DEVELOPMENT OF BIOMASS GASIFICATION SYSTEMS FOR GAS TURBINE COGENERATION IN THE CANE SUGAR INDUSTRY*

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ABSTRACT

The steam-injected gas turbine fired with gasified biomass is a promising cogeneration technology for the cane sugar industry. The prospects for its near-term commercialization are good. The required development and demonstration effort is modest, since it would build on the extensive previous work on coal gasifiers for gas turbines and pressurized biomass gasifiers for methanol synthesis. To prepare for a commercial biomass-gasifier gas-turbine demonstration, pilot-scale testing is needed of the most promising gasifier/hot-gas cleanup systems with bagasse and cane trash as fuels.

1. INTRODUCTION

The use of advanced cogeneration systems based on steam-injected gas turbines using gasified sugarcane residues for fuel would permit sugar and/or alcohol producers in Brazil and elsewhere to significantly raise revenues by exporting large quantities of electricity in excess of onsite needs, as discussed in a companion paper.[1] Improving the efficiency of energy use in the factory would help maximize the production of exportable electricity.[2]

In a biomass gasifier steam-injected gas turbine (GSTIG) system, cane residues would be gasified in a pressurized air-blown reactor, and the product gas would be cleaned of particulates at elevated temperature before being burned in the gas turbine combustor (Fig. 1). Hot gas cleanup would be used rather than wet scrubbing to avoid efficiency and cost penalties. Pressurized gasification would avoid losses associated with compressing the fuel gas after gasification. Air gasification would be dictated by the high cost of oxygen plants in the sizes required for sugar-industry and most other biomass applications.

In a more advanced gasifier-gas turbine system an intercooled steam-injected gas turbine (ISTIG)[1] would be substituted for the simple steam-injected gas turbine (STIG), but would be similar in other respects to the system shown in Fig. 1.

Neither the biomass-GSTIG nor GISTIG are commercially available today. STIG units fired with natural gas are used commercially in both cogeneration and central station applications, and the commercialization of natural gas-fired ISTIGs is being actively discussed by potential vendors and users.[1] However, biomass gasification systems are not available for gas turbines. In this paper we discuss the requirements and status of biomass gasification systems for gas turbine applications and the prospects for a near-term demonstration of the GSTIG technology,[1] which would be needed before the technology could be considered for commercial use in the sugar industry.

2. GASIFIER SYSTEMS FOR GAS TURBINES

Gasification of biomass has been successfully used previously in a variety of applications, including industrial heating, internal combustion (IC) engines, and methanol synthesis. The technical specifications for gas derived from biomass (particulate loading, tar content, heating value, etc.) are quite different for gas turbine applications than for these end-uses,[3] so a gasification development effort focussed on gas turbine applications is needed. There have been no previous significant efforts of this type. However, considerable efforts have been devoted to coal gasification for gas turbines in the USA, West Germany, and elsewhere.[4,5] While much of the coal work is also relevant for biomass, key differences between coal and biomass necessitate a focussed development effort on biomass. Biomass has a higher volatile content (75-85% versus 30-40%), making it much easier to gasify. It is typically less dense, which affects handling, feeding, and gasification. And it contains little or no sulfur, which eliminates the need for the sulfur removal required with coal.

2.1 Gasifier Designs

Candidate gasifier designs for biomass-gas turbine applications are the fixed-bed (also called moving-bed), updraft gasifier and the fluidized-bed gasifier.

In a fixed-bed updraft gasifier, combustion of biomass char occurs on a grate near the bottom of the reactor, where air is injected (Fig. 2a). Temperatures are highest at this point in the reactor (1000-1200°C), where steam is also injected to keep ash from melting. The combustion products cool as they travel up through the fuel bed. The fuel is pyrolyzed as it travels in counterflow to the gas, arriving as char at the grate. The product gas would be extracted from the reactor at 500-600°C to insure that its large tar/oil

[1] The prospects for demonstrating the GSTIG technology in the near term are better than those for the GISTIG, because natural gas-fired STIGs are already commercially available, while ISTIGs are not. If natural gas-fired ISTIGs are developed, a successful GSTIG demonstration could lead to rapid subsequent commercialization of GISTIG technology.

component is in vapor form.[2] The gas exits with relatively low particulate concentrations because of low exit velocities and the filtering effect of the fuel bed. Hot gas efficiency,[3] the efficiency measure of interest for GSTIG cycles, is typically high (90-95%) because of the high peak temperatures, the volatility of biomass, and the efficient (counter-current) heat transfer from the gas to the fuel bed.

