Gasification Technologies Program

U.S. DOE's Perspective on Long-Term Market Trends and R&D Needs in Gasification

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Introduction

The U.S. Department of Energy's Office of Fossil Energy and its predecessor organizations have been extensively involved in the development of advanced fossil fuel energy production and conversion technologies for many years. The Office of Coal and Power Systems together with the DOE's National Energy Technology Laboratory focus on developing advanced, clean, affordable fossil-based power and alternative fuels technologies. Enhancing the nation's energy security though the use of its abundant coal resource base while simultaneously protecting the environment and developing near-zero emission, high efficiency feedstock flexible energy plants are key program objectives. The priorities in the program are the development of competitive clean coal technologies, advanced environmental compliance technologies, ultra-high efficiency, feedstock flexible power generation, carbon management, and ultra-clean domestic transportation fuels. A fairly broad range of technologies are included in the program portfolio, including advanced gasification, to address the needs of the existing fleet of power generating units, to pave the way for advanced central and distributed generation facilities, to address greenhouse gas emissions, and to meet the needs of the future transportation market.

Within the Coal and Power Systems program, gasification is viewed as a key technology in the overall portfolio of technologies, especially for achieving the long-term vision of near-zero emissions and feedstock and product flexibility. As such, the gasification program's program funding is $43 million in Fiscal Year 2002, second only to fuel cells. The program focuses in the near term on enhancing the current state-of-the-art of gasification to improve reliability and performance and to expand the opportunities for gasification. In the mid term, the program is geared to reducing costs, improving plant efficiency, expanding market opportunities through feedstock and product flexibility, and reducing emissions, all through the research and development of advanced process concepts. Ultimately, gasification will be the key technology in the transition to a hydrogen-based economy and the capture and sequestration of carbon dioxide.

To ensure that the gasification program continues to address the current and future needs of the gasification community, industry input into the program is extremely valuable. This paper discusses the findings of a series of meetings with key industrial stakeholder to elicit their thoughts and ideas on the future markets, environmental challenges and opportunities, and technology needs for gasification to ensure that gasification is the technology of choice for future

Interview Purpose and Methodology

Beginning in the fall of 2000 through the early spring of 2001, representatives of the Department of Energy (DOE)/National Energy Technology Laboratory's (NETL) Gasification Product Team conducted a series of discussions with industrial teams from organizations representing a wide range of business lines in the U.S. gasification industry. The goal of this endeavor was to elicit the views of industry expert teams on their "vision" for the industry between the present and 2020 and to obtain the opinions from leaders in the industry on what are likely to be critical technology R&D needs both in the short and long term. This effort is intended to: 1) Provide Federal officials and managers a clearer understanding of technology trends and research needs;

2) Assist in establishing Federal funding priorities for gasification and related technologies; and 3) Provide industry decision makers with a broad spectrum of creative and forward-looking insights from industry experts.

The DOE team met with representatives from twenty-two organizations across a broad spectrum of the gasification industry:

Air Liquide	Air Products and Chemicals, Inc.
Allegheny Energy Supply	Bechtel/Nexant, LLC
Citgo/Lyondell-Citgo	Dakota Gasification Company
The Dow Chemical Company	Eastman Chemical Company
Enron	Fluor Daniel
Foster Wheeler	Gas Technology Institute
General Electric Company	Global Energy, Inc.
Praxair, Inc.	Shell Global Solutions
Siemens Westinghouse Power Corporation	Southern Company
Tampa Electric Company	Tennessee Valley Authority
Texaco Global Gas and Power	UOP LLC

The meetings and discussions were arranged 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 ability to discuss frankly and creatively about technology, market, and economic issues affecting the industry. To promote frank and open dialogue, all participants were informed prior to the meetings that any report produced from these meetings would not attribute particular comments or views to specific individuals nor to their companies. The discussions covered a broad range of topics: technology trends and needs, market drivers; “hands-on” experience with a particular process, technology, innovations; plus detailed operations knowledge. In every case, the individuals proved willing to engage in sensitive issues within the confines of the allotted time.

Gasification Markets

The process of estimating future markets for gasification technologies, both domestically and internationally, is quite complicated. Even if an accurate “model” of the myriad factors and interdependencies could be prescribed, forecasting uncertainties inherent to those factors would add 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, resource availability and utilization issues, research and development (R&D) funding availability and prioritization, partnering requirements, and the speed of innovation of competing technologies.

While recognizing the complexities inherent to these and other issues would have a major impact on how a market ultimately matures, the discussions typically focused on more easily discernable micro-economic factors, as well as factors germane to the technology itself such as price and availability of natural gas, feedstock type and availability, risk identification, key performance parameters, and issues affecting project development potential.

