DOE'S FINE PARTICULATE AND AIR TOXICS RESEARCH PROGRAM: RESPONDING TO THE ENVIRONMENTAL CHALLENGES TO COAL-BASED POWER PRODUCTION IN THE 21ST CENTURY

Thomas J. Feeley, III
U.S. Department of Energy
Federal Energy Technology Center
P.O. Box 10940
Pittsburgh, PA 15236

KEYWORDS

Fine particulate matter, air toxics, coal-based power production

ABSTRACT

In response to the many environmental challenges facing clean, efficient coal-based power production, the U.S. Department of Energy's Federal Energy Technology Center (DOE-FETC) is sponsoring research directed at the characterization and control of ambient fine particulate matter and air toxics. This focused, highly leveraged program encompasses ambient sampling and analysis, atmospheric chemistry and pollutant formation and transport studies, source emissions characterization, and control technology development. The goal of the DOE-FETC research is to provide a sound scientific and technology basis for future regulatory decision making related to ambient air quality and emissions from coal-fired power systems. This paper will present a summary of the research that DOE-FETC is currently sponsoring in the areas of fine particulates and air toxics.

BACKGROUND

The U.S. electric-utility industry has made considerable strides in reducing emissions of sulfur dioxide (SO_2), nitrogen oxide (NOx), and particulate matter (PM) since the passage of the 1970 Clean Air Act (CAA) and its subsequent amendments[1]. These declines in emissions are made even more dramatic in light of the fact that during the period from 1970 to the present there has been a greater than 150 percent increase in coal consumed to produce electricity. However, despite these successes, emissions of SO_2, NOx, and PM from coal-fired power plants continue to be targeted for further restrictions in reaction to ambient fine particulates, visibility impairment (i.e., regional haze), and air toxics.

Several regulatory drivers are in place or have been proposed that could potentially lead to a call for further reductions in emissions of both primary and secondary fine PM and air toxics from coal-fired boilers. Arguably the most significant of these are the new ambient air quality standards and regional haze requirements. Under Title I of the 1990 CAA amendments, the U.S. Environmental Protection Agency (EPA) promulgated National Ambient Air Quality Standards (NAAQS) in July 1997 to address PM with an aerodynamic diameter of 2.5 micrometers or less ($PM_{2.5}$). The new $PM_{2.5}$ standard is designed to protect human health from the chronic and acute effects associated with the respiration of fine PM.

In July 1999, a regional haze rule was announced to improve visibility in national parks and wilderness areas of the United States[2]. The rule calls for states to establish goals for improving visihility and to develop long-term strategies for reducing emissions of air pollutants that cause visibility impairment. Since coal-fired boilers may contribute to ambient fine PM and regional haze, these regulations and requirements could result in further controls on power plants.

Particulate emissions from coal-fired boilers may also be impacted by future regulatory action under Title III of the 1990 CAA amendments. Title III requires EPA to implement regulatory standards for 189 air toxics, or hazardous air pollutants (HAPs). EPA has established a goal of reducing air toxic emissions by 75% from 1993 levels to reduce the risk of cancer and other adverse health effects associated with these toxic pollutants. To this end, EPA has recently proposed an air toxics program that would include the measurement of ambient concentrations of air toxics at monitoring sites throughout the nation to determine the need for further control measures[3]. Should a link between human health and emissions of air toxics from coal-fired boilers be found, a call for additional reductions would be likely.

In addition to Title III, the Toxic Release Inventory (TRI) requirements of the Emergency Planning and Community Right-to-Know Act of 1986 (EPCRA) may also have potential ramifications on particulate and gaseous emissions from coal-fired power plants. TRI is a public database maintained by EPA on releases of toxic substances from various industries. Electric utilities began reporting for the first time under TRI on July 1, 1999. Although TRI is a reporting requirement, the public's reaction to the information provided could trigger further restrictions on emissions.

In response to these environmental challenges to coal-based power production, the U.S. Department of Energy's Federal Energy Technology Center (DOE-FETC) is carrying out a focused, highly leveraged research program. This program includes ambient air quality monitoring and sample analysis, atmospheric chemistry and pollutant formation and transport studies, source emissions characterization, and cost-effective control technology development. Where opportunities for synergism exist, other ambient air quality issues, such as ground-level ozone and mercury, and the impact of fine particulate matter on climate change, are being addressed.