In a fluidized-bed gasifier, the feedstock is "fluidized" with an inert heat-distributing material, e.g. sand, by air injected from below. The bubbling bed (Fig. 2b) was the first fluidized-bed design developed. The circulating fluidized bed (CFB) (Fig. 2b,lower) has been developed more recently. Control of air injection rates and excellent mixing in fluidized-bed gasifiers leads to uniform temperatures throughout the bed (Fig. 2b) and faster reactions than in fixed beds. Fuel throughput capabilities per unit volume are, therefore, much higher for fluidized-beds than for fixed-beds, leading to lower unit costs for fluid-bed reactors. Peak reaction temperatures are relatively low (700-800°C), which prevents ash melting without the need for the cooling steam required with a fixed-bed.[4] Higher average temperatures than in a fixed-bed (Fig. 2) contribute to less production of tars and oils. Hot gas efficiency is comparable to that for a fixed-bed. Particulate loading in the raw gas is one to two orders of magnitude greater.

2.2 Feedstock Considerations

The fundamentally different operating principles of fixed and fluidized-bed gasifiers lead to distinctly different feedstock requirements. Since most biomass feedstocks are similar in chemical composition,[3] differences in feedstock specifications relate primarily to physical characteristics.

For fixed-bed gasifiers, relatively large, dense, and uniformly-sized feedstocks are preferable to help prevent bridging, reduce feed losses, and reduce carryover (Table 1). Some designs have rotating agitators to assist the fuel flow. Feedstocks with as high as 50% mc (moisture content)[5] can be gasified, but the minimum acceptable gas heating value for gas turbines (about 4 MJ/Nm^3)[7] sets an upper limit of about 30% on the acceptable feedstock moisture content. This will usually mean some pre-drying of the fuel would be

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[2] In a GSTIG system using hot gas cleanup and "close-coupling" of the gasifier and gas turbine combustor, tars and oils, which condense between 150 and 500°C,[6] would not have an opportunity to condense. Thus, potential problems arising from condensed tars are avoided. Close-coupled arrangements have been incorporated into designs for advanced coal-gasifier gas turbine systems.[7,8]

[3] Hot gas efficiency is defined as the chemical plus sensible energy in the raw gas divided by the total energy input (chemical plus sensible) to the gasifier.

[4] Thus, more process steam could be supplied, e.g. for processing cane with a fluidized-bed/GSTIG than with a fixed-bed/GSTIG. Only the latter is considered references 1 and 2.

[5] Moisture contents are given on a wet basis in this paper.

needed. Most agricultural residues, including bagasse and cane trash, would also require some densification.

Fluidized-bed gasifiers can accept much smaller, less dense, and less uniformly-sized feedstocks than fixed-beds (Table 1). The minimum acceptable bulk density for fluid beds is much lower than for fixed-beds, though is not well established.[9] Requirements for fuel handling and feeding will most likely set the lower limit. Fuel moisture considerations are the same as those for fixed-beds. The range of acceptable feedstock characteristics is greater with circulating fluidized beds than with bubbling beds (Table 1). Most of the feedstocks listed in Table 1, including minimally processed agricultural residues like bagasse, would probably be acceptable fuels after drying.

2.3 Technology Status

A number of biomass gasifiers are of potential interest for use in GSTIG systems. The major activities worldwide relating to pressurized biomass gasification are summarized in Table 2. The table also describes three particularly noteworthy commercialized atmospheric-pressure gasifiers.

Because of their simplicity and high efficiency updraft gasifiers are widely used commercially with both coal (pressurized and unpressurized units) and biomass (atmospheric-pressure units). The pressurized Lurgi dry-ash gasifier has the longest commercial operating experience (dating to the 1930s) of any pressurized gasifier with coal and has been considered for coal-gasifier STIG and ISTIG systems.[7] The Lurgi-type gasifier also appears to be a good candidate for biomass applications. Successful, but limited, pilot-scale testing of a pressurized Lurgi-type unit has been carried out by the General Electric Company (GE) in the United States using biomass pellets[10] and RDF/coal briquettes[11] (Table 2). More extensive testing would be required to demonstrate the feasibility of operating on bagasse and cane trash.

Fluidized-beds also appear to be good candidates for gas turbine applications. A major coal-gasifier gas turbine demonstration project in the USA will utilize a KRW fluidized-bed gasifier,[8] and a similar project for the city of Berlin that would utilize a circulating fluidized-bed gasifier is under study by the Lurgi Corporation.[12] A 25-bar, coal-fueled Rheinbraun-Uhde HTW pilot plant for gas turbine applications is scheduled for start up in West Germany in late 1989.[13] Development of fluid-beds for biomass-gas turbines could build on such efforts and on the extensive previous development efforts on large-scale pressurized biomass gasification for methanol synthesis.[3] Of the units described in Table 2, the most extensive development and testing has been done with the Rheinbraun/Uhde HTW, Biosyn, IGT and MINO units. Of these, only the Rheinbraun/Uhde unit has significant commercial operating experience: a 13.5-bar, peat-fueled unit began commercial operation in May 1988 at an ammonia production plant in Finland.