Short-Term Markets

In the near term, the gasification market is being driven by a number of discrete factors including economics, feedstocks, regulations, and product integration. Project economics were the most important determinant in short-term and was driven by the price and supply of natural gas. Even at relatively low and stable natural gas prices (i.e., \$2.50/MMBtu), the prospects for new Integrated Gasification Combined Cycle (IGCC) facilities were considered favorable, in certain cases, as a hedge against volatility in future gas prices. The use of biomass as a base-load fuel was not considered viable in the short term, except in niche situations (i.e., pulp and paper) due to technical issues and feedstock availability/transportation logistics and cost.

There was widespread opinion that additional market penetration would result from demonstrated improvements in unit economics and operations over existing technology. Incremental improvements in cost of plant operations and steady improvements in overall plant availability are seen as necessary to enable IGCC technologies to be attractive to power producers. For gasification to be deployed, factors such as process complexity, protracted engineering, procurement, and construction schedules (EPC), high capital and operating costs, and relatively low plant availability must be addressed in the near-term to position the technology for future applications. Although feedstock and product flexibility enhances the attractiveness of gasification, those features alone will not justify its selection at today's high capital cost and perceived risks.

In the United States, the current best fit for gasification is in niche markets such as refinery applications. This is due to the low cost of petroleum coke and other residual materials, the ability to thermally integrate the gasification process into the refinery, and the capability to produce multiple products such as steam, electricity, and hydrogen. Market opportunities also exist in chemical plants where hazardous wastes must be disposed, the synthesis gas can be employed as fundamental building blocks in the production of higher value chemicals, and low-pressure steam is required. Deployment of gasification is expected to continue in Europe because of the shrinking market for high sulfur fuel oil.

For "new" international markets, gasification will be limited to coal for the production of power, ammonia, and other chemicals in China and also India. However, the gasification of high ash coals, while technically doable, is not economically attractive. Although gasification has positive environmental benefits, these benefits will not be exploited because there is no monetized incentive for improved environmental performance in these countries.

Long-Term Markets

For gasification to successfully transition into a long-term commercially viable mainstream technology, the following must occur:

- Overall gasifier performance, especially availability and reliability, must be improved
- Use of gasification as an economically and environmentally superior alternative for the disposition of hazardous wastes must be fully demonstrated

- Investor confidence must be raised through replication of plants and the achievement of cost, schedule, and performance, including guarantees
- Streamlining of the environmental regulatory process is required to entice broader participation in the development of projects
- National grassroots educational program on the benefits of clean coal technology

A significant increase in market activity, both domestically and internationally, is envisaged beyond 2008, contingent upon the success in addressing the above issues. By and large, the industry foresees considerable growth in two primary markets, differentiated by clean power generation and clean energy conversions. For the United States, in particular, there is a likelihood of greater market pull from the national security perspective of using the country's abundant coal resources. Coal to electricity is an attractive long-term economic proposition to developers if high natural gas prices prevail in the future and environmental emissions are further ratcheted down. Today, approximately 50% of the coal used in the United States for electricity production is processed in boilers that are over 25 years old. Such plants have the lowest thermal efficiency and are the largest emitters of pollutants in the existing fleet and are prime targets for repowering applications. Although petroleum coke is the fuel of choice today, the ultimate potential for power generation from petroleum cokes is estimated to be about 50,000 MWe worldwide; therefore power generation must focus on coal in the long-term.

Gasification will continue to be attractive in the long term because of its ability to process multiple feedstocks and to produce multiple products. Other feedstocks include gob, pond fines, biomass, animal wastes, and industrial wastes. For these feedstocks to be considered, their use must not depend on site-specific parameters, but rather be broadly applicable and have significant market potential. Gasification is preferable to combustion for the destruction of hazardous industrial wastes because of the absence of dioxins and furans in the product gas. There are conflicting views about the overall potential of biomass because of high its high costs associated with production and transport and its low energy density. The pulp and paper industry appears to be the best opportunity for biomass gasification. To utilize these alternative feedstocks, a tolerant, flexible, and robust gas purification block is required.

Beyond 2015, the market for hydrogen (H_2) will likely expand based on the commercial implementation of fuel cell technology and other industrial requirements. Depending on natural gas pricing and supply, environmental regulations, and, in particular, the greenhouse gas issue, and the advances in R&D to reduce the costs of H_2 from gasification, the potential exists for the development of a H_2 infrastructure that could have gasification as a pivotal supply technology. The issue of carbon efficiency in the future will make carbon management a key element in the list of decision-making criteria.

Environmental Issues

Environmental Benefits of Gasification

Producing ultra-clean energy from gasification is the most environmentally attractive alternative to utilize solid fuels, including coal. Compared to other power generation technologies, IGCC has an advantage with regard to atmospheric mercury emissions, as well as SO_2 and NO_x, emissions and solid waste generation. Gasification also has a notable advantage in overcoming a significant environmental hurdle to utilizing solid carbonaceous fuels, i.e., controlling CO_2 emissions. If CO_2 controls are mandated in the future, gasification provides a viable and effective way of capturing CO_2 by shifting carbon monoxide to CO_2 prior to the combustion turbine. In addition, due to IGCC's high efficiency, less CO_2 is emitted per unit of electric power produced.