DISCUSSION

DOE-FETC's Research Program

The goal of the DOE-FETC PM/air toxics research program is to help ensure that a sound scientific and technology knowledge base exists for future regulatory decision making related to ambient air quality and emissions from coal-fired power systems. To achieve this goal, the program has three specific objectives:

X To characterize the chemical and physical composition of ambient fine PM, air toxics (e.g., mercury), and precursor gases;

X To characterize the emission of primary and secondary fine particulates from coal-based power systems and to investigate the atmospheric formation and transport mechanisms associated with fine PM and the interactions between secondary fine particulate and precursor gases; and

X To develop and evaluate technologies to cost-effectively control primary PM and associated trace metals, secondary fine particulate precursors, and acid gases.

Ambient Sampling and Analysis

The implementation of the $PM_{2.5}$ standard requires the collection and analysis of data from a nationwide ambient monitoring network. The majority of these monitoring sites are for compliance purposes. However, a significant subset will be used to collect detailed information on the physical and chemical properties of the collected samples. In support of this effort, DOE-FETC is collaborating with EPA, local and state agencies, and industry in the operation of a number of ambient PM/air toxics monitoring stations. These sites are equipped with a variety of instrumentation necessary for the collection and analysis of the chemical, size, and time-resolved characteristics of aerosol, gas-phase, and biological PM. The data obtained from these sites will be used to apportion sources, evaluate emission inventories and air quality models, measure trends, assess diurnal, seasonal, and annual variations in ambient fine-particulate and air toxics composition, support epidemiological and human-exposure studies, and evaluate regional haze impacts. In addition, the sites serve as research platforms for field testing emerging ambient fine particulate monitoring equipment.

The following is a brief description of the projects being carried out in this area:

- Upper Ohio River Valley Project – This represents the largest component of the DOE-FETC ambient monitoring program. This effort involves the collection and analysis of data from five ambient fine particulate/air toxics monitoring sites in southeastern Ohio, northwestern West Virginia, and southwestern Pennsylvania. One of the sites is also part of the Mercury Deposition Network. The overall objective of the UORVP is to better understand the relationship between emission sources and air quality in the upper Ohio River Valley region. Collaborators include EPA, state environmental agencies, and EPRI.

- Great Smoky Mountain National Park - Under an Interagency Agreement with the Tennessee Valley Authority, ambient monitoring sites are being operated to investigate the impact of coal-fired boilers on visibility in the GSMNP. Collaborators include EPRI and the State of Tennessee

- Aerosol Research Inhalation Epidemiology Study – As part of the TVA Interagency Agreement, air quality measurements are being performed at an urban monitoring site in Atlanta, Georgia. This effort also supports a concurrent epidemiological study. The Atlanta site is part of the EPA-sponsored $PM_{2.5}$ "supersites" program. EPRI, TVA, Southern Company, and several other electric utilities are co-sponsoring the project.

- Big Bend Regional Aerosol and Visibility Observational Study - The BRAVO study will collect atmospheric and ambient air quality data to help identify the U.S. and Mexico emission sources responsible for the haze in the Big Bend National Park in Texas. Participants in this project include EPA, U.S. and Mexican electric-power industry representatives, PROFEPA, Mexico's environmental enforcement agency, the Texas Natural Resource Conservation Commission, and the U.S. National Oceanic and Atmospheric Administration.

- Healy Clean Coal Project - Ambient monitoring is being performed as part of the Healy (Alaska) Clean Coal Technology project to ensure that the project does not impact visibility in the adjacent Denali National Park and Preserve National Park and Preserve (DNPP).

Emissions Characterization and Plume/Atmospheric Studies

The combustion of coal produces primary PM and the precursors to secondary aerosols. Key to apportioning ambient $PM_{2.5}$ and air toxics is a well-defined source-emissions inventory. This component of the DOE-FETC fine particulate program is directed at the characterization of emissions from coal-based power systems. In addition, the program includes an investigation of the formation and atmospheric transport of fine PM and air toxics. The following is brief summary of the projects being carried out in this area:

- Cumberland Plume Study – As part of the TVA Interagency Agreement, fine PM formation in the plume of the Cumberland Fossil Plant is being investigated to assess the impact of the installation of SO_2 and NOx control technology. Primary and secondary PM data will be gathered at various distances downwind from the plant. TVA and EPRI are co-funding this effort.

