. A number of organizations believe that the current suite of gasifier technologies is adequate to meet most needs. This group believes that the cost to develop a new concept is prohibitive especially in the current economic climate. This group prefers to improve the RAM and performance of existing technologies via R&D and to optimize and standardize existing gasifier concepts. Historically, the cost of an effort to develop a "new" gasifier is in the neighborhood of $750 million to take the technology to the demonstration phase.

However, a number of organizations express a need for new gasifier concepts. While many still believe that larger gasifier units are the only way to go, because of the need for economies of scale, there is, nevertheless, surprising interest in the development of small-scale gasifiers (less than 100 MW capacity). Some believe that the smallest practical size gasifier is about 60 MW, based on the smallest available gas turbine. Although some of the existing technologies can be easily scaled down to smaller sizes, there is an economic penalty that must be paid. In addition, there also is an efficiency penalty with the smaller gas turbines due to their lower firing temperatures. Some of the interest in small gasifiers centers around the use of alternative feedstocks such as MSW and use by refineries that do not generate large quantities of petcoke, *e.g.*, 500 tpd, but still want to take advantage of the opportunities for heat integration. Many believe that smaller, standardized systems that can be easily replicated will help stimulate the market for gasification.

Some believe that gasifiers will ultimately be employed in distributed generation applications. However, conventional gasifier technologies are not viewed as compatible with such applications, which might integrate a gasifier with a fuel cell. Such gasifiers have to be fairly small in size. Gasifiers that are geared to hydrogen production and are first to market are projected to have the advantage in the distributed generation market. However, the hydrogen distribution infrastructure is viewed as not progressing well, and the limited application of hybrid vehicles projected over the next several years is expected to delay the market penetration of fuel cells. Integration of gasifiers with fuel cells in commercial offerings is not expected to occur for another fifteen years or more.

There is expressed interest in the development of low-temperature, non-slagging gasifiers to reduce plant capital and operating cost. Although it is widely accepted that slagging gasifiers are much more advanced from a technology maturity standpoint, lower temperature operations are thermodynamically favored and are believed to be more reliable. Operation below the ash fusion temperature requires much less oxygen, resulting in a reduction in parasitic power and a concomitant increase in thermal efficiency. There is also an economic penalty paid for the energy contained in the ash which cannot be recovered because of its low temperature, about 200 °F. In addition, the existing fleet of high-temperature gasifiers is not very amenable for processing lower rank coals such as sub-bituminous coals and lignites or high-ash-containing feedstocks. Such coals represent a substantial portion of the resource base in the United States and worldwide. One technology that appears to be of interest to some is the transport gasifier; however, the low heating value of the gas being produced today by the transport gasifier as a result of air-blown operations is considered to be a major drawback.

Needs

- **Conduct a comprehensive market analysis to help define the applications and needs for smaller gasifiers, including the appropriate gasifier size or sizes, and the potential market size.**
- **Develop low-temperature, non-slagging gasifiers to reduce plant capital and operating costs.**

Fundamental Studies

Fundamental research is needed to better understand the reaction kinetics and fluid dynamics inside the gasifier in order to operate gasifiers within their thermodynamic limits. A more thorough understanding of the molecular chemistry of coal and how it impacts gasification is needed. Also, ways are needed to increase the rate of the gasification reactions and improve carbon conversion, especially for low-temperature operations.

Needs

- **Model the kinetics of gasification reactions, including the reaction sequence and kinetics for small particles, particles less than 150 microns, because no such data is known to exist.**
- **Investigate the use of catalysts to increase gasification reactions, and the means to separate the catalyst from the ash/slag.**

Gas Cleaning

Synthesis gas cleaning, and in particular the removal of HAPs and trace metals is another priority item for the industry. For synthesis gas cleanup, improvements in performance and reliability are needed. For a conventional IGCC plant, the capital cost of removing particulate and chemical contaminants from the synthesis gas generally accounts for about 10–12 percent of the total capital cost. In most plants, amine-based systems coupled with a Claus plant are sufficient for removing contaminants such as sulfur to the levels required by current environmental regulations. However, lower cost approaches are viewed as advantageous, such as single-step processes to convert H_2S to elemental sulfur and for the simultaneous removal of carbonyl sulfide (COS) and H_2S. Many opportunities are believed to exist in the gas cleaning area to improve cost, performance, and reliability, including entirely new concepts for “novel gas purification.”

The need for innovative deep cleaning technologies that can meet future environmental regulations is well recognized. The industry’s goal is to have gas cleaning technologies that can perform comparable to Rectisol (an existing cleanup technology) in removing contaminants, but at an equal or lower cost than conventional amine-based systems (*i.e.*, less than 50 percent of the cost of Rectisol). The operating temperature of these new technologies is not of significant concern, as long as all contaminants can be effectively removed; however, there is an expressed desire on the part of many to operate the new processes at temperatures that are close to downstream process requirements. At present, gas turbine inlet temperatures are limited to about 600 °F and synthesis gas conversion processes typically range from 450 °F to 600 °F. Operating at such moderate temperatures obviates the need to cool the synthesis gas and condense the moisture in the gas stream prior to cleaning — a process which reduces overall thermal efficiency and produces a contaminated water stream that must be processed. In addition, it becomes much more difficult to flare synthesis gas at higher temperatures in the event of an upset in the plant. The industry prefers to have a suite of technologies operating over a range of process temperatures to meet specific downstream applications.

A significant issue of concern to the gasification industry relates to the requirements for synthesis gas quality. In particular, the components that must be removed from the synthesis gas need to be clearly defined and the target levels must be established. In addition, it is recommended that an effort be made to quantify the emissions of HAPs, including trace metals, from existing gasification plants and to close material balances for HAPs.

As mentioned previously, mercury is expected to become a major issue in the not too distant future. The removal of mercury from coal-derived synthesis gas has been successfully accomplished using an activated-carbon guard bed at ambient temperatures. Based on experience with activated carbon for mercury removal in other industries, the performance of such materials declines as the temperature of the process increases. For higher temperature gas cleanup technologies, new materials or approaches to mercury capture must be developed. If technologies cannot be developed for capturing mercury at higher temperatures, then cleanup technologies operating at these temperatures have limited applicability, *i.e.*, for feedstocks containing no mercury. In addition to mercury, other volatile trace contaminants such as arsenic and selenium and carbonyls must also be removed to low levels. If non-regenerable processes are used, then proper disposal of such materials must be investigated because of the toxicity of many of the trace components.

Regardless of the approach to contaminant removal, technology developers must focus on reducing the number of process steps to achieve the desired synthesis gas quality. Although a challenge, a single multi-contaminant control device for removal of chemical contaminants is desired. Process cost and complexity must be reduced to improve overall plant economics and reliability.

Cold Gas Cleaning

The opinions on the need for further improvements in, or development of new, low-temperature (ambient temperature) gas cleaning technologies are mixed. While conventional technologies are believed to be fairly adequate and not overly expensive, opportunities for improving the cost and performance of conventional solvent processes, both physical-based and chemical-based, are believed to still exist. It is recognized that some developments may yield only incremental improvements. The current state-of-the-art amine-based cleanup systems are unable to meet the near-zero emission levels envisioned for the future and are currently unsuitable for preparing the synthesis gas for use in fuel cells or synthesis gas conversion technologies. The high carbon monoxide (CO) environment in the amine-based systems also promotes the formation of heat-stable salts that not only enhance corrosion but also limit the ability to recycle the amine. Because of amine degradation experienced in current systems, there has been some shift to physical-based solvents instead. Regardless, industry has not invested much effort to improve these technologies for many years.

To achieve required sulfur emission levels, it is necessary not only to remove H_2S, but also the COS contained in the gas. Conventional gas cleaning technologies require the COS to be converted to H_2S prior to the cleanup unit.

Needs

- **Develop cost-effective technologies that can remove heat-stable salts from existing processes, and new solvent systems with enhanced performance.**
- **Place a development priority on systems that can remove both COS and H_2S simultaneously, as well as chlorides.**
- **Conduct additional work to improve the performance of both physical solvents and amine-based systems.**
- **Pursue development of both wet and dry novel ambient temperature approaches.**

Warm Gas Cleaning

Considerable interest is expressed in the development of warm gas cleaning technologies. Although the temperature range of interest varies from company to company, technologies that operate between 300–700 °F are preferred. This temperature range is more consistent with the needs of most downstream process applications as discussed above. Such technologies must be able to not only reduce sulfur to near-zero levels but also remove mercury, ammonia, and other trace contaminants. There is concern that if mercury cannot be removed to potential regulatory levels, then such technologies have limited utility — they would only be applicable to feedstocks containing very little or no mercury. As stated previously, mercury removal using activated carbon becomes more difficult as the operating temperature of the gas cleanup process is increased and is ineffective in the 300–700 °F temperature range.

Needs

- **Develop a synthesis gas cleanup system operating in the range of 300–700 °F to reduce sulfur to near-zero levels and to remove mercury, ammonia, and other trace contaminants.**

Hot Gas Cleaning

High-temperature gas cleaning technologies, those that typically operate above 900 °F, are not considered to be a high priority. Removal of contaminants is expected to be much more difficult as the temperature increases, especially for mercury, chlorides, alkali, and other trace metals. In addition, deep cleaning of the gas to meet ultra-clean gas requirements is also expected to be a formidable task at high temperatures.