Although gasification's environmental benefits are superior to any other solid fuel technology, many of these benefits are not economically beneficial because current environmental regulations do not provide an associated economic incentive. In some respects, gasification is being held to a higher environmental standard than pulverized coal (PC) plants.

Gasification is proving to be the most effective and efficient means for dealing with various carbonaceous wastes, such as petroleum coke, refinery bottoms, and especially hazardous organic wastes. By converting these wastes into commercially valuable products, such as electricity, fuels, and synthesis gas, and recovering process chemicals, gasification allows one to replace disposal with one of two, more preferable, options in the waste hierarchy, i.e., source reduction or recycling. (Source reduction is the most preferred option for dealing with waste, followed by recycling, then treatment, then disposal.) Gasification could also be employed to help dispose of municipal solid waste that would ordinarily be sent to a landfill.

Relative to toxic compounds, gasification is environmentally superior to combustion for the destruction of wastes. Consequently, it is the technology of choice in cases where combustion cannot meet emissions standards. Unlike incineration, gasification has been proven to not produce dioxins.

Environmental Hurdles to Gasification

Public Misperception: The public's perception that coal and petroleum coke are dirty fuels, along with their perception that emissions from coal gasification plants are equivalent to other coal plants, significantly limits the attractiveness of gasification. Public concerns over dust, smoke, water discharges, and solid waste disposal make siting a gasification plant very difficult. Furthermore, the requirement for IGCC plants to have a hazardous operations design review that addresses emergency releases also has a negative influence on public perception.

Permitting: Navigating through the current myriad of environmental regulations applicable to the development of a gasification project is very costly and time consuming. In some locations, state and local regulations are likely to prohibit the construction of gasification projects. In other locations, such projects are encouraged. But even in favorable locations, the process is multi-year and expensive.

Regulatory Uncertainty: The uncertainty over if, when, and how new environmental regulations and rules will 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/LAER[1] requirements, would hamper efforts to develop gasification over the next decade, perhaps before the technology could prove itself commercially. Compliance with tightening regulations must be done cost effectively, and whether this can be achieved will largely depend on how environmental rules and regulations ultimately play out for NO_X, greenhouse gases, trace contaminants (especially mercury), and solid wastes (ash and slag).

NO_x Emissions The uncertainty of regulatory requirements related to NO_x is a major problem for the industry. Based on what appears to be a fundamental misunderstanding of the differences between IGCC and natural gas combined cycle (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. Although gasification systems can already meet a 9 ppm NO_X emission standard by using state-of-the-art gas turbines, applying the NGCC standard would require NO_X emissions to be reduced to 3 ppm, potentially causing major process problems.

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. greenhouse gas (GHG) regulations as a "wild card." Not surprisingly, there was no strong consensus regarding if, when, or how such regulations would be implemented, and this uncertainty adversely affects business decisions.

One strong consensus about the GHG issue that did emerge from the interviews was 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 swinging away from high carbon fuels towards natural gas. During negotiations for new projects, customers are starting to request the rights to any associated GHG emission 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 is justifiable.

If GHG regulations are issued in the U.S., the extremely high costs of CO_2 removal and sequestration would strongly favor hydrocarbon feedstocks that have higher hydrogen/carbon ratios than petroleum coke or coal. Consequently, if the timing and structure of GHG regulations is poorly conceived, many companies believe that industry would aggressively switch their fuels to natural gas, thereby adversely impacting 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 poor for gasification than for other alternatives. Since gasification systems can shift carbon to CO_2 for pre-combustion removal, 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 could also

[1] Best Available Control Technology (BACT) is required on major new or modified sources in clean areas, i.e., attainment areas. Lowest Achievable Emission Rate (LAER) is required on major new or modified sources in non-attainment areas.

potentially offset their CO_2 emissions by gasifying biomass.

Mercury and Other Trace Contaminants: New regulations may be enacted for trace metal emissions, notably mercury. Depending on their details, such regulations could become an obstacle to gasification and other solid-fuel technologies. Although technologies may be available to comply with trace metal regulations, compliance would increase plant costs.

Mercury regulations are expected to be issued in the near term. If mercury regulations are introduced, IGCC plants would have to capture mercury upstream of the combined cycled plant. Although the sorbent used to capture the mercury would be a hazardous waste, only a small volume would be produced, thus limiting the problem of disposal.

Gasification's advantage in controlling trace contaminants maybe underappreciated. To demonstrate this advantage and also assess the need for emission regulations, the various trace contaminants in a gasification system should be precisely characterized, such as the partitioning of mercury. It is noteworthy that most of the EPA-sanctioned mercury measurement techniques are for oxidizing environments nor is there proven instrumentation. For reducing environments, there are no reliable mercury measurement techniques. A better way to measure the mercury concentration in gasification process streams is needed.