- Fine PM Characterization - McDermott Technology (Babcock & Wilcox) is characterizing primary PM and associated trace metal emissions from their 10 MW_e Clean Environment Development Facility. The focus of the project is on the impact of Low-NOx burners on the emission of ultra-fine carbon soot. Collaborators include the Ohio Coal Development Office.

Control Technology Development

To varying degrees, the sulfate, nitrate, carbon, and trace element composition of ambient fine PM can be attributed to coal. The combustion of coal may also lead to the formation of acid gases that can create localized visibility concerns and are a major consideration relative to reporting TRI. Therefore, a critical component of the FETC particulate matter/air toxics program is the development of cost-effective control technology should further restrictions be placed on emissions from coal-based power systems.

The DOE-FETC research portfolio includes advanced technology for capturing: (1) primary fine particulates and associated trace metals (e.g., lead, mercury, arsenic, etc.); (2) secondary $PM_{2.5}$ precursors; and (3) acid gases (e.g., H_2SO_4, HF, and HCl). These efforts will be closely allied to the ambient and source sampling and characterization activities to ensure that the control technology research focuses on the pollutants of most concern. A summary of each of these technical areas is presented below.

Primary Fine PM Control

- Advanced Hybrid Particulate Collector - The University of North Dakota Energy & Environmental Research Center will continue development of the Advanced Hybrid Particulate Collector (AHPC) technology in order to obtain necessary engineering data for scale-up to full-scale demonstration size. The AHPC optimizes the combination of electrostatic separation and collection with fabric filtration.

- *ElectroCore*™ Separation Technology - LSR will demonstrate at pilot scale (1.5 MW_e) its *ElectroCore*™ fine particle separation technology on a slipstream at the Alabama Power Company Gaston Steam Plant.

- Flue Gas Conditioning - ADA Environmental Solutions will develop and commercialize a family of non-toxic flue gas conditioning agents to improve the capture of PM at coal-fired generating units.

Secondary Fine PM Precursor Control

- Ultra Low-NOx Burner - ABB Combustion Engineering is developing an Ultra-Low NOx Integrated System that will involve an aggressively air staged, in-furnace NOx reduction system, building upon ABB C-E's TFS 2000™ system. Improvements to be investigated include milling system enhancements, low NOx oxidizing pyrolysis burners, selective non-catalytic reduction, high velocity over fire air, neural net controls, and the recovery/reuse of unburned carbon.

- Ultra Low-NOx Burner - McDermott Technology, Babcock & Wilcox, and Fuel Tech are teaming to provide an integrated solution for NOx control comprised of an ultra Low-NOx pulverized coal burner technology (B&W's DRB-4Z™) plus urea-based, selective non-catalytic reduction system (Fuel Tech's NOxOUT®).

- METHANE de-NOx® - The Institute of Gas Technology will develop a PC combustion system that is an extension of IGT's METHANE de-NOx® technology. Specifically, the technology is composed of a novel PC burner design using natural gas fired coal preheating developed and demonstrated in Russia, low-NOx burner with internal combustion staging, and additional natural gas injection with overfire air.

- Low-NOx Combustion Optimization - Reaction Engineering International will optimize the performance of, and reduce the technical risks associated with, the combined application of low-NOx firing systems and post combustion controls through modeling, bench-scale testing, and field verification. This will include the evaluation of real-time monitoring equipment to evaluate water-wall wastage, soot formation, and burner stoichiometry, demonstrating analysis techniques to improve LNFS in combination with reburning/SNCR, assessing selective catalytic reduction catalyst life, and developing UBC/flyash separation processes.

- Oxygen Enhanced NOx Reduction - Praxair will develop and demonstrate oxygen enhanced combustion and oxygen enhanced secondary control technologies for controlling NOx, as well as a novel oxygen separation process.