Currently, there is not much incentive for operations above 700 °F. Most credible engineering analyses have persuaded the industry that the efficiency improvements from operating at temperatures above 800 °F are offset by the additional capital costs due to increased material costs and increased equipment size needed for larger volumetric flows. Adapting high-temperature, dry, sorbent-based, regenerable technologies to lower temperatures is a concern because effectiveness may be compromised, as is efficiency of regeneration at lower temperatures. In the future, higher gas turbine inlet temperatures may justify cleanup at 1,000 °F, on a cost/benefits basis.

The few organizations that expressed interest view the development of such approaches as a long-term goal and applicable primarily to the production of electricity using fuel cells. The higher temperatures are advantageous when employing fuel cell technologies, however, the technology must be able to remove sulfur, alkalis, ash, HCl, and Hg to very low levels, which is not currently feasible with high-temperature systems.

If a suitable hot gas technology can be developed, it may have application to non-quenching type gasifiers and low-temperature gasifiers. In low-temperature gasifiers, tar formation in the gasifier is a major problem in downstream gas cleaning technologies. For such gasifier applications, gas cleaning technologies that operate above 800 °F, *i.e.*, the condensation temperature of the tars, or possess tar cracking capabilities, are desirable.

Needs

- **Evaluate and explore developing synthesis gas cleanup systems that operate above 800 °F in the long term for gas turbine and fuel cell applications, addressing removal of sulfur, alkalis, ash, HCl, and Hg to very low levels.**
- **Develop synthesis gas cleanup systems that operate above 800 °F for cleanup of tars produced from non-quenching and low-temperature gasifiers.**

Particulate Filtration

Removal of particulate matter from the raw synthesis gas stream is of particular interest for those gasifiers that do not employ quench systems for cooling the raw synthesis gas and for protection of the gas turbine. Technology that removes particulate at high temperatures up to 1,000 °F is the only hot gas cleaning technology that is viewed to have a need for the near-term and mid-term horizons. Operating at temperatures below 1,000 °F allows alkalis to condense and deposit on the ash in the synthesis gas stream.

Improvements to existing barrier filter technologies that are inexpensive and simple are of interest. Filter element cost and longevity are viewed as critical to the successful deployment of such technologies, although cost reduction may be slightly preferred over life extension since current filter life can fit into scheduled outages. Ceramic filters are of interest, especially for the temperatures of 1,000 °F and above, but thus far, these elements have yet to achieve satisfactory performance. However, satisfactory performance has been achieved with metallic filters at temperatures above 700 °F. No large market for these filters has evolved so far, and potential vendors are disappearing.

In addition to further development of the current candle type filters, the development of new filtration approaches is recommended. Granular bed filters and hybrid wet/dry systems are two examples that are cited, although there is some concern that granular bed filters may not be suitable for IGCC applications.

Needs

- **Develop more durable, reliable, and cost-effective ceramic and metallic filter elements with a useful life of at least three years.**
- **In addition to filter elements, develop reliable safeguard devices to protect down-stream processes from particulate matter in case of premature breakage of an element.**
- **Involve manufacturers in programs to develop filters and safeguard devices to assure that a market for such products materializes.**
- **Develop techniques to sample and analyze the particulate matter and trace metals in the gas to complement filter development.**
- **Conduct R&D to resolve chloride cracking (stress corrosion) of pipes and valves in the gas flow path and the erosion of valves used for hot solids handling.**
- **Develop new particulate control concepts.**

Heat Recovery

The topic of heat recovery in gasification-based plants is a matter of interest raised by about 25 percent of the participating organizations. In general, heat recovery systems are not considered to be a major contributor to downtime of the process. Improvements to heat recovery systems for cooling the raw synthesis gas and gas turbine exhaust as well as improved heat management relating to the air separation unit have the potential to lower capital costs and improve efficiency of the process.

As with several other technology areas, there is an expressed need for project operators to share the lessons they have learned regarding heat recovery operations with the rest of the industry. In particular, information on advances in metallurgy and corrosion prevention and the impact such work has on heat recovery needs to be discussed openly. The establishment of a database containing such information that would be available to all is suggested. However, the sharing of such information and experience may be problematic for many because of concerns related to intellectual property rights.

Synthesis Gas Cooling – Non-quench Operation

Over the years, boiler designers have made significant progress in heat recovery applications. However, opportunities are believed to exist to better and more fully utilize waste heat with new or improved equipment and through process integration. New synthesis gas coolers need to be less expensive, more reliable, and be capable of cooling the gas to below 1,000 °F. Reliable and economic waste heat boilers improve the thermodynamics of the gasification process compared to using quench systems.

The major issue with existing waste heat boilers is the condensation of trace metals (*e.g.*, selenium, arsenic, and germanium) in the synthesis gas that deposit on the inside of the heat exchanger tubes, especially when processing high-ash feedstocks. This deposition is a major run-limiting parameter because it leads to plugging. In addition, removal of the metallic deposition is also problematic.

Needs

- **Develop technologies for longer term markets that are capable of removing vapor phase trace metals from the hot raw synthesis gas stream before it enters the heat exchanger, with removal at temperatures of 1,800–2,000 °F.**
- **Investigate new heat recovery processes that minimize deposition and improve techniques for removing the deposits from the heat transfer surfaces.**
- **Develop dynamic modeling and control systems to aid in understanding and preventing upsets in the heat recovery systems.**

Synthesis Gas Cooling – Quench Operation

Quench-based gasification systems are by far the dominant technology employed today. Although there is a thermodynamic penalty when employing quench-type gasifiers (the efficiencies are lower than non-quench systems), they offer better reliability and lower capital costs than non-quench systems. In the past, industry was willing to sacrifice efficiency for reduced capital costs. However, with the possibility of regulations for greenhouse gas emissions on the horizon, many companies are beginning to look more closely at efficiency, especially if there is some incentive to enhance efficiency.

The quench process takes place in a harsh, high-temperature (over 2,600 °F), corrosive environment that produces aqueous hydrochloric acid at 212 °F. Efficiency improvements for low-ash feedstocks in this harsh environment have been identified. Emphasis needs to be placed on high-ash feedstocks because of problems associated with downstream heat recovery operations. Pursuing improvements is complicated by the fact that the quench process is not fully scalable.

Another process weakness is that conventional designs — although effective at quenching — shift a lot of the CO in the process.

Needs

- **Pursue process development to improve quench process efficiency for high-ash feedstocks in a commercial plant to address scale-up issues.**
- **Investigate improved designs that quench effectively with less conversion of CO to CO_2.**

Heat Recovery Steam Generator

Advances in technology have opened up the possibility for improving heat recovery. This opportunity extends to bottom cycle components such as the HRSG.

Needs

- **Investigate replacing the HRSG with a higher-temperature method of heat recovery, such as a hot oil or molten salt system to improve heat integration and efficiency.**

Gas Separation

The topic of gas separation is focused on the separation of major components in gas streams, *i.e.*, oxygen from air and hydrogen from synthesis gas.

Air Separation

For years, many believed that air-blown gasification processes provided the more economical route for IGCC compared to cryogenic oxygen-based plants. At that time, the cost of cryogenic air separation units was significantly higher than the added costs due to larger-size equipment required to accommodate the additional gas volume using air (air contains 78 percent nitrogen). The economics of the air-blown processes depended upon the successful development of hot gas cleanup technologies in order not to suffer inefficiencies inherent in cooling the large gas volume for subsequent removal of contaminants using conventional sulfur removal technologies. However, improvements in cryogenic air separation technologies continued to be made to the point where many organizations now believe that the cost of oxygen-blown gasification systems are equal to or less than air-blown units. Additionally, older generation gas turbines were much more amenable to extracting air for the gasifier. However, new advanced turbines cannot extract sufficiently large quantities of air for air-blown operations. This factor makes oxygen-blown gasification the preferred approach for large centralized production facilities.

The market potential for air-blown gasification systems is limited primarily to utility applications for the production of power. Such air-blown systems have little application in the co-production of other products such as hydrogen, fuels, and chemicals. It is also extremely difficult to capture any of the CO_2 generated in the process for sequestration. Retrofitting such as an air-blown process for oxygen-blown gasification results in a non-optimal operation. Considering the potential for greenhouse gas regulations and the competitive cost of today's oxygen-blown gasification systems, a very compelling reason is needed to justify building large air-blown IGCC systems today. Several organizations believe that the poor performance of the Piñon Pine IGCC process has severely hampered the future development and deployment of air-blown systems. Air-blown systems may find niche applications when coupled with small gasifiers. Even in such niche applications, however, new technologies for air separation as discussed below, may put air-blown units at a disadvantage.

The capital cost of a cryogenic air separation unit in a conventional IGCC plant typically runs between 12 and 15 percent of the total capital cost of the facility and consumes upwards of 10 percent of the gross power output of the plant, depending upon the oxygen purity required. Most often, oxygen purities range from 95–98 percent. Although the cost of cryogenic air separation units has continually been reduced over the years (current costs are typically $15/ton), most believe that there are very limited opportunities for further cost reductions. Over one-third of the organizations believe that the cost of oxygen must be further reduced to less than $15/ton to improve the economic viability of gasification-based processes. It is also suggested that part of the solution should encompass a reduction in the specific oxygen demand, for example, through dry feeding and lower temperature gasification.

The development of advanced air separation membranes is viewed as a worthwhile goal by most because of its potential to not only reduce the capital cost of the air separation unit, but also to increase the efficiency of the plant through reduced power consumption. These membrane-based technologies have recently been reported to reduce capital costs of an IGCC plant by about $75–100/kW, improve plant efficiency 1–3 percentage points, and increase net power production by 7 percent.