Solid Waste Disposal: Another source of regulatory uncertainty is the EPA's pending decision on whether or not to classify as hazardous waste the synthesis gas and byproducts (i.e., slag) produced by gasifiers that utilize a hazardous waste feedstock from refineries. The proposed rule would provide that carbon-containing hazardous wastes from petroleum refining operations be exempt from Resource Conservation and Recovery Act (RCRA) jurisdiction. In the longer term, not being able to secure permits to gasify certain wastes from other sources could potentially become an obstacle to gasification. The GTC is currently working to have gasification recognized as the preferred technology for waste disposal (over incineration).

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. When gasifying waste materials, attention needs to be paid to the composition of the slag, which may require special treatment. However, since landfill disposal is expected to become an issue in the long run, new ways to economically utilize ash and slag need to be developed.

Water Consumption and Discharge: As the importance of water management issues continue to increase, the consumption and discharge of water will be an environmental hurdle for any new power plant, including gasification plants. New projects will likely face zero water discharge requirements in the future.

Technology Issues/Needs

One of the main focuses of the stakeholder 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: Feedstocks; Gasification; Gas Cleaning; Heat Recovery; Gas Separation;

By-Products; Synthesis Gas Utilization; Integration; System Analyses; Instrumentation and Controls; and Models.

For the gasification as a whole, process reliability was 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 scheduled and achieve 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 could not be tolerated by privately financed commercial projects.

Although single train reliabilities of 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 trains or sparing to ensure reliability targets are achieved, but at a significant cost. The use of multiple trains must be phased out to improve the economic competivitness of gasification. The general consensus is that the reliability for single train plants must be at least 90% for utility applications. For refinery applications, availabilities must be at least 97%. To improve the performance of gasification-based plants, many believe that R&D should focus on standardizing and modularizing the overall process rather than designing new systems for each project. Such an approach would not only allow for lower EPC costs and shorter schedules, but should also prove valuable in improving reliability.

Gasification

There was general agreement that the priority for the gasification should be reducing the capital cost and increasing the reliability of the gasifier island. Feed injectors, refractory liner, and temperature instrumentation were identified as key area requiring further development.

Feed Injectors: Feed injectors are considered to be the weakest links in the process for achieving high on-stream factors. A typical injector is reported to lasts between two to six months; however, a minimum life of twelve months is desired. In order to extend the life of the injector, a comprehensive study should be conducted using Computational Fluid Dynamics (CFD) modeling around the injector to define the factors that lead to failure. New materials and/or coatings for existing materials are needed to provide protection from sulfidation and corrosion at high reactor temperatures. Developments should focus on materials that also lower the manufacturing and refurbishing costs of the injectors. Injector life is also believed to be highly dependent on whether a dry or wet feed system is used. Although the dry feed system may be more difficult to operate at higher pressures, injector life may be better due to the absence of large amounts of evaporating water. There was also an expressed desire to have multi-fuel injectors to accommodate transitioning feedstocks and variable orifice injectors to more rapidly respond to load changes.

Refractory: Refractory liners in high temperature slagging gasifiers are known to undergo significant deterioration over a relatively short period of time. Depending upon the operating temperature of the gasifier and the feedstock, refractory liners are reported to last between 6-18 months. The upper end of this is usually achieved by operating the gasifier at lower than desired temperatures which generally limits to about 95%, thereby reducing process efficiency and simultaneously increasing the carbon level of the slag. The costs associated with rebricking a gasifier include about $1 million for materials and three weeks of down time. This down time, if it occurs more than once per year, establishes an upper bound on plant availability. Instead, an owner would rather replace the lining during their regularly scheduled outages. New materials need to be developed that are less prone to degradation and have an expected useful life of three years or more. Ultimately, however, concepts that completely eliminate the use of refractories would be most beneficial.

Temperature Measurements: Thermocouples used to measure the temperature inside the gasification zone are reported to last about 30-45 days. Failure of the thermocouples is 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 was proposed, but something approaching that of the refractory lining would be worthwhile from a maintenance perspective.

Slag Properties: An improved understanding of the properties and characteristics of the molten slag inside the gasifier was thought to beneficial by some organizations. A better knowledge of flux effectiveness and slag flow properties for solid fed units was of primary concern. New fluxing agents need to be developed that will reduce the ash fusion temperature to below 2,200 ^{o}F. A database that contains coal properties of interest to gasification, such as ash fusion temperature under reducing conditions and gasification reactivity versus temperature, is needed for various coals and various solid fuel blends. For example, when mixing different types of coals, the resulting slag viscosity can be very unpredictable. Databases such as those maintained by the US Geological Survey contain compositional analyses of coals but need to be expanded to include additional properties.