Acid Gas Control

- In-Furnace Control of Acid Gases - Radian is teaming with EPRI, FirstEnergy, the Tennessee Valley Authority, and Dravo Lime Company to demonstrate in-furnace control of sulfur trioxide (SO_3)/sulfuric acid, HCl, and HF emissions. Specifically, Radian will investigate the injection of four different alkaline chemicals into the upper furnace of three different full-scale boilers.

SUMMARY

The DOE-FETC is carrying out a collaborative, highly leveraged research program that will provide timely, high-quality technical and scientific data addressing key uncertainties, such as source-receptor relationships, fine-particle composition, and human-exposure and visibility impacts, associated with $PM_{2.5}$ and air toxic emissions from coal-fired power plants. The program also includes concurrent research directed at the characterization of emissions from coal combustion, the study of plume and atmospheric processes, and the development of cost-effective control technology should further restrictions be placed on the emission of primary particulates (and associated HAPs) or secondary fine particulate precursors. The results from this program will serve to help develop, as needed, effective management strategies that target the appropriate emission sources. Moreover, it will help to further ensure that coal-based electric power generation can remain a viable, environmentally sound, component of the U.S. energy mix well into the 21st Century.

For further information on the DOE/FETC PM/Air Toxics Research Program, please visit our website at www.fetc.doe.gov/products/power/enviro/pm25/index.html.

REFERENCES

1. U.S. Environmental Protection Agency, "National Air Pollutant Emission Trends, 1900-1996," EPA-454/R-97-011, December 1997.

2. U.S. Environmental Protection Agency, "National Air Toxics Program: Integrated Urban Air Toxics Strategy; Notice," **Federal Register**, July 19, 1999 (Volume 64, Number 137).

3. U.S. Environmental Protection Agency, "Regional Haze Regulations, Final Rule," **Federal Register**, 40 CFR Part 51, July 1, 1999.

The principal technologies for producing syngas from natural gas feed are summarized and compared on Table 1. The predominant commercial technology for syngas generation has been, and continues to be, steam methane reforming (SMR), in which methane and steam are catalytically and endothermically converted to hydrogen and carbon monoxide. An alternative approach is partial oxidation, the exothermic, non-catalytic reaction of methane and oxygen to produce a syngas mixture. SMR and partial oxidation inherently produce syngas mixtures having appreciably different compositions. In particular, SMR produces a syngas having a much higher H_2/CO ratio. This, of course, represents a distinct advantage for SMR in hydrogen-production applications and, in large measure, accounts for its overall dominance among syngas production technologies to date.

Table 1
Comparison of Syngas Generation Technologies
(Natural Gas Feed)

Technology	Advantages	Disadvantages
SMR	• Most extensive industrial experience • Oxygen not required • Lowest process temperature requirement • Best H_2/CO ratio for hydrogen production applications	• H_2/CO ratio often higher than required when CO also is to be produced • Highest air emissions
Heat Exchange Reforming	• Compact overall size and "footprint" • Application flexibility offers additional options for providing incremental capacity	• Limited commercial experience • In some configurations, must be used in tandem with another syngas generation technology
Two-step reforming[1]	• Size of SMR is reduced • Low methane slip favors high purity syngas applications • Syngas methane content can be tailored by adjusting secondary reformer outlet temperature	• Increased process complexity • Higher process temperature than SMR • Usually requires oxygen
ATR	• Natural H_2/CO ratio often is favorable • Lower process temperature requirement than POX • Low methane slip • Syngas methane content can be tailored by adjusting reformer outlet temperature	• Limited commercial experience • Usually requires oxygen
POX	• Feedstock desulfurization not required. • Absence of catalyst permits carbon formation and, therefore operation without steam, significantly lowering syngas CO_2 content • Low methane slip • Low natural H_2/CO ratio is an advantage for applications requiring ratio < 2.0	• Low natural H_2/CO ratio is a disadvantage for applications requiring ratio > 2.0. • Very high process operating temperatures • Usually requires oxygen • High temperature heat recovery and soot formation/handling adds process complexity • Syngas methane content is inherently low and not easily modified to meet downstream processing requirements

[1] SMR followed by oxygen-blown secondary reforming

Source: Reference 2 and SFA Pacific, Inc.