Also noteworthy is the commercial availability of three atmospheric-pressure CFB gasifiers (Table 2). One manufacturer of CFB gasifiers, Ahlstrom, has announced plans to startup a 10 MW^{fuel} pressurized CFB combustor in the spring of 1989 to demonstrate the feasibility of CFB combustion plus hot-gas cleanup for direct firing of gas turbines with solid fuels.[14] Since CFB gasifiers are similar to CFB combustors in many respects, if this demonstration is successful, it would be an important step toward development of a CFB gasifier/gas cleanup system for gas turbines.

3. PROSPECTS FOR COMMERCIAL DEVELOPMENT OF GSTIG TECHNOLOGY

Because much of the previous coal and biomass-related hardware development efforts are also relevant to biomass gasifier-gas turbine systems, the near term development of the GSTIG technology for commercial applications in the cane sugar industry is a distinct possibility. In fact, only a relatively modest development-demonstration effort would probably be sufficient to resolve technical and economic uncertainties. The most important of these relate to hot gas cleanup, expected capital costs, and pre-gasification processing requirements for bagasse and cane trash.

3.1 Hot Gas Cleanup

Cleaning of raw gas from the gasifier would be required to avoid damage to turbine blades and to meet emissions regulations in many countries. Pilot-scale testing with biomass feedstocks would be needed to determine the levels of cleanup required and appropriate cleanup technologies. A limited amount of work has already been done on pressurized hot cleanup of biomass gas, for methanol production[15] and more recently for direct firing of gas turbines using pressurized combustion.[16,17] Extensive work has been done on hot cleanup for coal-gasifier gas-turbines[18-21] and for directly-fired gas turbines using pressurized-fluidized-bed combustors (PFBC).[22] Much of the coal-based work is relevant for biomass, but cleaning biomass gases is simpler, since most biomass gas does not require sulfur removal.

Particulate cleanup would require particular attention in a biomass gasification development effort, since the size and quantity of particulates varies substantially with the type of feedstock and design of gasifier. Two technologies are usually considered for hot particulate removal.

Cyclones are commercially proven and relatively inexpensive. In pilot-scale tests using GE's pressurized Lurgi-type fixed-bed gasifier cyclones provided adequate cleanup of coal-derived gas (Fig. 3). Limited data on fixed-bed (atmospheric-pressure) biomass gasification indicate production of a larger fraction of submicron particles than with coal gasification.[6] Pilot-scale pressurized biomass gasification testing is needed to determine whether cyclones would provide adequate particulate removal for gas turbines. Such testing could be undertaken in the GE gasifier or a comparable existing facility.

The larger number of particles from fluidized-bed biomass gasifiers would probably require the use of more efficient particle removal technology. Barrier filters provide more complete filtration than cyclones, but have not yet been commercially proven for gas turbines. For coal-gas cleanup, the emphasis has been on silicon-carbide candle filters,[23] which would also work with biomass. Sintered metal-alloy filters also appear promising for biomass.[15] The key technical issues to resolve in a demonstration effort would be the ability of such filters to withstand thermal and mechanical shock and to maintain effective seals in gas turbine systems. Demonstration projects using ceramic candle filters in the USA[8] and Finland[14,16] are addressing these issues, among others.

3.2 Capital Costs

A detailed engineering/cost study, followed by a commercial-scale (20-MW) demonstration would be required to accurately determine the captial cost of biomass gasifier-gas turbine systems. However, estimates of likely capital costs can be obtained from detailed engineering/cost studies of coal gasifier-gas turbine systems. Table 3 gives capital cost estimates for a 100-MW coal-gasifier STIG ($1300/kW) and 109-MW ISTIG ($1040/kW), both of which would use fixed-bed Lurgi-type gasifiers, cyclones for hot particulate removal, and hot sulfur-removal systems. A 100-MW coal-fired fluidized-bed gasifier-ISTIG, based on a KRW gasifier with in-bed sulfur removal and ceramic candle filters for particulate cleanup, has been estimated to have roughly the same installed cost as the fixed-bed ISTIG ($1010/kW, Table 3).