Novel Gasifiers: The ability to process different feedstocks was considered to be a desirable attribute for gasification, especially all ranks of coal. However, such flexibility probably could not be achieved with one gasifier. Instead, gasifiers should be developed to handle classes of feeds and/or employ multiple injectors. New highly efficient concepts for utilizing low energy density feedstocks such as biomass and high ash/high moisture coals are desirable.

While many believe that economies of scale are needed for gasification projects, there was nevertheless surprising interest in the development of small-scale gasifiers, i.e., gasifiers <100 MWe capacity. The interest in small, economical gasifiers centers around the integration advantages that can be achieved in refineries that produce small quantities of petroleum coke, i.e., 500 tons/d, processing of alternative feedstocks such as municipal solid waste (MS), and distributed generation applications utilizing fuel cells.

Synthesis Gas Cleanup

Synthesis gas cleaning, and in particular the control of hazardous air pollutants (HAPs) and trace metals is an area of concern in light of future regulations of emissions. The capital cost of removing particulates and chemical contaminants from the synthesis generally accounts for about 10-12% of the total capital cost of an IGCC plant. Reduced capital cost and improved performance and reliability are desired.

Deep Cleaning of Contaminants: In most plants, amine-based systems are sufficient for removing contaminants such as sulfur to the levels required by environmental permits, provided that the formation of heat stable salts can be minimized or that the salts can be removed. However, amine-based systems are unable to meet the near-zero emission levels envisioned for the future nor are they suitable for preparing the synthesis gas for use in fuel cells or synthesis gas conversion technologies. In these cases, deeper cleaning technologies such as Rectisol must be employed, at a significant increase in capital and operating costs. In short, technologies that can perform comparable to Rectisol in removing contaminants but at an equal or lower cost than conventional amine-based systems are desired.

Cold Gas Cleaning: Opportunities are believed to exist for improving the cost and performance of conventional solvent-based processes, both physical and chemical. Little investment has been made in these technologies for many years to improve their performance. The high carbon monoxide (CO) environment produced by the gasifier promotes the formation of heat-stable salts in the amine-based system which not only enhances corrosion but also limit the ability to recycle the amine. Cost effective technologies that can remove these salts are desirable. To achieve required sulfur emission levels, it is necessary not only to remove H_2S but also the carbonyl sulfide (COS) contained in the gas. Conventional systems require the COS to be shifted to H_2S prior to the cleanup unit. A system that can remove both COS and H_2S simultaneously is believed to be a worthwhile goal. It was also recommended that novel approaches, both wet and dry, be investigated.

Warm Gas Cleaning: Although the temperature range of interest varied somewhat, technologies that operate in the range of 300 to 700 ^oF are preferred. At present, gas turbine inlet temperatures are limited to about 600 ^oF and synthesis gas conversion processes typically range from 450 ^oF to 600 ^oF. Operating at such temperatures would obviate 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. Such technologies must be able to not only reduce sulfur to near-zero levels but also remove mercury, ammonia, and other trace contaminants. There are concerns about the ability of systems operating in this temperature range to remove mercury to potential regulatory levels. If not, then such technologies would have limited utility, i.e., they would only be applicable to feedstocks containing very little or no mercury. The lack of interest in higher temperature technologies (i.e., >900 ^oF) is because mercury removal becomes much more difficult as temperature is increased and there is no compelling reason at this time for operations in such a regime.

Gas Separation

Air Separation*:* The capital cost of a cryogenic air separation unit in a typical IGCC plant typically runs between 12-15% of the total capital cost of the facility and consumes upwards of

10% of the gross power output of the plant, depending upon the oxygen purity required. Most often, oxygen purities range from 95-98%. Although the cost of cryogenic air separation units have continually been reduced over the years (current costs are typically $15/ton), most feel that there are very limited opportunities for further cost reductions. Novel, step-out approaches must be developed to achieve significant improvements in the cost of oxygen.

The development of advanced air separation membranes was viewed as a worthwhile goal because of their potential to not only reduce the capital cost of the air separation unit but also increase the efficiency of the plant through reduced power consumption. Development of the current membranes should be completed before the next generation of membranes is pursued. It is believed that the cost of the membrane systems will be reduced substantially following initial commercialization, much the same as improvements to cryogenic technologies have brought the cost to where they are today. 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, i.e., up to 37% for Model E turbines (and 50% with some nitrogen return) and 20% for Model F turbines. Advanced turbines will likely be able to provide much less air. Air extraction/return is considered a priority area for membrane-based technologies.

Almost no interest was expressed in air-blown systems. The potential for GHG regulations dictates the use of oxygen-blown systems, or at a minimum, oxygen-enriched air. Although some interest was expressed in enriched air technologies, it was considered a lower priority.