As shown in Table 2, the product syngas composition from either process can, within limits, be manipulated by altering various process conditions and/or by means of additional process steps. Nonetheless, even with such manipulation; neither SMR nor partial oxidation is ideally suited to GTL applications. This is due to the fact that F-T synthesis calls for a H_2/CO ratio of about 2, a value higher than that achievable with partial oxidation and lower than that obtainable with SMR.

A solution to this dilemma is to use both technologies. For example, partial oxidation and SMR may be used in parallel to produce syngas streams that have differing compositions but, when mixed, form a total F-T feedstock of the desired composition. An alternative to this approach is autothermal reforming (ATR), which combines partial oxidation with catalytic steam reforming in one reactor. The process is "autothermal" in that the endothermic reforming reactions proceed with the assistance of the internal combustion (or oxidation) of a portion of the feed hydrocarbons -- in contrast to the external combustion of fuel characteristic of conventional tubular reforming.

Table 2
Techniques for Adjusting Syngas H_2/CO Ratios

	Decreases Ratio	Increases Ratio
Recycle CO_2	X	
Import CO_2	X	
Remove H_2 via Membrane	X	
Remove CO_2		X
Increase Steam		X
Add Shift Converter		X

Approximate variation in H_2/CO ratio for natural gas feed:

	SMR	Two-Step Reforming[1]	ATR	POX
Import CO_2 *OR* Remove H_2 via Membrane	<3.0	<2.5	<1.6	<1.6
Total CO_2 Recycle[2]	3.0	2.5	1.6	1.6
No CO_2 Recycle[2]	5.0	4.0	2.65	1.8
Increase Steam	>5.0	>4.0	>2.65	>1.8
Add Shift Converter	∞	>5.0	>3.0	>2.0

[1] *SMR followed by oxygen-blown secondary reforming*
[2] Shaded figures show range of "natural" H_2/CO ratios.

Source: Reference 2 and SFA Pacific, Inc.

ATR properly refers to a stand-alone, single-step process for feedstock conversion to syngas. However, the same basic idea can be applied to reactors fed by partially reformed gases from a primary reformer. Such reactors form a subcategory of ATR that is commonly called secondary reforming. Due to feed composition differences -- in particular, the lower concentration of combustibles in secondary reformer feeds -- ATR reactors and secondary reformers have different thermal and soot-forming characteristics that require different burner and reactor designs. Nonetheless, the distinction between ATR and secondary reforming is not consistently drawn by technology users and vendors, with the result that secondary reformers often are referred to as ATRs. As will be discussed further, most commercial experience with autothermal reforming has, in fact, involved secondary reformers -- most notably, oxygen-blown units for methanol production and air-blown units for ammonia production.

Much of the forward-looking consideration of syngas production for GTL has focused on ATR. In part, this is due to the technology's basic compatibility with F-T feed chemistry requirements. However, this focus also reflects the perception that ATR has other attributes -- relative compactness, lower capital cost, and greater potential for economies of scale -- which will contribute significantly to the economic viability of GTL plants.

Ongoing efforts to develop lower-cost syngas generation technologies include the following:

- The development and application of "compact reformers" and of "heat exchange reformers," in which a portion of the heat of reaction is provided by heat recovery from the reformed gas, rather than by burning fuel. Potential advantages over conventional tubular reactors include improved efficiency, smaller plant footprint, lower capital cost, and reduced emissions. Companies active in this area have included Air Products, KTI, ICI, BP/Kvaerner, Kellogg, Haldor Topsoe, Krupp Uhde, and Lurgi.

- Development and application of air-blown autothermal reformer technology, thereby eliminating the need for an oxygen plant. (Air-blown secondary reforming is well-established, being commonly utilized for syngas production for ammonia plants.) The chief proponent of the air-blown approach is Syntroleum.

- New reformer reactor approaches, most notably that employed by Exxon's AGC-21 process for converting natural gas to liquids. The first step in this process is syngas generation via oxygen-blown catalytic autothermal reforming in a fluidized bed reactor. The process has been demonstrated at large pilot scale -- about 200 b/d.