Integration of the gas turbine with the membrane (or any air separation unit) may be problematic depending upon the amount of air that must be extracted from the compressor of the gas turbine. Older gas turbines are capable of providing larger amounts of air, up to 37 percent (and 50 percent with some nitrogen return) and 20 percent for newer turbines. Advanced turbines emerging now provide much less extraction air. Air extraction/return is identified as a priority area for membrane-based technologies.

Although most felt that the membrane approaches can greatly benefit gasification, there is some concern that such systems only make sense in small-scale applications and that other continuous separation processes are much more economical at large scales. It is believed that membrane-based systems can be very bulky and expensive at large scales because the required membrane surface area scales linearly with the quantity of gas being processed. Others point out that while the scaling factor is correct, other parameters have a much greater impact on the cost and performance of such systems.

In general, conventional gas separation technologies, particularly for air separation, but also for other gases, operate at very low temperatures (-300 °F) while the membrane-based technologies currently under development operate at very high temperatures (1,650 °F). Some believe that future gas separation technologies need to operate closer to ambient temperatures, *i.e.*, -50 °F to 350 °F.

The development of technologies using enriched air (typically 20 percent more oxygen) is mentioned in a few cases; however, this is viewed as a lower priority than producing high purity oxygen. In the past, all engineering analyses generally show that the economics favor either air-blown or oxygen-blown gasification processes. Enriched air systems do not appear to be competitive because the pressure drop across the membrane used to enrich the air must be reduced, and the longevity of such membranes must be improved by eliminating fouling and plugging.

One safety-related issue surrounding the production of high-purity oxygen is addressed. This issue relates to the problem of the concentration of small carbonaceous particles in the ambient air. Such conditions tend to prevail in areas where there is considerable smoke from fires. The accumulation of these particles in the air separation unit, particularly on filters and heat exchange surfaces can lead to explosions in the unit.

Needs

- **Complete development of the current suite of membranes before pursuing the next generation of membrane materials, and allow time for the anticipated substantial cost reductions following initial commercialization associated with technology improvement and maturation.**
- **Develop an efficient and effective air extraction/return capability.**
- **Preferably through the Clean Coal Power Initiative, implement a viable DOE demonstration program to ensure future commercial financing of advanced gas separation technologies.**
- **Conduct R&D in materials development for new sorbent and membranes compatible with the -50 °F to 350 °F temperature range, with initial exploration of new materials and concepts at universities.**
- **Conduct R&D to determine the fate of trace metals and other potential contaminants in the separation process to prevent contamination of the final product, which inhibits its marketability.**

- **Through efforts on the part of air separation unit vendors, resolve the problem of accumulation of small carbonaceous particles on surfaces in the presence of high-purity oxygen.**

H_2/CO_2 Separation

Hydrogen (H_2) and CO_2 can be separated directly from the raw synthesis gas or from a synthesis gas containing mostly H_2 and CO_2. Three options exist. First, the CO_2 contained in the synthesis gas stream can be collected without any converting (shifting) of the CO. This option reduces the amount of CO_2 emitted to the atmosphere, but does not allow for near-complete capture of all of the carbon in the gas, nor the production of hydrogen. This option may be acceptable depending on the extent of any greenhouse gas control regulations. The second approach is to separate the hydrogen from the CO_2 in a shifted synthesis gas. The hydrogen can then be combusted in a gas turbine or used elsewhere, such as in refining operations or fuel cells. In this approach nearly all of the CO_2 is available for sequestration. Hydrogen-fired turbines can be offered commercially today if required. Finally, hydrogen can be separated from the unshifted synthesis gas stream for refining or other applications. Such an approach permits the hydrogen to be used more efficiently. This option does not allow for the capture of CO_2 unless oxygen, rather than air, is fed to the combustion turbine.

If required today, existing technologies, such as Rectisol and Selexol, can be applied to capture CO_2; however, such applications are expensive and impart a severe energy penalty on the system. It is the opinion of most in the industry that for IGCC plants, the CO_2 needs to be removed prior to the combustion turbine.

The first priority identified is the development and demonstration of sequestration and utilization technologies. Technologies for CO_2 sequestration need to be proven before CO_2 removal is mandated. Nearly half of the participants view this as a top priority area in which the government plays a key role. Although some industrial organizations are already investing in such research, many other organizations cannot justify the cost in such expensive R&D projects.

For the production of CO_2 and hydrogen as identified in the above options, it is desirable to have all product streams from the separation processes at high pressures. Having hydrogen at high pressures improves the economics of the process and affords more opportunities for downstream applications in other industries besides power production. Regardless, many express interest in membrane-based technologies, but recognize that membranes always produce one stream at low pressure. High-pressure CO_2 is desired because it must be further compressed to at least 2,000 pounds per square inch-gauge (psig) for sequestration applications. In addition to the high pressure requirements, lower cost, more efficient $H_2/CO_2/CO$ separation technologies that operate at temperatures below 800 °F, and preferably at ambient temperatures, are desired.

Besides membrane-based technologies, other novel approaches to the separation of H_2 and CO_2 also need to be investigated that have potential for achieving the desired requirements. In addition to separation of hydrogen from shifted synthesis gas, the separation of hydrogen from synthesis gas without prior shifting also warrants pursuit.

Needs

- **Place a high priority on development and demonstration of carbon management, including capture, sequestration, and utilization technologies, with the government taking a lead role.**

- **Implement fundamental research at universities and national laboratories on “outside-the-box” approaches to the separation of hydrogen and CO_2.**

- **Develop lower cost CO_2 capture technologies, with emphasis on systems that remove the CO_2 prior to the combustion turbine.**
- **In developing separation technologies, place emphasis on pressurizing the product streams for economic considerations and target separation technologies operating at temperatures below 800 °F and preferably at ambient temperature.**

By-Products

General

Utilization of by-products from gasification plants is of considerable interest from a market perspective. By-products include ash/slag, sulfur, ammonia, and CO_2.

Needs

- **Perform a market assessment of future (5–10 years) off-take options for all by-products, with a range of characteristics, produced from gasification-based plants.**

Ash/Slag

As the number of gasification plants continues to increase in the United States, the disposition of the ash and slag becomes increasingly important. New markets and ways of utilizing the ash/slag from gasifiers need to be developed because disposing of this material in a landfill is expected to become a significant issue in years to come. Currently, it is difficult to find a market for the ash and slag where its value exceeds transportation costs. It is desirable for the ash/slag to be a revenue-generating stream and help drive the technology to full utilization of all waste materials.

Currently, some of the gasification plants have found it difficult to market the slag because of its high carbon content due to poor carbon conversion. The carbon content must be reduced to less than five percent by weight for it to be marketable. Such material can be used in road construction, while slag containing two percent by weight carbon can be used for sandblasting grit. The slag currently passes the Toxicity Characteristic Leaching Procedure (TCLP), but the method does not ensure that the release of toxic substances will not occur under different erosion and leaching environments.

Opportunities may also exist for extracting certain components from the slag. For petcoke-derived slag, the recovery of nickel and vanadium is already being considered. Recovery of components from the slag that detract from its value, such as lead, may also be an attractive alternative. Moreover, the solid by-products generated during the gasification of waste materials, either alone or in combination with coal, may have different properties that can potentially impact its marketability.

Needs

- **Develop new leaching test methods for each ash/slag application to ensure that long-term release is not occurring.**
- **Implement R&D to reduce ash/slag carbon and moisture content, and to reduce the size of the product.**
- **Develop means to reduce the cost of grinding and classifying the ash/slag to a level significantly lower than the market value of the resulting product.**
- **As a further cost consideration, explore opportunities for recovery of components that either detract from ash/slag value or are in themselves valuable.**
- **Characterize the solids produced from gasification of waste materials and coal/waste blends to determine whether the solid properties are sufficiently different to affect the marketability of the material.**

Sulfur

Approximately 25,000 tons per year of sulfur are produced from “an average” 300 MW IGCC plant. There is a growing concern that as more and more gasification facilities are constructed and operated, especially those processing petcoke and high-sulfur coals, the production of high-grade sulfur will eventually exceed demand.

There is some mention of potential improvements to sulfur recovery units. One improvement involves the potential for eliminating the Claus plant through integration with the acid gas removal unit to convert H_2S and CO_2 to synthesis gas and elemental sulfur. A patent on such an approach exists.

In exploring new markets, it is noted that Canada is addressing this issue by using sulfur to make concrete for highly corrosive environments. Also, the U.S. Department of Transportation has developed roadbed material containing sulfur.

Needs

- **Determine the level of IGCC capacity at which the sulfur market becomes saturated and sulfur no longer generates a revenue stream.**
- **Develop new markets and ways to utilize sulfur.**
- **Follow-up investigations on the potential elimination of the Claus plant.**

CO_2 Utilization

As mentioned previously, the most important issue is the development and demonstration of technologies for the sequestration and/or utilization of CO_2. Utilization of CO_2 is a formidable task because of the thermodynamic stability of the molecule. However, some investigations are ongoing in this area.