With biomass, sulfur removal would not be required, which would eliminate 15-20% of the capital cost from that for a fixed-bed coal system. Also, the greater ease with which biomass can be gasified means less harsh reactor conditions are required than with coal, which would further reduce costs. For a 53-MW fixed-bed biomass gasifier-STIG, the installed capital cost has been estimated to be in the range of $1000-$1100/kW.[1] For a 20-MW_e plant, the cost is estimated to be about $1300/kW,[1] reflecting the relatively weak scale economies inherent in gas turbine technology. Based on the coal fixed-bed/fluid-bed cost comparison (Table 3), a biomass fluid-bed GSTIG plant would have a capital cost comparable to that for a biomass fixed-bed GSTIG.

3.3 Feedstock Pre-Processing

Because of wide variations in the physical properties of various biomass feedstocks, particular feedstocks of interest would need to be tested in pressurized gasifiers to determine the feasibility of using them in gas turbine systems. Such testing could be undertaken at relatively modest cost at one or more of the existing biomass gasification facilities (Table 2). Wet feedstocks would require drying to at least 30% mc. For fluidized-bed gasifiers, little additional processing would probably be needed. With fixed-bed gasifiers some degree of densification would likely be required with sugarcane residues.

Determining fuel processing requirements would be important since the required level would significantly affect the economics of cogeneration at a sugar factory. Since cane residues can have other uses than energy (pulp-mill feedstock, cattle feed, etc.), their opportunity value must also be considered.[6] The effect of fuel processing level on lifecyle costs of producing exportable electricity from a sugar factory are shown in Fig. 4 as a function of the opportunity value of the fuel for 20-MW_e and 53-MW_e GSTIG units. (The two sizes correspond to sugar factory throughputs of 70 and 180 tc/hr.) The calculations assume that fuel for the fixed-bed gasifiers requires drying plus briquetting (lower-cost line) or pelletizing (higher-cost line). For the fluidized-bed gasifiers drying or briquetting is assumed. For comparison the estimated costs of new coal or hydroelectric central station power are also shown.

Fixed-bed and fluidized-bed GSTIG cogeneration systems would produce power competitively with central station alternatives over a wide range of opportunity values, even at the 20-MW_e scale. For a given opportunity value, the range of electricity costs shown for fluidized-bed gasifiers is narrow, reflecting the relatively small incremental cost of briquetting compared to drying. Fixed-bed GSTIG systems would have economics comparable to those for the fluid-bed systems if fixed-bed operation requires only briquetting. If pelletizing is needed, however, the economics of the fluidized-bed systems would be substantially more attractive.

4. CONCLUSION

Biomass-gasifier STIG or ISTIG systems fueled by bagasse and cane trash appear to be attractive technologies for the cane processing industries. The development and demonstration of appropriate gasification systems would be required to commercialize the GSTIG technology. It appears that only a relatively modest effort would be required to accomplish this, since the effort could build on extensive previous development work on coal-gasification systems for gas turbines and pressurizied biomass gasification for methanol production.

Fixed-bed and fluidized-bed gasifiers are potential candidates for biomass-GSTIG applications. Advantages of fixed-bed units include their simpler operation, extensive commercial experience operating at high pressure (with coal), and potentially simpler gas cleanup (i.e., cyclones may be sufficient). Pressurized fluidized-beds have less commercial operating experience, are more complex, and may present more challenging gas cleanup (i.e., barrier filters are likely to be required). Fluidized-beds can more easily accommodate bagasse and cane trash as fuel, but if briquetting provides an adequate fuel for fixed-beds, the overall economics of fixed and fluidized-bed systems would be comparable.

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[6] The opportunity value of the feedstock is defined here as the difference between what the cane processor could sell it for and the cost of collecting and processing it for gasification.

Because of the potential operational advantages of fixed-bed systems, the development of the GSTIG technology should probably focus initially on this option. Low-cost pilot-scale testing could be undertaken in the GE Lurgi-type gasifier or at a comparable existing facility to determine whether briquettes are an adequate fuel and whether cyclones provide adequate particulate cleanup. With successful testing, the development work could proceed directly to a demonstration, perhaps at the 20-MW_e scale, to prove commercial viability. A unit of this size could be built adjacent a large, efficient exisiting cane processing facility and use surplus bagasse for fuel. Such a demonstration effort would probably cost $40-50 million.[24] No significant scale-up work would be required beyond this, since 20-MW_e represents a commercial size for sugar-industry and many other applications.