Additional technologies for the production of oxygen should be explored that operate between –50 and 350 ^{o}F, a temperature range between cryogenic technologies and the high temperature membrane systems currently being developed (which are believed to have additional advantages).

H_2/CO_2 Separation*:* Prior to the development of new separation approaches, first and foremost is the need to develop and demonstrate technologies for the sequestration and/or utilization of CO_2. If required today, existing technologies such as Rectisol are capable of capturing CO_2; however such applications are expensive and impart a severe energy penalty on the system. The development of technologies for sequestering or utilizing captured CO_2 is viewed as a top priority for which the Government should play a key role. Technologies for CO_2 sequestration need to be demonstrated before CO_2 removal is mandated. The DOE should sponsor fundamental research on "outside-the-box" approaches at universities and national laboratories. Although some industrial organizations are already investing in such research, many other organizations cannot justify cost-sharing in such projects until CO_2 controls are actually mandated.

Hydrogen and CO_2 can be separated directly from the raw synthesis gas or from a shifted synthesis gas containing mostly hydrogen and CO_2. Three options exist. The CO_2 contained in the synthesis gas stream can be collected without any shifting of the CO. This option reduces the amount of CO_2 emitted to the atmosphere, but will not allow for complete capture. The second approach is to separate the H_2 from the CO_2 in a shifted synthesis gas. The H_2 could then be combusted in a gas turbine or used elsewhere such as in refining operations. Finally, H_2 could be separated from the unshifted synthesis gas stream for refining or other applications. This option does not allow for the capture of CO_2 unless oxygen rather than air is fed to the combustion turbine.

In the above options, it is desirable to have all product streams from the separation process at high pressures. Having H_2 at high pressures improves the economics of the process and affords more opportunities for downstream applications. High-pressure CO_2 is desired because it must be further compressed for sequestration applications. Lower costs, more efficient H_2/CO_2 /CO separation technologies that operate at temperatures below 800 ^oF, preferably at ambient temperatures are desired. New approaches to achieve these goals should be pursued. Despite the fact that membranes generally result in low pressure hydrogen, there remained considerable interest in these approaches. To ensure commercial financing of such technologies, the DOE should fund demonstrations of membrane-based systems in the future.

Feedstocks

For the next fifteen years, coal and petroleum-based materials, e.g., petroleum coke, residua, and high sulfur fuel oil, are generally accepted to be the feedstocks of choice for gasification projects. As such, emphasis in the near term should be directed to improving the cost and reliability of feed systems, especially for solid feedstocks. For other feedstocks to be considered in the near term, their use must 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 petroleum coke are generally 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 burners in the gasifier, and thus plant availability.

Feedstock preparation issues focused mainly on the use of low-rank coals and alternative feedstocks such as Municipal Solid Waste (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. New and/or improved approaches to dewatering and densifying these materials will be key to their use in the future. Even after dewatering some materials, problems with feeding have been experienced, especially for fibrous materials such as biomass. 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 must be developed in parallel with the preparation technique.

Feed Systems: The biggest challenges in existing dry and slurry-based feed systems are O&M issues relating to erosion and corrosion of valves, pipes, and pumps. Still, the development of new and/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. Also, systems that feed different solid feedstocks separately and together should be investigated.

Slurry-based Feed Systems: Systems that transport the feedstock into the gasifier via a liquid medium pay 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. Mechanical and safety issues associated with preparing and feeding a CO_2 slurry need to be identified and addressed. Additionally, the impact of high concentrations of CO_2 on the performance of the gasifier and its impact on the gasification reactions themselves need to be investigated.

For slurry-based systems using water, the concentration of coal in the slurry is typically 61-62%. Increasing this concentration to 70% or more is desirable while maintaining the viscosity of the slurry sufficiently low for pumping. Operating with such high concentrations in the feed could result in less expensive feed systems than for dry feed operations that incur high cost for removing moisture from the feedstock. To achieve the higher concentrations new, less-expensive surfactants must be developed that can produce a stable slurry. More durable slurry valves are also needed.

Dry Feed Systems: Because of the thermodynamic penalty inherent in slurry-based systems, many would prefer reliable, cost-effective dry feed systems. Currently, only lock-hopper technology is employed to transfer the feedstock across the pressure boundary. Some believe that work should be performed to improve these systems, including the feeding of very fine coal, <150 microns, as well as developing new approaches. The solid to gas ratio in such systems must be kept as high as possible. R&D should also focus on dry feed systems that use synthesis gas or air as the transport medium.