Needs

- **As discussed under Gas Separation, implement long-term, high-risk R&D to realize efficient, cost-effective capture and recycle or sequestration of CO_2.**

Synthesis Gas Utilization

Gas Turbines

The most compelling issue in the gas turbines area is the need to qualify and optimize the gas turbines on synthesis gas, particularly for advanced gas turbines. Currently, there is no long-term strategic path for accomplishing synthesis gas testing and systems integration for these machines. The DOE’s Advanced Turbine Systems (ATS) program, which is coming to closure, focused primarily on natural gas. Currently, there is no specific follow-on development path for ATS operation on synthesis gas. Since the gas turbine market is being driven by natural gas, there is justifiable concern about the future availability of gas turbines for gasification applications and about keeping gas turbine development responsive to the needs of the gasification industry.

Considerable effort must be devoted to determining the tolerance of gas turbines to various trace contaminants. Although there are a number of machines currently operating on synthesis gas, deposition, erosion, and corrosion problems have been encountered that may be due to the quality of the synthesis gas feedstock. Currently it is believed that the synthesis gas for a gas turbine ought to contain less than 10 ppm of particulate matter and less than 10 ppm of alkali. However, the current alkali specification is based on experience of turbine manufacturers with alkali in fuel oil, and there is concern that alkali in the synthesis gas may affect the performance of the gas turbine differently than fuel oil. In addition, different gas turbine models may perform differently on the same fuel, requiring separate specifications for each machine.

Another issue of concern is NO_x emission levels from the gas turbine. Over the past year, there has been a move among some state regulators to drive down the level of NO_x emissions on existing, as well as planned gasification plants, to levels that would require the use of SCR units. This would add capital and operating costs to the gasification plant and add potential operational problems in the HRSG unit due to the possible formation of ammonium bisulfate. On new gasification plants using diffusion flame combustors, NO_x emissions can now be reduced to about 9 ppm through the use of a combination of diluents (steam, nitrogen, carbon dioxide); however, this appears to be about the limit for this technology. Also, the stability of diffusion flame combustors is poor with high levels of diluent.

There is a desire on the part of the industry to further reduce NO_x emissions in anticipation of future tightening of emissions. To achieve NO_x emission levels of 3–5 ppm, which is equivalent to NGCC systems, new gas turbine combustion technologies must be developed. New low-NO_x combustor designs can change the design of the entire gasification system, including the gasifier and air separation unit, since the plant is designed around the gas turbine.

Needs

- **Continue the ATS program, or other DOE programs, focusing on synthesis gas applications and encouraging gas turbine manufacturers to design turbines that can burn synthesis gas.**
- **Expand the range of the fuel handling system and gas turbine nozzle performance to accommodate the use of multiple compositions of diluted fuels having a broad range of hydrogen content and time-varying heating values caused by swings in product output.**
- **Conduct combustion testing on existing as well as future machines to cover a wider range of fuel heating values.**
- **Establish a cost-effective U.S.-based user test facility to perform full-flow combustion tests at pressure, determine performance during turn-down situations, evaluate changes to the fuel compositions, and determine fuel specifications.**
- **Characterize the deposition, corrosion, and erosion that results from feeding synthesis gas to a gas turbine to address delamination, spalling, embrittlement, and deterioration of thermal barrier coatings.**
- **Develop new low-NO_x gas turbine combustion systems, such as dry low-NO_x burners for low-Btu gas and catalytic synthesis gas combustion.**
- **Develop improved diagnostic instrumentation for gas turbines, including fuel gas flow and flame stability monitors, imbedded temperature sensors for turbine blades, foreign object and vibration detectors, combustion temperature sensors, and instrumentation to measure turbine performance and monitor corrosion and erosion.**

Fuel Cells

Integrating fuel cells with gasification offers the potential to achieve very high thermal efficiencies. The major hurdle to deployment of the technology is the cost of the fuel cell, which must be drastically reduced from today's costs. Some believe that integration of gasification and fuel cells can occur within the next 10 to 15 years. Another key process issue surrounding the use of fuel cells is the synthesis gas quality requirement.

Needs

- **Develop specifications on maximum contaminant levels in the synthesis gas, as well as other process requirements, for the various fuel cell technologies to guide those organizations developing advanced gas cleaning technologies.**
- **In addition to gas cleaning, direct efforts toward developing more poison-tolerant fuel cells.**
- **Thoroughly investigate integration and optimization of the fuel cell in the overall plant configuration.**
- **Support development of synthesis gas-based fuel cell systems through pilot-scale testing and demonstration projects.**

Synthesis Gas Conversion

Product flexibility in a gasification plant is a desired feature to address market issues such as swings in electrical power demand over the course of a day. The ability to produce a second or third product in addition to electricity has been shown to have some notable synergies and permits continuous operation of the gasifier at full load while adjusting to varying power demand. However, the technology used to produce the co-product must be sufficiently robust to withstand swings in its operation. A properly sized process can also act as a buffer between a standard size gasifier and the primary synthesis gas application, such as use in a gas turbine. The production of value-added products compared to electricity helps to improve the overall economics of gasification-based plants. Studies have shown the potential of fuel co-production approaches to achieve over 70 percent thermal efficiency and to be cost competitive with petroleum at $25/barrel. However, current technologies for the conversion of synthesis gas to fuels and chemicals are believed to be inefficient.

In F-T plants, the H_2/CO ratio is a critical measurement for the stream entering the F-T synthesis reactor. This ratio has significant impact on the yield of desired F-T products, and a system to vary feed inputs to alter the H_2/CO ratio helps to maximize product yield.

Needs

- **Pursue new approaches for synthesis gas conversion that are less costly and more efficient to improve the economics.**
- **Explore new routes for the conversion of synthesis gas to chemicals and C_2 and C_2 alcohols.**
- **Direct near-term efforts at the development of synthesis gas conversion to F-T products.**
- **Develop process schemes for an integrated gasification/F-T plant, focusing on optimizing plant integrations and follow with the operation of an integrated demonstration plant.**
- **In the long term, develop an F-T fuels market.**
- **Establish a user facility where companies can scale-up and demonstrate new technologies for synthesis gas conversion.**

Other Identified Needs

There are a number of other opportunities relative to synthesis gas utilization that warrant attention to improve cost and performance.

Needs

- **Increase efficiency by developing technologies that can utilize synthesis gas from high-pressure gasifiers, rather than expanding the synthesis gas prior to the gas turbine, which wastes energy.**
- **Develop and test sour gas expander materials for use with high-pressure gasifiers (1,000 psig).**

- **Reduce the cost of the power block through enhanced performance and cost reductions in the gas turbine.**
- **Develop alternative bottoming cycles.**
- **Develop materials compatible with raw synthesis gas at temperatures up to 1,400 °F.**

Integration

Proper integration of process units has potential for reducing capital costs and improving plant efficiency. The need for commercialization of the technology and system flexibility in addition to recent problems experienced with highly integrated systems has driven the industry towards less integration. The problems encountered in highly integrated systems in the pursuit of high efficiency have led to reduced availability of the plant in most cases and have created problems for the general acceptance of IGCC. The market is also moving away from long-term fuel contracts and toward more diverse fuel mixes, which complicates the design and integration of gasification plants. Consequently, some organizations are averse to integration, while others believe that integration will eventually occur as more operating experience is gained. Integration may be possible with newer gasification technologies; however, these technologies must be sufficiently demonstrated prior to commercialization.

Integration of technology blocks for more efficient process schemes requires alliances between technology suppliers. Intellectual property rights issues must be facilitated and resolved to make such alliances attractive.

Design Standardization and Modularization

Many believe that modularization of process units and standardization of designs stands to greatly benefit the commercialization of gasification. Currently, each new gasification plant is a special design based on the requirements of the customer in terms of feedstock, products, siting, and environmental issues. As a result, engineering costs are high for these facilities. Standardizing the design based on typical gas turbine size and systems currently being deployed and anticipated in the future can significantly lower engineering costs. Modularizing the process units also reduces construction costs. However, because the number of projects is too few and the market is dominated by only a few technology suppliers, there is little incentive for industry itself to invest in any approach to provide standard, "product line" designs that can significantly improve the technology.

It is deemed appropriate that the DOE sponsor a study from a "clean sheet of paper" that addresses optimized modular standardized IGCC plant designs for the power market, without imposing any equipment constraints. Market assessments would be incorporated into the study to address size and to develop a market growth strategy. In addressing size, the suggested guidelines are that plants must be reasonably deployed at many utility sites, but sufficiently small so as not to be overly burdensome to the customer. Suggested guidelines for the market growth strategy guidelines are to address repowering 20 to 25 percent of existing plant capacity with standardized plants. Once experience is gained with a standardized unit at a utility, parallel trains can be easily deployed to increase capacity.

Dynamic modeling is particularly important for the standardization of IGCC plants. A government role is suggested because it is difficult for industry to pass the cost of such modeling along to later plants. It is generally thought that the DOE can best address integration issues of such plants by continuing its modeling efforts. Equipment suppliers would need to provide dynamic modeling modules of their specific technologies for integration into the simulation of the IGCC plant. However, there is a concern that technology developers and equipment suppliers may be unwilling to share such models for fear of disclosing proprietary information and helping their competitors.

It is felt that a standardized plant approach allows for value engineering concepts to be employed that ultimately reduce the capital cost and improve the performance of the system for the customer. This approach has the potential to reduce the footprint of the plant by as much as 20 percent; and, also increases customer confidence that construction and startup will proceed according to the proposed schedule and without any undue surprises.