Table 1. Required biomass feedstock characteristics for alternative gasifier designs and properties of actual biomass feedstocks.[a]

GASIFIER FEEDSTOCK REQUIREMENTS:

	Fixed-bed	*Fluidized-bed*	
	Updraft	*Bubbling*	*Circulating*
Length (mm)	13-75	0-50	0-100
Max. thickness (mm)	6-13	0-3	0-50
Size variability	small	large	larger
Moisture (wt%)[b]	< 30%	< 30%	< 30%
Bulk density (kg/m^3)	> 240	(c)	(c)

ACTUAL FEEDSTOCK PROPERTIES:

	Length (mm)	*Thickness* (mm)	*Bulk density*[d] (kg/m^3)
Wood chips			
Hardwood	16-22	1.5-3	280-480
Softwood	16-22	3-6	200-340
Sawmill residues	max. size < 50 mm		290-400
Biomass pellets	6-19	6-19 (diam.)	610
Non-woody biomass			
Pits (cherry, olive, etc.)			360
Straw (baled)			160-300
Bagasse			160
Rice hulls			130
Shells (walnut, coconut, etc.)			64

(a) From reference 3.

(b) Fuel moisture level to produce raw gas of suitable quality for gas turbines. The moisture level at which gasification can be sustained is about 50%.

(c) The minimum acceptable bulk density for stable operation of fluid beds is much lower than for fixed beds. Fuel handling and feeding considerations are likely to set the lower limit.

(d) Bulk densities vary with moisture content. For wood chips, the range given here is for 15 to 50% mc. Bulk densities for mill wastes (hog fuels) vary widely. The indicated range is for 50% mc samples. Pellets and non-woody biomass have 10-15% mc, except the figure for bagasse, which is for 50% mc. The baled straw range is for standard and "double compressed" bales.

Table 2. Gasifiers that have operated with biomass feedstocks.[a]

	Status[b]	*Capacity (t/h)*	*Pressure (bars)*	*Blast*[b]	*Tested feedstocks*
PRESSURIZED FIXED-BED					
Lurgi-type (USA)	P[c]	2	21	A/S	Wood pellets, RDF briquettes
Syn-Gas Downdraft (USA)	P	2	10	A,O	Wood chips, wood pellets, corn cobs, peat pellets
Wright-Malta Kiln (USA)	P	0.2	21	S	Wood chips, municipal solid waste
PRESSURIZED FLUIDIZED-BED					
Rheinbraun -Uhde HTW (FRG)	D C	3 27	10 13.5	A/S O/S	Wood chips, peat Peat
ASCAB (France)	D	5	25	O/S	Wood chips
Biosyn (Canada)	C D	6 10	8 14	A A,O	Wood chips Bark, sawdust, wood pellets
IGT Renugas (USA)	P	1	34	A/S, O/S	Wood chips, corn stover, pulp mill wastes
MINO (Sweden)	P	0.5	28	O/S	Wood chips, peat, lignite
Tech. Res. Center (Finland)	L	0.09	10	A	Peat pellets
COMMERCIAL ATMOSPHERIC-PRESSURE FLUIDIZED-BED					
Lurgi CFB (FRG)	C	16	1	A	Bark, wood wastes
Gotaverken CFB (Sweden)	C	8	1	A	Bark, sawdust, wood wastes
Ahlstrom CFB (Finland)	C	8	1	A	Wood waste, peat

(a) See reference 3 for additional details.

(b) C = commercial, D = demonstration, P = pilot, L = laboratory, A = air, O = oxygen, S = steam.

(c) Large-scale pressurized Lurgi gasifiers for coal have been in commercial operation since the 1930s. However, only pilot-scale testing has been done with biomass.

Table 3. Capital cost estimates (1987 $/kW$_e$) for coal-gasifier STIG and ISTIG power plants based on General Electric LM-5000 gas turbines and either Lurgi fixed-bed or KRW fluidized-bed gasifiers.[a]

	Lurgi/STIG[b]	*Lurgi/ISTIG*[b]	*KRW/ISTIG*[c]
Coal handling/preparation	41.5	38.4	
Blast air system	14.0	10.1	
Gasification plant	168.5	87.0	
Raw gas physical cleanup	9.1	8.0	
Raw gas chemical cleanup	183.3	158.0	
Gas turbine/HRSG	308.3	268.5	
Balance of plant			
Mechanical	42.0	34.6	
Electrical	68.1	50.7	
Civil	68.6	63.6	
SUBTOTAL, PROCESS CAPITAL	**903.4**	**718.9**	**698**
Engineering home office	90.2	71.9	
Process contingency	56.0	44.4	
Project contingency	157.4	125.2	
SUBTOTAL, PLANT COST	**1207.6**	**960.4**	**932**
AFDC cost	21.8	17.3	
SUBTOTAL, PLANT INVESTMENT	**1229.4**	**977.7**	**949**
Preproduction costs	33.7	27.5	
Inventory capital	32.8	27.7	
Initial chemicals	2.6	2.4	
Land	1.5	1.4	
TOTAL CAPITAL REQUIREMENT	**1300.0**	**1036.7**	**1007**

(a) The USA gross national product deflator has been used to convert all costs to mid-1987 dollars. All cost estimates shown here were prepared using consistent costing procedures developed by the Electric Power Research Institute in the USA.