By-Products

Ash/Slag: As the number of gasification plants continues to increase, the disposition of the ash and slag will become increasingly more important. New markets and ways of utilizing the ash/slag from gasifiers need to be developed since 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 would be 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 incomplete gasification. The carbon content must be reduced to ≤ 5 wt.% for it to be marketable. Such material can be used for road construction, while slag containing ≤ 2 wt% carbon can be used for sandblasting sand. 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. New test methods will have to be developed for each application to ensure that that the public will not be harmed by the use of these materials. Also, it needs to be determined whether the specifications for certain markets could be relaxed some to accommodate the high moisture and carbon content of the slag

R&D is also needed to beneficiate the ash/slag to reduce its carbon and moisture content and to reduce the size of the particles. The cost of grinding and classifying the ash/slag must be reduced to a level sufficiently lower than the market value of the resulting product. Opportunities may also exist for extracting certain components from the slag. For petroleum coke-derived slag, the recovery of nickel and vanadium is already being considered. Recovery of components from the slag that detracts from its value, such as lead, may also be an attractive alternative.

The solid by-products generated during the gasification of waste materials, either alone or in combination with coal, may have different properties that could potentially impact its marketability. Characterization of the solids produced from such operations will be needed to determine if the solid properties are sufficiently different to affect the marketability of the material.

Sulfur: On average, approximately four million tons/year of sulfur are produced from a 300 MWe IGCC plant. There is a growing concern that more and more gasification facilities are constructed and operated, especially those processing petroleum coke and high-sulfur coals, the production of high grade sulfur will eventually exceed demand. The level of IGCC capacity at which the market becomes saturated and sulfur no longer generates a revenue stream needs to be determined. New markets and ways to utilize sulfur need to be developed. It was reported that the Canadians are already working on this issue. It was also mentioned that sulfur is now used to make concrete for highly corrosive environments and that the U.S. Department of Transportation has developed roadbed material containing sulfur.

There was some mention of potential improvements to sulfur recovery units. One of those involved 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.

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. Such long-term, high risk R&D is what the government should be pursuing.

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, and in particular the advanced gas turbines. Currently, there is no long-term strategic path for accomplishing synthesis gas testing and systems integration for these machines. 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 keeping gas turbine development in sync with developments in the gasification industry. Continuation of the ATS program is desired with focus on synthesis gas applications as well as other DOE programs that would encourage gas turbine manufacturers to design turbines that can burn synthesis gas. In addition, the fuel handling system and the range of gas turbine nozzle performance must be expanded 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.

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, problems have been encountered that may be due to the quality of the synthesis gas feed. There is a need to characterize the deposition, corrosion, and erosion that results from feeding synthesis gas to a gas turbine. Different gas turbines models may perform differently on the same fuel, obviating the need for separate specifications for each machine. Focus of the work should include delamination, spalling, embrittlement, and deterioration of thermal barrier coatings.

There is a desire on the part of the industry to further reduce emissions in anticipation of future NO_x regulations. To achieve NO_x emission levels of 3-5 ppmvd, new combustion technologies must be developed such as dry low-NO_x burners for low Btu gas. The development of catalytic synthesis gas combustion is another possible route to achieve these ultra-low NO_x emission levels. New low-NO_x combustor designs could change the design of the entire gasification system, including the gasifier and air separation unit, since the plant is designed around the gas turbine.

<u>Fuel Cells:</u> Integration fuel cells with gasification offers the potential to achieve very high thermal efficiencies compared to gasification combined cycle technology, even when employing advanced turbines such as the H-turbine. The major hurdle to deployment of the technology is the cost of the fuel cell which must be drastically reduced from today's costs. Another key process issue surrounding the use of fuel cells is the requirement on the quality of the synthesis gas. However, the integration of gasification and fuel cells could occur within the next ten to fifteen years.

Design Standardization and Modularization

The modularization of process units and standardization of designs will greatly benefit the commercialization of gasification. Currently, each new gasification plant is a special design based on the requirements of the customer. Engineering costs for these facilities are high. 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 will also reduce construction costs. However, because the number of projects is too few and the market is dominated by a few technology suppliers, there is little incentive for industry itself to invest in any approach to provide "product line" designs that could significantly improve the technology.

A study should be performed that would design a modular, standardized IGCC plant that is optimized for a niche of the power market into which many such standardized/modularized plants could be sold. The size of such plants would be based on that which could reasonably deployed at many utility sites but sufficiently small as not to be overly burdensome to the customer. A market analysis should be conducted to help determine the size of a standardize plant. A market growth strategy should be pursued to repower a portion (say 20-25%) of existing power plant capacity with standardized plant designs. Once experience is gained with one unit at the utility, parallel trains could be easily deployed to increase capacity. Such a study should start from a “clean sheet of paper” without imposing any equipment constraints. It was felt that such an approach would allow for value engineering concepts to be employed that would ultimately reduce the capital cost and improve the performance of the system for the customer. This approach should result in reduced foot print of the plant (a 20% reduction is targeted) and also increase customer confidence that construction and startup will proceed according to the proposed schedule and without any undue surprises.