- "Ceramic membrane reactors," based on the use of ionic or oxygen transport membranes, which would couple air separation and partial oxidation in one unit operation, thereby eliminating the need for a conventional oxygen plant. Although being aggressively pursued by two industrial consortia, work in this area is still at a fundamental level. One consortium, led by Air Products, is being co-funded by the U.S. Department of Energy. The participants in this effort include ARCO, Babcock & Wilcox, Chevron, Norsk Hydro and others. The second consortia, based entirely on industrial funding, involves Amoco, BP, Praxair, Statoil, Phillips Petroleum and Sasol.

Large-Scale Syngas Generation For GTL – Relevant Commercial Experience

Commercial experience relevant to large-scale syngas generation for GTL plants may be derived principally from two areas -- (1) prior and existing F-T synthesis facilities and (2) large-scale methanol plants.

Methanol plants are relevant, in part, because they require a syngas composition similar to that required for F-T synthesis. Moreover, world-scale methanol plants have become increasingly large. Single-train methanol plants already are producing more than 2,500 mtpd of methanol, and even larger plants, approaching 3,000 mtpd, have been announced. In syngas terms, a 20,000 b/d F-T plant would be comparable to three 2,500 mtpd methanol plants. Accordingly, syngas generation in the largest methanol plants may be considered to be on a scale analogous to that required for a multiple-train F-T facility of appreciable size.

Another aspect of syngas generation in methanol plants that is relevant to GTL is the fact that methanol plants consistently have been cited as logical applications for ATR. The general rationale is that while SMR can offer good economics at small-to-moderate scale, tubular reformers do not offer significant economies of scale as single-train methanol plant capacities increase. As a result, two-step reforming and, ultimately, ATR should become the technologies of choice for larger plants. This conclusion is premised on the more favorable economies of scale offered by ATR and secondary reformer reactors and, especially, by ever-larger air separation plants. According to rules-of-thumb publicly offered by Haldor Topsoe and Lurgi, for example, two-step reforming is economically preferred over SMR for methanol plant capacities above about 1,500 mtpd, with ATR becoming the economic choice for capacities above 2,500-3,000 mtpd.

In practice, oxygen-blown ATR has yet to see application in a large-scale methanol plant, although oxygen-blown secondary reformers have seen operation in a limited number of plants, sucb as the 2,400 mtpd Conoco/Statoil methanol plant, of Haldor Topsoe design, that started up in Norway in 1997. This plant, which also contains a prereformer upstream of the SMR, is said to be operating well.

Interestingly, a number of large methanol plants recently built or announced -- such as those by Methanex for Chile and Qatar -- have been based on SMR, despite capacities approaching 3,000 mtpd. According to ICI, their Leading Concept Methanol (LCM) process, which employs heat exchange reforming followed by oxygen-blown secondary reforming, may be considered for the second of three 2,950 mtpd plants announced by Methanex for construction/startup in Qatar by 2006. Application of the LCM technology has thus far been limited to a small (165 mtpd) plant in Australia.

Other relevant syngas generation experience comes from Shell's F-T operation in Bintulu, Malaysia and from the operations of Mossgas and Sasol in South Africa. The 12,500 b/d Shell plant employs partial oxidation of natural gas for its primary syngas generation. A small SMR is operated in parallel with four partial oxidation reactors to provide a secondary syngas stream for adjusting the overall syngas composition. Idled by an explosion in the air separation area last year, the plant is expected to resume operation in 2000. The restarted facility will boast a 3,200 air separation facility, larger than the original plant's, to accommodate increased F-T synthesis capacity made possible by improved catalysts. [3]

The 20,000 b/d Mossgas plant consists of three trains, each equivalent (in syngas terms) to a 2,500 mtpd methanol plant. Started up in 1992, the plant utilizes Lurgi's two-step reforming process -- i.e., SMR followed by oxygen-blown secondary reforming. A unique feature of the Lurgi process is the bypassing of a portion of the natural gas feed around the SMR to the secondary reformer. Lurgi also provided two-step reforming technology for a grass roots methanol facility in Malaysia which started up in 1984. Operating experience, some of which has been documented by Lurgi and Mossgas, has included some problems with burner operation and life and with metal dusting. [4, 5]

Since the Sasol F-T operation in South Africa is coal-based, its primary syngas generation is not directly relevant to the natural gas-based plants now being considered for GTL. However, Sasol also has operated 16 oxygen-blown ATRs of Lurgi design since 1982. These units operate on recycle methane and have now been retrofitted with burner technology provided by Haldor Topsoe. [6] Although small -- each unit is about 1/10 the capacity required for a 20,000 b/d F-T plant -- these units represent the largest oxygen-blown ATRs to have been commercially operated to date.