(b) The Lurgi/STIG and Lurgi/ISTIG plant sizes are 2x50-MW$_e$ and 1x109-MW$_e$ capacity, respectively. Each involves use of a single gasifier. From reference 7.

(c) The KRW/ISTIG cost was developed for a nominal 100-MW$_e$ unit using the ISTIG and a single KRW gasifier.[26] The more detailed cost breakdown was not publically available at the time of this writing. See also reference 21.

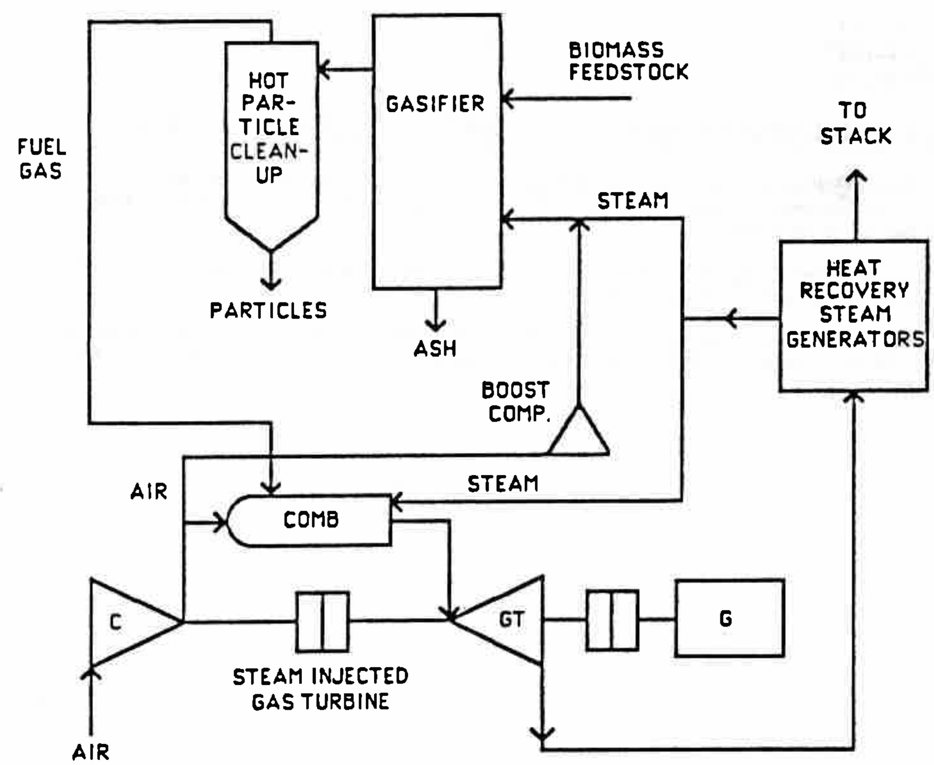

Fig. 1. A biomass-gasifier steam-injected gas turbine (GSTIG) cycle, which includes a pressurized gasifier, hot particulate cleanup, and a steam-injected gas turbine.