Needs

- **Conduct a study that addresses design of a modular, standardized IGCC plant that is optimized for a niche power market into which many such standardized, modular plants can be sold.**
- **Continue DOE dynamic modeling efforts in support of standardization, incorporating equipment costs for integration into the simulation of an IGCC plant; and, verify the model with data from existing plants.**

Air Separation Unit/Gas Turbine Integration

The integration of the gas turbine with the air separation unit (ASU) is an area that has created much debate. Full versus partial integration between the ASU and gas turbine is still an unresolved issue. Considering the higher pressure ratios of future gas turbines, integration is likely to continue to be problematic. Some organizations are very wary of the integration of these two process units because of operability issues that have arisen in prior projects. There is also concern as to whether or not nitrogen re-injection to the gas turbine should be practiced.

Other organizations recommend that partial integration of the units be pursued. With partial integration, there are still significant issues that must be resolved, especially with the gas turbine. Start-up and shutdown of the plant are the most critical operational issues that must be addressed regarding integration of the two units. This becomes an even more important issue as advanced turbines with their higher pressure ratios are deployed. Although the industry is still wary of full integration, some believe that in time full integration eventually will be practiced.

Needs

- **Conduct R&D to address the issue of integration of the gas turbine with the air separation unit.**

Databases

Sources of information on gasification system design and performance appear to be, at best, very minimal. Numerous requests are made for the development of databases, which industry can utilize in the development of projects. It appears that there is considerable concern that designers are not aware of past mistakes and that important learning experience benefits are being lost.

A critical hurdle to the commercialization of gasification projects is their inability to meet scheduled deadlines for key performance milestones upon which economics are based. Typical start up is a year late and target availability is two years behind schedule. The primary reason for this is that development teams are continually repeating the same mistakes because information is not openly shared. It is also uncertain as to whether many of the technical issues that are encountered in such projects are adequately addressed to prevent repetition. An industry-wide “knowledge management system” is a possible mechanism for enabling companies to avoid common problems by sharing non-proprietary information. Such a system can include a database of reliability statistics for existing gasification plants to help in the design of future plants as well as in improving current operations. The mean time between failures (MTBF), causes of the failures, approaches for mitigating future problems, and the mean time to repair (MTTR) need to be addressed. Many of the existing facilities experience high restart time. Historical costs and availability of subcomponents in a gasification plant helps to provide a better understanding of component availability and reliability. Because gasification systems are highly complex, comprehensive research may be required to delineate the root causes of downtime. The proposed information system has to be a "living" interactive knowledge exchange system in which users have to input information in exchange for extracting information. Since reluctance of companies to share such information would make the collection of information difficult and its usefulness limited, information in such a database has to be sanitized to prevent linking information to a particular plant. It is suggested that the DOE, the GTC, and the Electric Power Research Institute (EPRI) serve as brokers for such a system and that the beginnings should initially concentrate on the DOE-funded projects to prove the value of such an undertaking.

To speed the design process, more data are needed on feedstock quality versus gasification system characteristics. A database on feedstock properties important to gasification is needed that is similar to the U.S. Coal Quality Database maintained by the U.S. Geological Survey. Information is required for a range of individual feedstocks and feedstock blends, such as chemical and physical properties, reactivity versus temperature, and ash fusion temperature and ash viscosity versus temperature under reducing conditions. Even for coal feedstocks alone, the U.S. Coal Quality Database needs to be expanded to include some of these gasification specific properties and to address coal blends. Data on blends is important because blends display characteristics different from the individual constituents. For example, when mixing different types of coal, the resulting slag viscosity can be very unpredictable. A database addressing gasification specific properties can be employed in conjunction with on-line feedstock analysis to instantaneously control the operation of the gasifier.

Also, there is an expressed need for the industry to address generic operation and maintenance problems that are common to the gasification industry. One example is the need for information on the effects of coal slurry characteristics on pipes and valves as discussed in the "Feedstocks" section. Gas is easy to deal with, but any material that has to be pumped is potentially problematic. Other examples of databases that would assist the gasification industry include: (1) a "Water Chemistry" lessons learned database, addressing the design and operation of water systems within a gasification plant; (2) an "Emissions" database, providing a compilation of stack emissions from gasification plants employing different feedstocks to aid those permitting new facilities; and (3) a "COS Hydrolysis" database, providing a compilation of lessons learned on COS hydrolysis to support catalyst design and performance improvement efforts.

Needs

- **Establish an industry-wide "knowledge management system" to include: (1) a database of reliability statistics for existing gasification plants, addressing both the MTBF, causes of the failures, approaches for mitigating future problems, and the MTTR need to be addressed; (2) historical costs and availability of subcomponents in gasification plants; (3) a "living" interactive knowledge exchange system in which users have to input information in exchange for extracting information; and (4) sanitized information to prevent linking information to a particular plant.**
- **Establish a database on feedstock performance to include: (1) chemical and physical properties, reactivity, and gasification characteristics of various gasification feedstocks; and (2) coal ash fusion temperatures under reducing conditions and gasification reactivity versus temperature for various coals and various solid feedstock blends.**

CO_2 and Hydrogen Integration

The potential future liability of CO_2 is an issue that organizations are beginning to consider in planning future projects. The integration of technologies and infrastructure to store and transport hydrogen are important for gasification-based plants, particularly during a transition to a hydrogen-based economy.

Needs

- **Conduct pilot and commercial-scale demonstrations of CO_2 capture and sequestration from a gasification facility.**
- **Demonstrate hydrogen production resulting from CO_2 capture, with emphasis on storage and transport.**

Other Integration Ideas

Most of the technologies used today in gasification plants are mature technologies. However, innovative integration of two or more technologies to produce a single technology warrants consideration as a way to improve process economics. Combining process streams across non-traditional boundaries needs to be considered. The ultimate plant can consist of a single block rather than the piping together of several individual pieces.

Needs

- **Pursue integration opportunities in the following interfaces: (1) refinery bottoms with the gasifier, (2) gasifier with the gas purification block (recycling metals back to the gasifier for disposal in the slag to prevent plating out on the turbines), (3) gas purification block with gas turbines, (4) synthesis gas with petrochemicals production, (5) F-T technology with F-T product upgrading, (6) gas purification block with the air separation unit, and (7) air separation unit with a refinery.**

Systems Analysis

General

Studies are needed to improve the understanding of the cost and performance implications of technology applications. For many of these studies, it is imperative that teams of industrial organizations play a role to ensure that meaningful designs and results are obtained, with funding directed at cooperative/interrelated programs to ensure team cooperation.

Needs

- **Define the optimum configuration of a gasification system to accommodate CO_2 capture and sequestration and quantify the economics of the process.**
- **Assess the economic and process performance implications of employing SCR with deep sulfur capture for NO_x control.**
- **Analyze future gasifier size, pressure requirements, and heating values to meet gas turbine developments.**
- **Analyze system performance and economics of utilizing compressed air energy storage during off-peak times (IGCC power is competitive only during peak loads, but plants must operate under a constant load to maximize availability. Co-producing other products is another option but at a cost).**
- **Conduct value engineering assessments of gasification plants to optimize cost and performance and develop low-cost design templates.**
- **Evaluate options for co-producing value-added products.**
- **Examine optimization of gasification plants producing hydrogen for power-only applications.**

- **Explore integration of pressure swing absorption units for both hydrogen and oxygen separation with the gas turbine.**
- **Explore repowering of existing power plants with partial gasification technologies (the hybrid gasification/combustion concept).**

Instrumentation and Controls

There is clearly a need for the development of new and improved techniques for monitoring and controlling all processes and process streams within a gasification plant. Many believe that improved instrumentation and controls are key areas to further the advancement of gasification and to other highly integrated processes in general. Labor reduction issues have not been a high design priority. How instrumentation is employed in other industries should be reviewed for ideas. Many of the needs coming out of the specific discussions on instruments and control mirror the needs identified elsewhere in this report. Other instrumentation needs not mentioned previously are detailed below.

Needs

- **Develop advanced, predictive controls to regulate the total system, especially if load following is required.**
- **Develop advanced logic supervisory/optimization systems.**
- **Develop simulators that can be used to train operators on new plants in a consistent manner.**
- **Develop tunable diode laser technology for gas measurements in high-particulate environments.**
- **Develop a reliable pH meter capable of operating under elevated pressures and temperatures up to 300 °F for scrubbing system applications.**
- **Integrate instrumentation technology to provide diagnostics on key elements within existing systems to help identify potential improvements that can be implemented to improve process reliability and performance.**
- **Develop diagnostic procedures and tools to identify process issues affecting plant reliability.**

Models

Although the need for more advanced gasifier and other process models ranks quite high, comments are mixed. Most companies have already developed gasifier and associated process models and many expressed the need to develop even more sophisticated gasifier models than presently exist. The major concern with the development of such models is safeguarding the company's intellectual property rights and proprietary information associated with their technology, whether it is a gasifier, an air separation unit, or a gas turbine.

The general perception is that DOE has spent a considerable sum of money to develop models that already exist in industry. Before embarking on further efforts, the government should fully understand what models are currently available to avoid redundancy and duplication of effort.

There is a poor understanding of the fluid dynamics in the gasifier and subsequent synthesis gas cooling approaches. Dynamic modeling has proven to be very useful for control system design. Such models may also provide an understanding of physics occurring during start-up and shut-down that sometimes leads to operation problems such as excessive carbon deposition in the gasifier and gas turbine/ASU integration issues.

While some believe that DOE needs to fund IGCC equipment suppliers to develop dynamic modeling modules that can be used to integrate their equipment into an IGCC plant, there is concern expressed that equipment suppliers most likely are reluctant to cooperate because of concerns about proprietary information. As a result, the government's role is difficult to define. The role undertaken by the government needs to be agreed to with industry. One possibility is to assist in the validation of the models rather than their development.