Development of two bellwether F-T projects -- a 20,000 b/d facility by Chevron and Sasol in Nigeria and a plant of like capacity by Phillips and Sasol in Qatar -- reportedly is proceeding on the basis of using ATR technology provided by Haldor Topsoe, which (along with Chevron) now has a commercial arrangement with Sasol for providing process technology for GTL plants. Viewed in the context of the limited commercial experiencc previously summarized, such commercial application of ATR represents a considerable extrapolation and scale-up of prior technology.

It appears that considerable confidence is being placed in advances in the engineering tools now available for designing autothermal reforming burners and reactors. Both Lurgi and Haldor Topsoe claim to now have rigorous computer models to facilitate the scale-up and design of oxygen-blown ATRs. [7, 8] ICI claim a similar capability with respect to their oxygen-blown secondary reformers. By way of contrast, the design and scale-up of the prior Malaysian and Mossgas secondary reformers relied heavily on empiricism and engineering judgment.

Air-Blown vs. Oxygen-Blown Autothermal Reforming

The importance of syngas production to overall GTL costs is vividly illustrated in Table 3, which shows the cost distribution for a facility that is based on the use of oxygen-blown ATR. As shown, GTL costs are dominated by capital charges, which comprise about two-thirds of the total costs. Syngas production, in turn, accounts for about half of the capital investment, in part due to the significant capital cost of the oxygen plant.

Not surprisingly, the oxygen plant investment has been an attractive target of GTL cost-cutting strategies. This target has spawned both long-term strategies -- e.g., the previously mentioned ceramic membrane reactor -- and short-term strategies -- e.g., air-blown ATR. It remains to be seen how successful ceramic membrane reactor development will be. However, SFA Pacific sees no apparent advantage that would favor air-blown over oxygen-blown systems.

Indeed, air-blown reforming technology is unlikely to be economically competitive with oxygen-blown systems and appears much less flexible. Factors which more than negate the savings associated with elimination of the oxygen plant include: lower thermal efficiency, high air compression power requirements, the inability (because of its composition) to recycle F-T tail gas, and the larger downstream equipment sizes and pressure drop associated with handling the much larger volumetric flow of gas. Questions also remain about the potential for forming ammonia and other nitrogen compounds in the downstream F-T conversion units.

Table 3
Estimated Cost Of Fischer-Tropsch Liquid

Manufacturing cost (% of total)	
Natural gas @ $0.50/Mscf	14.9
Operating labor	1.8
Other operating costs[1]	19.2
Capital charges @ 20%/yr[2]	64.1
Total	100.0

[1] Includes catalysts, cooling water, process water, plant maintenance, overhead, property taxes and insurance.
[2] A capital charge of 20%/yr (simple 5-year payout) is equal to about a 12% DCF rate of return under the current U.S. tax structure.

Capital Cost Distribution[1]	
Plant Section	**% of Total Capital Cost[2]**
Oxygen Plant	23
Reforming[3]	28
Fischer-Tropsch Synthesis[3]	24
Product Upgrade	13
Power Recovery	12
Total	**100**

[1] Basis: 20,000 bbl/day liquid product
[2] Exclusive of port and other general facilities
[3] Including allocated portion of heat exchange cost

Source: SFA Pacific, Inc.

Also problematic with air-blown operation is the low heating value of the F-T tail gas. From an economic standpoint, utilizing this tail gas to generate power for export sale is a potentially key contributor to the overall viability of the GTL plant. However, combustion turbine technology and commercial experience with the use of such low quality gas remains quite limited.