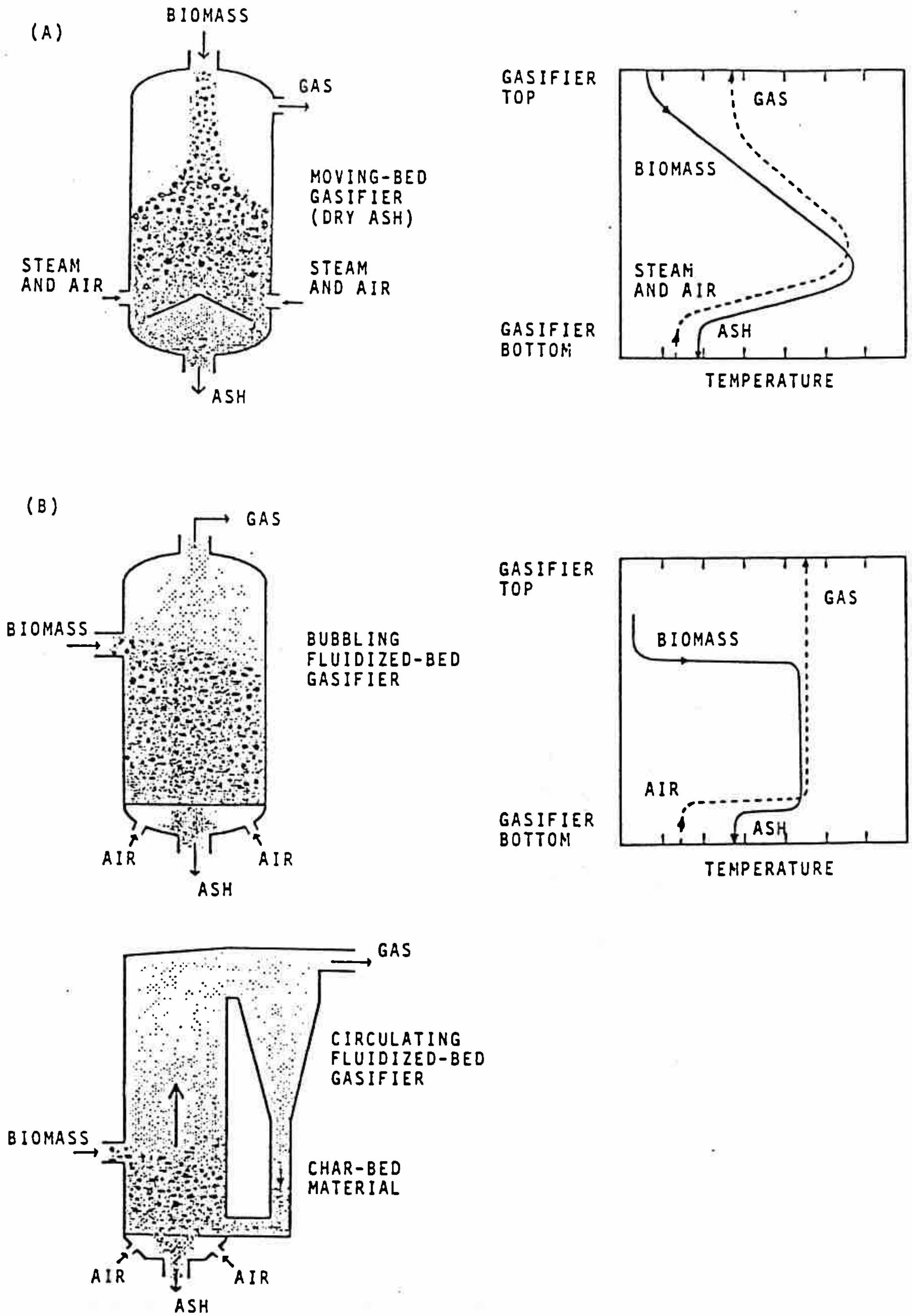

Fig. 2. Operating principles and temperature profiles for (a) fixed-bed and (b) bubbling fluidized-bed gasifiers. Also shown is a circulating fluidized-bed (CFB) gasifier.