Needs

- **Define and develop the models that are clearly needed to benefit the entire industry, such as new dynamic models of gasification plants.**
- **Focus model development on dynamic models that can be used not only to predict the steady-state performance of a gasifier, but also to simulate transient events, such as load changes and trips in various units, gasifier ramping, and pulsations in filtration devices.**
- **Validate the models with actual plant data rather than using theoretical diagnostics or dynamic modeling as substitutes for actual operational experience.**

Government Role

Government-Sponsored Testing Facilities

The evaluation of gasification technologies and feedstocks needs to be done in test facilities that are as close as possible to commercial-scale. Ideally, such facilities should be accessible by more than one company. However, some companies may be reluctant to participate in such tests because they may reveal a problem or produce data leading to more stringent regulations.

Since testing at full-scale demonstration facilities is not always feasible, the availability and use of commercial-scale component testing facilities is critically important for the commercialization of gasification technologies.

Needs

- **Through government support, improve the utilization of existing, full-scale demonstration facilities, such as the Wabash River and Tampa Electric IGCC plants for testing.**
- **Use existing IGCC facilities: (1) to show the efficacy of controlling mercury emissions by installing a carbon guard bed prior to the stack; (2) to scale up and demonstrate F-T processes; and (3) to evaluate gas cleanup technologies.**
- **Expand R&D at government component testing facilities at Wilsonville, Grand Forks, NETL, and LaPorte; for example, installing a slipstream unit at the Power Systems Development Facility at Wilsonville to develop filters made from new materials.**
- **Establish a government-sponsored full-scale demonstration plant that includes slip streams specifically designed for testing new technologies in a "plug and play" fashion.**
- **Establish a government-sponsored pressurized biomass gasification facility for testing feeder systems, gas cleanup, and other advanced components.**
- **Establish a government-sponsored high-temperature/high-pressure gasification facility for testing fuel cells on real, high-pressure synthesis gas (testing which is beyond the atmospheric capabilities that are currently being demonstrated).**
- **Establish a government-sponsored common laboratory using a consistent method to validate sorbent testing for contaminant removal.**
- **Establish a government-sponsored full-flow, full-pressure synthesis gas test facility in the United States for F- and G-class gas turbines, as well as ATS and next generation machines.**

Government Incentives for Gasification Projects

Government incentives, both direct and indirect (such as environmental regulations), have played a significant role in developing the gasification projects that are currently in operation, under construction, or under consideration. However, the commercial application of gasification continues to be limited by the investment risks arising from changing environmental regulations and the technical hurdles associated with the newness of the technologies.

For example, to mitigate the risks of incurring liquidated damages on first- or second-of-a-kind gasification projects, contractors must significantly increase capital costs. If the government can somehow reduce the project-specific uncertainties associated with developing and constructing gasification plants (notably construction time and capital cost), it would greatly enhance their commercial attractiveness.

It is suggested that an existing federal program called the Overseas Private Investment Corporation (OPIC) be used as a template to develop a concept to help the private sector manage investment risk. The essence of the OPIC concept is to stimulate investment in third-world countries by providing insurance for those investments, where the private sector perceives the risk to be too high, but the government believes that the actual risk is much less. It is believed that if a government program guaranteed a 48-month development period, at $1,250/kW capital cost and 42 percent efficiency, some companies might decide to invest in an IGCC project today.

Another way the government can help industry expand the application of gasification and progress to the “nth plant” is by funding another wave of demonstration projects, albeit with one significant change. Government cost-sharing needs to be structured as a “carrot and stick” approach with the amount of cost share tied to project performance, such as capacity factor. The closer the participant comes to achieving the performance goal, the more funding the government needs to provide. This encourages proposals from companies who are in the business of operating gasification plants, instead of the typical proposals from companies that are just interested in building the plant. In addition, because a single demonstration is often insufficient to overcome the technical risks and economic/market hurdles for commercial offerings, the government needs to sponsor multiple commercial demonstrations of a given gasification technology. Tax credits, insurance or other financial incentives for first-, second- and third-of-a-kind plants, both greenfield and repowered, are also considered to be beneficial, even as capital costs decline.

Federal incentives are also needed to encourage the use of certain gasification feedstocks. Coal can become a viable gasification feedstock during the next 10 years if legislation is passed that provides tax incentives for plants that surpass a certain thermal efficiency, such as 80 percent. It is suggested that this would also be an excellent way for the government to start addressing the global warming issue. Certain opportunity fuels also require tax incentives to achieve long-term economic viability. For example, if the current tax credit for biomass fuels expires in 2007 (as currently scheduled), it is unlikely that biomass will be an economically feasible fuel for gasification due to its handling, safety, and contamination issues.

Needs

- **Have the government provide insurance on the schedule, cost, and performance of initial commercial IGCC plants, collecting premiums from private sector stakeholders for the insurance.**
- **Fund another wave of IGCC demonstrations that ties government cost-sharing to project performance, increasing funding as the participant approaches established performance goals; and replicate the most promising technologies to overcome technical risk.**
- **Provide tax credits or other financial incentives for initial commercial IGCC plants that are tied to performance targets, such as efficiency or CO_2 emissions, to encourage coal and biomass utilization.**

Government Action on Environmental Regulations

The uncertainty over if, when, and how future environmental regulations are to be implemented adversely impacts the business development of gasification projects and especially discourages the deployment of coal-based gasification plants. Unfavorable changes in environmental regulations — similar to those imposed on the refining industry — can stall the development of gasification before the technology has a chance to prove itself. Many of the recommendations below will require DOE and EPA to work together to achieve common goals.

Needs

- **Bring additional streamlining to the New Source Review process.**
- **Educate regulatory officials about gasification, demonstrating to them that gasification is an environmentally friendly process as opposed to an incinerator.**
- **Promulgate regulations that encourage the environmentally friendly conversion and use of wastes for gasification.**
- **Streamline the regulatory process such that the time required to permit a gasification plant is reduced to about six months.**
- **Change environmental regulations such that they both recognize and provide incentives for efficiency-related emission reductions (which can make coal a viable gasification feedstock within the next 10 years).**
- **Conduct more studies on trace metals to assess the need for emission regulations.**
- **Support DOE's Vision 21 program.**

Need for Government-Sponsored R&D

The federal role in technology research, development, and demonstration is predicated on serving some tangible public good that would not otherwise be served without federal involvement. The government role is needed in particular to support long lead time, higher risk R&D that the industry itself has identified as a requirement, but is unable to solely undertake with any comprehensive effort because of high risks (technical, market, regulatory, cost) and lack of sufficient resources to go it alone. As has been identified in this report, there are many cases in which there is no immediate market driver or monetary incentive to spur the development of an environmentally superior technology, either domestically or internationally. It is almost certain, however, that future regulations governing coal use will follow the historical perspective of requiring even more stringent emission limits.

Government investment in gasification technologies is needed to sustain economic growth by ensuring the availability of a technology with the capability of producing affordable electricity and other valuable products while, at the same time, responding to even more challenging regional and global environmental concerns. Government investment is needed to cost-effectively meet environmental regulations and address energy security and issues related to developing an electric power and industrial portfolio that provides for feedstock and product diversity.

Needs

- **Continue government investment in gasification technologies to ensure clean, affordable, reliable, and secure energy for our nation's future, which is requisite to economic growth and societal well being.**

Summary

The findings of this report are to be used to develop a more comprehensive technology roadmap for the DOE's Gasification Technologies Program and to support future budget requests. In addition, key findings are to be incorporated into the overall DOE portfolio planning and budgeting process.

Two new efforts have already been initiated in response to the gasification industry interviews. First, because many ideas expressed by participants involve fundamental research applicable to the gasification industry as a whole, the DOE is exploring the possibility of establishing a university consortium for gasification technology R&D. Similar to the university consortium that supports the Advanced Turbine Systems program, the Gasification Technologies Research Consortium features an industry management council that defines R&D areas for universities to investigate and makes recommendations on project selection and continuation. As technologies are developed and become of interest for specific applications, the DOE entertains specific industry-led projects via a separate competitive procurement mechanism to further develop and demonstrate the technology for a particular application of interest.

Second, because gasifier reliability is identified as the key factor limiting commercialization, the DOE has issued a solicitation to focus on approaches and technologies that will enhance the performance and reliability of gasifiers to meet the industry's needs.

Appendix A

Meeting Confirmation Letter

U.S. Department of Energy

National Energy Technology Laboratory

"Date"

Mr.

Dear _______:

On behalf of the Department of Energy's National Energy Technology Laboratory's Gasification Technologies Product Team, let me thank you for agreeing to meet with us on (**Date**), to discuss (Company Name)'s view of gasification technology research needs and market opportunities. In addition to myself, two members of the product team, John Wimer and Stewart Clayton, will also attend. The names/titles of the DOE participants are provided on the enclosed agenda. We would appreciate receiving a list of the names, titles, and responsibilities of your participants at the earliest opportunity.

In preparation for our meeting, I have enclosed a draft agenda for the meeting, a brief summary of our current program, and a list of the questions that we plan to cover with you (see enclosures). For more detailed information on the program, I welcome you to visit our website at www.netl.doe.gov/products/power1/gasificationframeset.htm.

We are particularly interested in your view of the current and anticipated research needs in each of the technology areas described in the program summary. Additionally, we would like to hear your thoughts on market opportunities for gasification between now and 2015 and what the industry must achieve to penetrate these potential markets.