Outlook

Although not yet confirmed by new, large-scale, commercial F-T plants, there is good reason to believe that proposed and future GTL facilities will be substantially less costly than their very expensive predecessors. In large measure, such cost reductions will be attributable to improvements in F-T catalyst and reactor design, the most significant of which have been pioneered by Sasol.

At the same time, in the absence of a breakthrough technology, economy of scale will be the only significant mechanism by which GTL can achieve greater economic viability. To be sure, additional evolutionary cost reductions due to further reactor scale-up, catalyst development and the "learning curve" benefits of repetitive plant design will materialize. However, even with such further cost reductions, the economic viability of GTL plants will remain confined to special situations until crude price levels rise substantially.

How does syngas generation fit into this picture? In the near term, prospects for reduced syngas generation cost would appear to lie with the application of ATR proposed for Qatar and Nigeria. In addition to providing a landmark demonstration of the technology's commercial readiness, these projects will help confirm its projected investment and operating cost benefits.

However, while large-scale ATR may in some sense be considered a commercial technology breakthrough, it is likely that many economic analyses of GTL already have taken credit for its assumed benefits. If so, the cost reduction potential of ATR already has been discounted, and further reductions in syngas generation cost via ATR already may be confined to less dramatic, evolutionary improvements in the technology, particularly since additional economies of scale appear to be limited. The 20,000 b/d Qatar and Nigeria projects are each proceeding on the basis of two, 10,000 b/d trains. Haldor Topsoe, Lurgi and others have variously pegged the largest ATR reactor size as that consistent with producing 5,000 to 10,000 mtpd methanol -- equivalent in syngas terms to about 13,000 - 26,000 b/d of F-T liquids. Accordingly, further dramatic cost reductions may require the application of still newer reforming technologies. One such development to watch is Exxon's oxidation-blown, fluidized bed ATR, which could offer increased potential for economies of scale.

As discussed, considerable resources are being devoted to the development of the ceramic membrane reactor, with a goal of operating a sizable scale demonstration facility in 5-7 years and reducing GTL investment costs by 20%. If realized, these ambitious goals, which face formidable technical barriers, could legitimately make GTL economically viable at crude prices below $20/b.

References

1. "Hydrogen and Synthesis Gas: Technology, Economics, and Market Outlook," a private multiclient-sponsored analysis, SFA Pacific, Inc., January, 1998.

2. Tindall, B. and Crews, A. (Howe-Baker Engineers), "Natural Gas Reforming Technologies," Gas-to-Liquids Processing: Bringing Clean Fuels to Market, San Antonio, TX, March 18-20, 1998.

3. Mackor, F. and Bruder, O. (Air Liquide) and de Graaf, J.D. (Shell International Oil Products B.V.), "The Bintulu Project," Energy Frontiers International members conference, Gas Conversion Projects, Technologies & Strategies, San Francisco, CA, October 7-9, 1998.

4. Shaw, G. and de Wet, H. (Mossgas) and Hohmann, F. (Lurgi), "Commissioning of the World's Largest Oxygen Blown Secondary Reformers," AIChE Ammonia Safety Symposium, Vancouver, BC, October 3-6, 1994.

5. de Wet, H., Minnie, R.O. and Davids, A.J. (Mossgas Pty Ltd.), "Post-Commissioning Operating Experience at the Mossgas Reforming Plant," AIChE Ammonia Safety Symposium, San Francisco, CA, September 22-25, 1997.

6. Marriott, J. (Sasol Limited), "Implementation of the Sasol Slurry Phase Distillate Process," Energy Frontiers International members conference, Gas Conversion Projects, Technologies & Strategies, San Francisco, CA, October 7-9, 1998.

7. Gronemann, V. (Lurgi Öl Gas Chemie GmbH) and Wechsler, A.T. (Lurgi Corp.), "New Developments in Syngas Production," Energy Frontiers International members conference, Gas Conversion Projects, Technologies & Strategies, San Francisco, CA, October 7-9, 1998.

8. Newland, R. (Haldor Topsoe A/S), "New Developments in Syngas Production," Energy Frontiers International members conference, Gas Conversion Projects, Technologies & Strategies, San Francisco, CA, October 7-9, 1998.