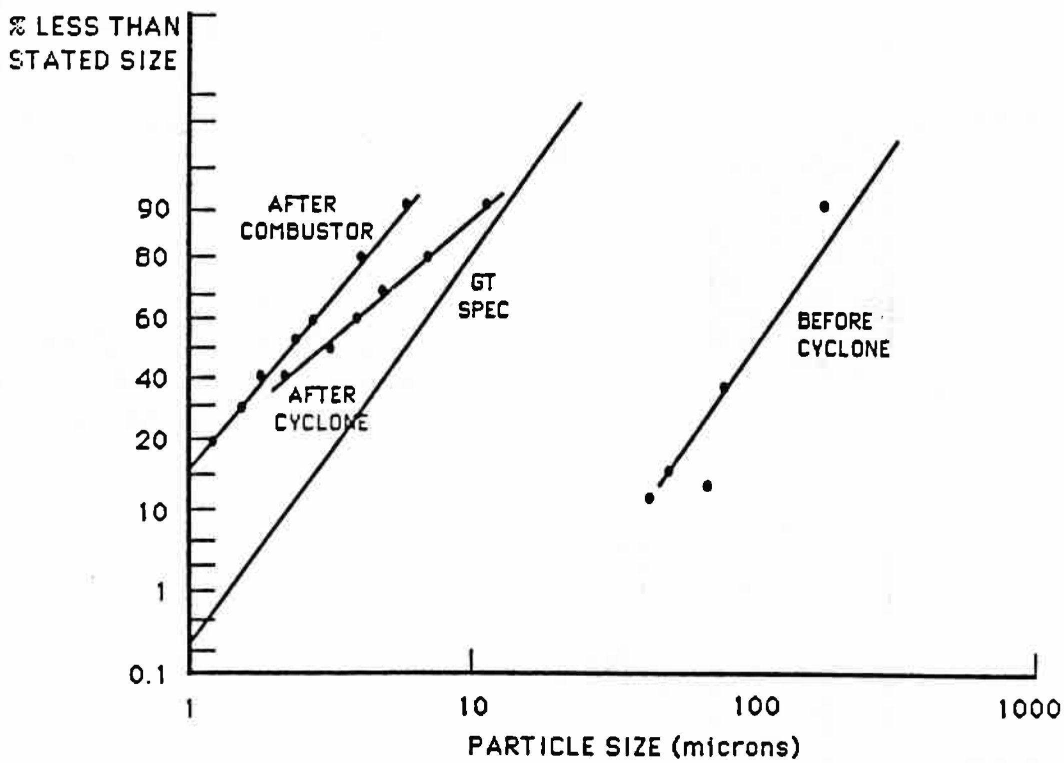

Fig. 3. Measured particulate size distribution in tests with pilot-scale fixed-bed coal gasification.[18] The data are for the raw gas at the gasifier exit, after the cyclone, and after a simulated gas turbine combustor. They are compared to a set of recommended gas turbine specifications.

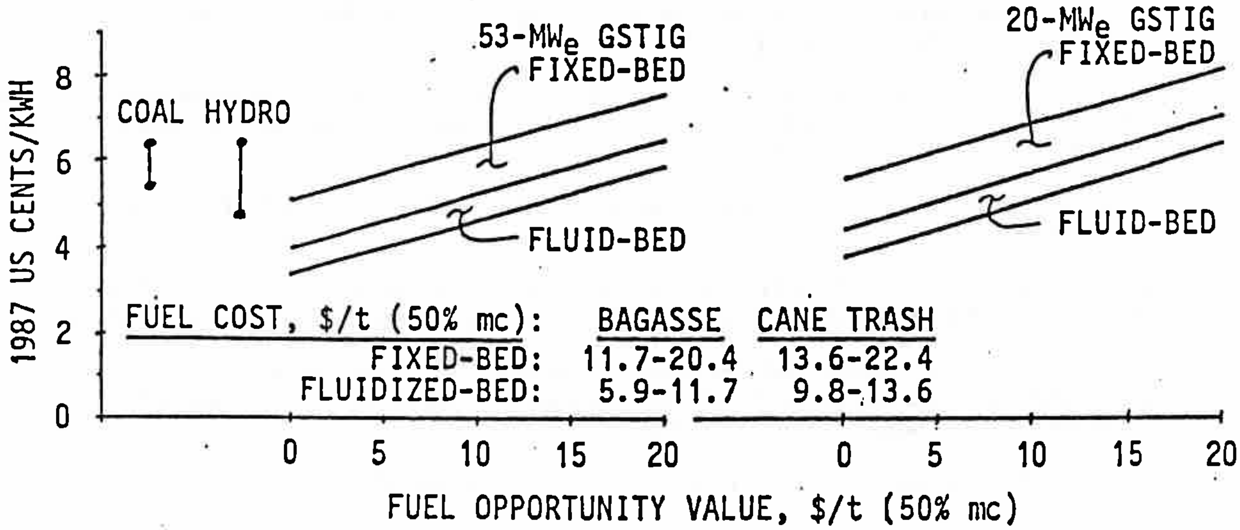

Fig. 4. Calculated lifecycle costs of producing exportable electricity (1987 US cents per kWh) at sugar factories using GSTIG systems with fluidized-bed or fixed-bed gasifiers. Costs are shown as a function of the opportunity value of the fuel, i.e., the value of the fuel (in an alternative use) in excess of its production cost. Also shown are cost estimates[1] for new central station power from a 61-MW_e coal-fired plant in Jamaica (with coal costing $42-$61/tonne) and from new hydroelectric plants in the Amazon supplying electricity to Southeast Brazil (at a capital cost of $1460-$1880/kW).[1]

Installed capital costs for the 20-MW_e GSTIG (at a 70 tc/hr sugar factory) and 53-MW_e GSTIG (180 tc/hr factory) are assumed to be $1300/kW and $1050/kW, respectively, with either a fixed or fluidized-bed. An additional $62/$kW_e$ are included for steam-conservation retrofits at the sugar factory,[2] which operates 206 days per year, during which time bagasse fuels the GSTIG. In the off-season, cane trash is the fuel. The fixed-bed fuel production cost range corresponds to the costs of briquetting up to pelletizing. The fluid-bed cost range is from drying up to briquetting. Fuel production cost estimates are from references 27 and 28. A 10% discount rate, 30-year lifetime, and 90% availability are assumed in the calculations.

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