The Gasification Technologies product team plans to visit with a number of gasification technology users and developers as well as regulatory agencies over the coming months to hold similar discussions. Once these industry interviews are completed, our findings will be summarized in a report. We will preserve anonymity by not attributing any comments or information to any specific organization or person. We will, of course, provide you with a copy of this summary report so that you can see how your organization's views compare with others in the industry.

Again, thank you in advance for meeting with us to identify gasification technology R&D needs and potential markets. This information will provide direct input to our program, ensuring that it addresses future needs of your organization and other industry partners related to advancing the commercialization of gasification technologies.

3610 Collins Ferry Road, P.O. Box 880, Morgantown, WV 26507-0880 ❖ 626 Cochrans Mill Road, P.O. Box 10940, Pittsburgh, PA 15236-0940
REPLY TO: Pittsburgh Office • stiegel@netl.doe.gov • Voice (412) 386-4499 • Fax (412) 386-4922 • www.netl.doe.gov

We look forward to meeting with you on (**Date**).

Sincerely,

Gary J. Stiegel
Product Manager, Gasification Technologies
Office of Coal & Environmental Systems

Enclosures

Appendix B

Interview Meeting Agenda

AGENDA

Industry Interview
"Gasification Technologies Market Opportunities and Research Needs"

"Name"
"Company Name"
"Date"
"Time"

Introductions

DOE Presentation — 30 minutes

Meeting Purpose
DOE's Expectation of Contributions from "Company Name"
Intended Outcome of This Meeting
Gasification Technology Program Overview

Interview and Discussion – "Company Name" — 2.5 hours

- Gasification Vision
- Environmental
- Gasification Technology R&D Needs
- Integration Issues
- System Analysis

Comments on NETL's current program & Wrap-Up — 30 minutes

DOE Participants:

Name	Title	Responsibilities
Gary J. Stiegel	Product Manager Gasification Technologies	Management and Direction of the Gasification Technologies Product Area
John Wimer	General Engineer Evaluation & Planning Division	Economics and Planning
Stewart Clayton	IGCC Portfolio Manager	Management, Strategic Planning, Program Requirements for the DOE Fossil Energy Headquarters Office

Appendix C

Gasification Technologies Program Presentation

Gasification Technologies Program

Program Overview

Gary J. Stiegel
Product Manager
National Energy Technology Laboratory

Meeting with "Company Name"
"Date"

NETL

Purpose of Meeting

- **Expected Product of This Meeting**
  – A DOE/"Company Name" joint contribution to be incorporated with similar contributions from other companies and agencies
  – Improved insight into the planning and direction of the Gasification Technologies Product program to provide stakeholder based guidance
- **What is Expected from "Company Name"?**
  – Your vision of opportunities for gasification
  – Your view of the current and anticipated research needs in the technology areas
  – Your assessment of constraints and limitations
  – Your evaluation of our program direction

NETL

Gasification Technologies Program Mission and Vision

- **Mission**
  - Foster the commercialization of gasification-based processes that convert low-cost carbonaceous feedstocks to some combination of electricity, steam, fuels, chemicals, and hydrogen
- **Vision**
  - Compared to competing technologies, gasification-based systems are technology-of-choice
    - **More economical**
    - **Higher thermal efficiency**
    - **Superior environmental performance**
    - **Fuel and product flexible**

NETL

Gasification

Drivers For Gasification

- **Environmental**
  - near-zero sulfur/nitrogen oxides, particulate matter
  - Eliminate hazardous waste
- **Ease of CO_2 separation**
- **Product slate and feed flexibility**
  - syngas route to electricity, clean transportation fuels, chemicals, hydrogen, substitute natural gas
  - coal, biomass, petcoke, etc. as feedstock
- **Efficiency**
  - high power generation efficiency using combined cycles or fuel cells

NETL

Gasification

Technology Performance Goals

- **Cost and Efficiency Targets**

Year	Capital Costs ($/kW)	Efficiency (%HHV)
2000	1250	42
2008	1000	52
2015	850	>60

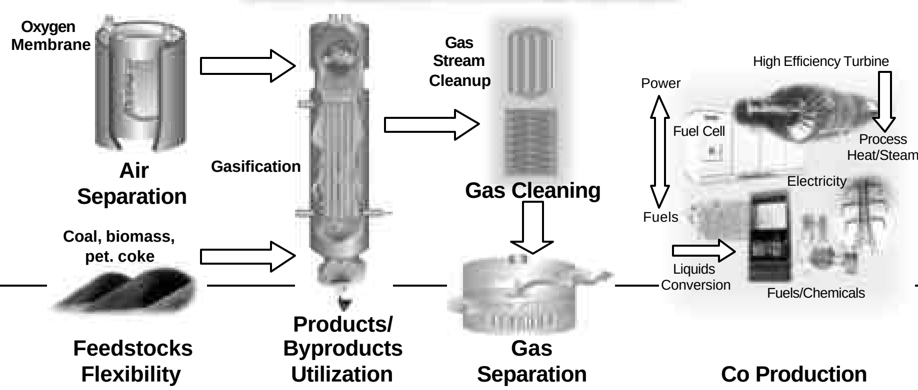
- **Environmental Performance Targets**
  - Near-zero pollutants
  - For combustion applications --- ppm levels
  - For fuel cells and fuel or chemical conversion technologies --- ppb levels
- **Feedstock and Product Flexibility Capabilities**

NETL

Gasification

Gasification Technologies Program

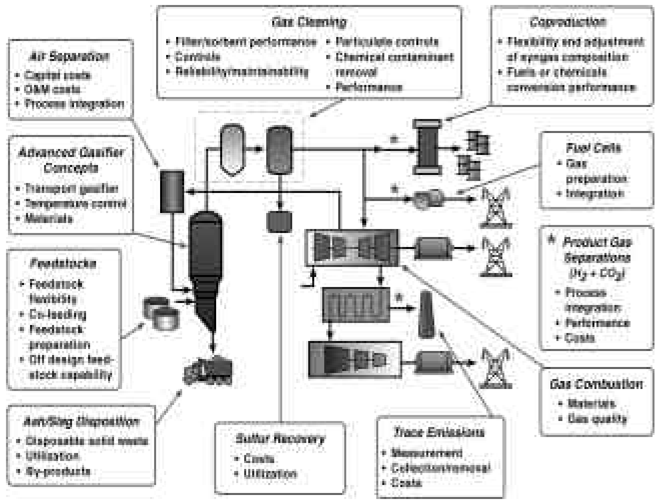
Clean, Affordable Energy Systems



Gasification Technologies R&D Issues

Overall System:

- Instrumentation/ control
- Capital/operating/ product costs
- Process integration/ optimization



NETL

Gasification Technologies Program Gasification Systems

- Southern Company
  - Electric Power Research Institute
  - Foster Wheeler Corporation
  - Kellogg, Brown & Root
  - Siemens Westinghouse Power
  - Corporation
  - Combustion Power Company
  - Peabody Group

Development and demonstration of modular industrial scale gasification-based processes and components at Power Systems Development Facility (PSDF)

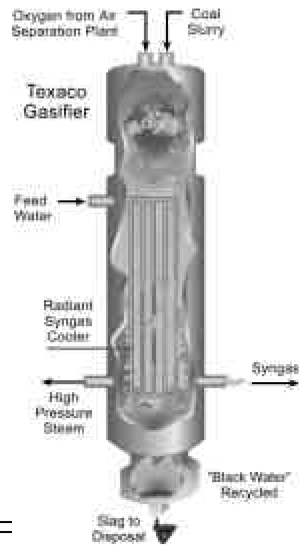
NETL

Gasification Technologies Program
Gasification Systems

GE Energy & Environmental Research Corporation

- Southern Illinois University
- California Energy Commission
- Others

Development of advanced gasification process for CO_2 separation and H_2 production



Foster Wheeler Development Corporation

- Nexant
- REI
- ADA Technology
- Praxair
- Corning

Development of advanced partial gasification module for use in fuel-flexible high-efficiency plants

University of North Dakota Energy and Environmental Research Center

- Kellogg

Development of transport gasification technology

NETL

Gasification

Gasification Technologies Program
Gasification Systems

Materials Development

Albany Research Center

Development of new refractory materials

Modeling

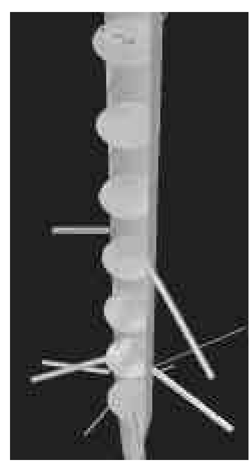
- Fluent
- CMU
- NETL in-house

CFD modeling of advanced gasifiers

Temperature Measurements

- Texaco
- Integrated Environmental Technologies
- Virginia Tech
  – Global Energy
- FluoreScience

Design, assemble, and test high temperature measurement systems



NETL

Gasification

Gasification Technologies Program
Feedstocks Flexibility

EnerTech Environmental

E-fuel from EnerTech's Slurry Carb™ process for future co-utilization with coal

GE Energy & Environmental Research Corporation

- Southern Illinois University
- California Energy Commission
- Others

Development of advanced gasification process for CO_2 separation and H_2 production

UNDEERC

- Gasification Engineering Corporation

Develop alternative fuel feed systems for future coal gasification-based power plants

Foster Wheeler

- Tekes

Develop and test alternative feedstock feeders into pressurized gasifiers

NETL

Gasification

Gasification Technologies Program
Gas Separation - O_2

Praxair

Develop cost effective oxygen separation membranes (OTM)

Air Products

- Cerametec
- Texaco
- McDermott
- Eltron Research
- Penn State University
- University of Pennsylvania
- Northern Research & Engineering Corporation

Develop cost effective ion transport membrane for oxygen separation (ITM)

NETL

Gasification

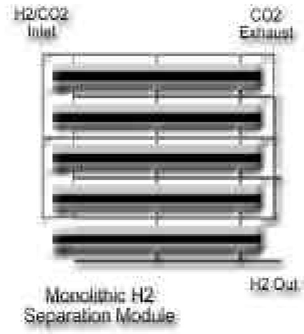
Gasification Technologies Program
Gas Separation - H_2

NETL In-house

Eltron Research
- Chevron Chemical
- Coors Ceramics
- Sud Chemie
- ANL
- ORNL
- McDermott International/B&W

ITN Energy Systems
- INEL
- Nexant
- ANL
- Praxair, Inc.