Informational Databases

Sources of information on gasification system design and performance appears to be, at best, very minimal. The development of databases from which the industry can utilize in the development of projects is sorely needed. It appears that there is considerable concern that designers are not aware of past mistakes and that important learning experience benefits are being lost. Several suggestions to remedy this problem were proposed:

Knowledge Management System: 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. 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 that many of the technical issues that are encountered in such projects are adequately addressed to prevent repetition. An industry-wide “knowledge management system” should be developed that would enable companies to avoid common problems by sharing non-proprietary information. Such a system could include a database of reliability statistics for existing gasification plants that would help in the design of future plants as well as improving current operations, and historical costs and availability of subcomponents in a gasification plant that would help to provide a better understanding of component availability and reliability. The system would have to be a “living” interactive knowledge exchange systems in which users would have to input information in exchange for extracting information. The reluctance from some companies to share such information will make the collection of information difficult and its usefulness limited. Information in such a database would have to be sanitized to prevent linking information to a particular plant. The DOE, the GTC, and the EPRI could serve as brokers for such a system, and the beginnings should initially concentrate on the DOE-funded projects to prove the value of such an undertaking

Feedstock Performance: To speed the design process, more data are needed on feedstock quality versus gasification system characteristics. A database, similar to the Coal Data Book, that lists the chemical and physical properties, reactivity and gasification characteristics of various gasification feedstocks should be prepared. A database that contains coal properties of interest to gasification, such as ash fusion temperature under reducing conditions and gasification reactivity versus temperature, is needed for various coals and various solid fuel blends. Databases such as those maintained by the US Geological Survey contain compositional analyses of coals but need to be expanded to include additional properties. Such a database could be employed in conjunction with on-line feedstock analysis to instantaneously control the operation of the gasifier.

Operation and Maintenance Problems: There is a need for the industry to address generic operation and maintenance problem 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. There is a need to answer question such as: What effect does coal composition have on how its slurry will erode and corrode pipes and valves? What is the optimal pH of a slurry to minimize or prevent pipe erosion and corrosion? What materials of construction should be used in specific applications?

Instrumentation and Controls

The ability to reliably measure a variety of process parameters and the composition and properties of various process streams and efficiently control the process is considered a high priority. Instrumentation and advanced control systems are considered key areas to further the advancement of gasification. High priority areas are given below:

1. An affordable on-line analytical device that that can provide the elemental composition (i.e., C, H, S, and inorganics) of the gasifier feedstock is needed, especially in those situations where the composition is constantly varying, when feeding a heterogeneous feedstock such as MSW, or in co-feed applications.

2. On-line feed analysis (composition, heating value, ash fusion temperature) to allow better control and optimized operation of the gasifier as fuel properties change and to guard against unforeseen changes in the feed’s slag viscosity

3. On-line instrumentation to measure flow rates to both dry and slurry-fed gasifiers, including measurement of feed density.

4. On-line analysis of slag viscosity and instrumentation to measure the thickness of the slag layer on the refractory would help to improve slag removal

5. On-line instrumentation to track the wear on the refractory liner would help to plan outages for replacement

6. On-line product gas analysis to determine the gas composition, including trace components such as mercury, arsenic, carbonyls, halides, sulfides, volatile metals, and other hazardous air pollutants, particularly in a reducing environment.

7. Isokinetic particulate measurement for process design and design verification (either inside the gasifier, which is preferable, or in the cool, raw synthesis gas)

Summary

This paper provides a preliminary report on the information obtained from a series of meetings with key stakeholders in the gasification industry. This information will be presented in a comprehensive report that will be sent to all participants and posted on the internet at www.netl.doe.gov/coalpower/gasification. This report is expected to be available shortly.

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

Based on the preliminary results, the Gasification Technologies Product Team plans to initiate two new efforts in FY 2002. Since gasifier reliability was identified as the key factor limiting commercialization, the DOE has issued a solicitation to focus on approaches/technologies that will enhance the performance and reliability of gasifiers to meet the industry's needs. Multiple awards are expected to be made this summer.

Because many of the ideas expressed by the participants could involve fundamental research applicable to the gasification industry as a whole, DOE is exploring the possibility of establishing a research consortium focusing on fundamental technology needs having broad applicability to the gasification industry. The Gasification Technologies Research Consortium would feature an industry management council that suggests R&D areas for investigation and makes recommendations on project selection and continuation. As technologies are developed and become of interest for specific applications, the DOE would entertain specific industry-led projects via a separate procurement mechanism to further develop and demonstrate the technology for a particular application of interest. This effort is currently on hold pending guidance for implementation from management.

In addition to the above, the DOE has recently issued a solicitation for cooperative, cost-shared projects between the government and industry to demonstrate emerging technologies for coal-based applications and to accelerate technology deployment. This solicitation represents the first installment of federal funding for a ten year, $2 billion program. This solicitation is open to any technology that results in advancements to the state-of-the-art in efficiency, environmental emissions, and economics.

We invite all interested organizations to participate in these and future solicitations.

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