ANL
High-temperature ceramic membrane to separate hydrogen from gas streams



Bechtel
- Simteche
- LANL
- GRS Associates
- IPSI

Low-temperature approach to H_2 and CO_2 separation

NETL

Gasification

Gasification Technologies Program
Gas Cleaning

NETL In-house

Develop sulfur sorbents suitable for transport/fluid bed applications

Develop gas cleaning technology at Gas Process Development Unit (GPDU)

Development and demonstration of gasification-related cleanup technologies at the Fuels Processing Research Facility (FPRF)

Develop models for transport desulfurizers to minimize cost and risk in technology

H_2S Direct Oxidation -- single step process for conversion of H_2S to elemental sulfur

Global Energy

Test hot gas filter elements at the Wabash River IGCC Plant

ORNL

Analyze and assess metallic hot gas filters

NETL

Gasification

Gasification Technologies Program
Ultra Gas Cleaning

Research Triangle Institute
- **SRI International**
- **Membrane Dupont Air Liquide**
- **Prototech Company**
- **North Carolina State University**

Develop processes to reduce H_2S and CO_2 (using membranes), NH_3 (sorbents), and HCl (sodium bicarbonate) to ppb levels

Siemens Westinghouse Power Corporation
- **Gas Technology Institute**

Develop a two-stage process to reduce H_2S, HCl, and particulates to ppb levels

NETL

Gasification

Gasification Technologies Program
Products and By-Products Utilization

Research Triangle Institute

Develop bench-scale demonstration of direct sulfur reduction process

Develop advanced sulfur control concepts for hot gas desulfurization technology (one step process for elemental sulfur)

Praxis Engineering, Inc.
- Fuller Company
- Silbrico, Inc.
- Harvey Concrete Products
- EPRI

Develop methodology to produce lightweight aggregate from coal gasification slag

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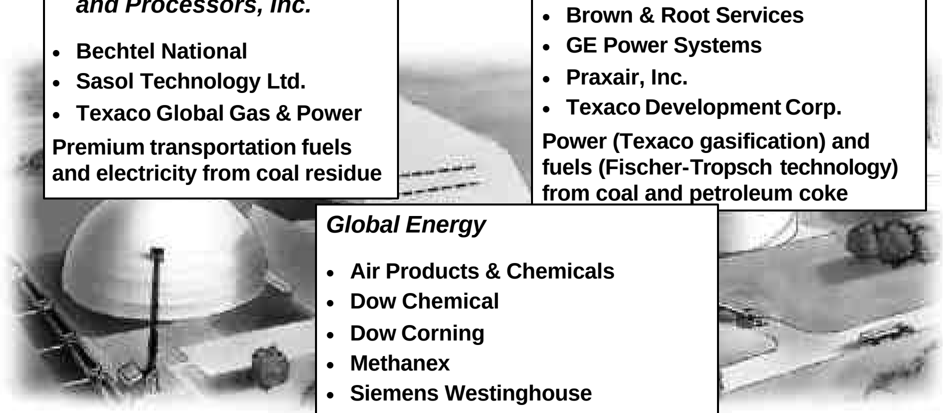
Gasification

Gasification Technologies Program
Co-Production



Waste Management and Processors, Inc.

- **Bechtel National**
- **Sasol Technology Ltd.**
- **Texaco Global Gas & Power**

Premium transportation fuels and electricity from coal residue

Texaco Natural Gas, Inc.

- **Brown & Root Services**
- **GE Power Systems**
- **Praxair, Inc.**
- **Texaco Development Corp.**

Power (Texaco gasification) and fuels (Fischer-Tropsch technology) from coal and petroleum coke

Global Energy

- **Air Products & Chemicals**
- **Dow Chemical**
- **Dow Corning**
- **Methanex**
- **Siemens Westinghouse**

Power and chemicals (liquid phase methanol) at Wabash site in Indiana

NETL

Gasification

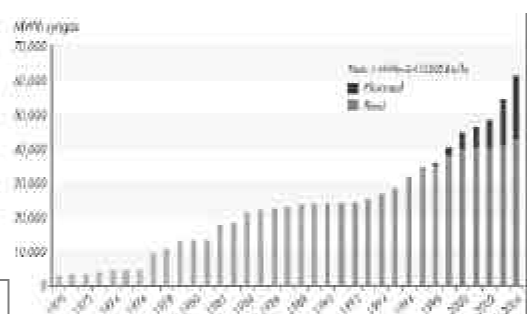
Gasification Technologies Program
Systems Analysis/Technology Integration

Nexant, Inc.

Gasification technologies financial model

Optimization of advanced gasification systems

Process systems analysis



Mitretek Systems

Market potential for gasification applications

SFA Pacific

Database of worldwide gasification projects

Critical needs assessment for future gas cleaning technologies

NETL

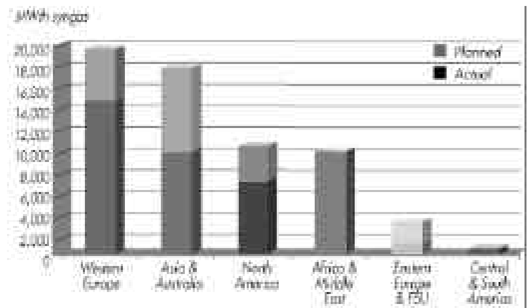
Gasification

Gasification Technologies Program
Systems Analysis/Technology Integration

Site Support

- E²S (SAIC and EG&G)
- CTC (Parsons)

Systems modeling and life cycle analysis of advanced gasification systems



Argonne National Laboratory

Modeling and life cycle analysis of multiproduct gasification-based power generation systems with CO_2 recovery

NETL In-House

Develop computational fluid dynamics models for gasification and cleanup

NETL

Gasification

Conclusions

- **Gasification-based processes expected to be technology-of-choice for future energy plants**
  - Cost competitive
  - Superior environmental performance
  - Market adaptability
- **The government plays an important role**
  - Implement strategic, time-phased R&D to achieve technology goals
  - Partner with government labs, academia, nonprofit institutions, and private industry to perform R&D
  - Provide information to public and private sectors for future decision making that will foster commercialization of gasification technologies

NETL

Gasification

Appendix D

List of General Interview Questions

INTERVIEW QUESTIONS

Gasification Vision

1. What are the strategic business opportunities/markets (domestic and international) that you see now and in the future (2015) for gasification technologies?

2. Has your company considered gasification as an option for specific projects you have evaluated in the last five years? If so, please discuss primary reasons for selection or non-selection of gasification.

3. What factors (technical, environmental, and financial) most limit or enhance the attractiveness of gasification in projects, and what are the key performance requirements now and in the future? (to 2015)

   Efficiency
   Technology Maturity
   Integration
   Reliability/Availability
   Environmental Considerations (including CO_2)
   Capital and Operating Cost
   Return on Investment/Payback
   Financing
   Siting Issues/Regulations
   Other

4. What gasification feedstocks do you consider to be viable now or in the future? What drives this feedstock selection? Would feedstock versatility be an important gasifier attribute in applications you foresee?

5. What do you see to be the most significant hurdles for new gasification technology commercialization?

Environmental

1. What have been the major environmental hurdles for employing gasification systems and what environmental hurdles do you anticipate for gasification systems over the next 15 years?

2. In what ways do you envision gasification technologies as a solution to environmental hurdles?

3. What do you expect to be the basis to calculate emissions/discharge for gasification plants?

4. How do you plan to overcome environmental hurdles, and what assistance can government R&D provide?

Technology R&D Needs

(Technology areas to discuss include: feedstock handling / preparation / feeding, gasification, heat recovery, gas cleaning, gas separation [air, H_2, CO_2], product/by-product handling & utilization)

1. In each of the above areas, what are the key issues and R&D needs to meet future performance requirements/applications?

2. Can you identify specific areas where technology improvements would substantially improve the competitiveness of gasification? Can you identify any specific areas that must be addressed before gasification can be competitive in applications you foresee?

3. What is the timing for technology requirements? Is there a window of opportunity that will be lost if improvements are delayed?

4. What types of government-sponsored facilities would be most beneficial for technology R&D?

Integration Issues

1. Based on your experience with gasification-based systems, what are the integration issues that limit the performance of gasification systems?

2. Based on your vision of future gasification markets and applications, what do you anticipate as integration issues?

3. What new control instrumentation and strategies will be needed for gasification systems?

System Analysis

1. For what purposes do you use systems analysis and models?

2. What new models and information would be valuable to you?

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