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CATALYTIC STEAM GASIFICATION OF BAGASSE FOR THE PRODUCTION OF METHANOL

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ABSTRACT

Pacific Northwest Laboratory (PNL) tested the catalytic gasification of bagasse for the production of methanol synthesis gas. The process uses steam, indirect heat, and a catalyst to produce synthesis gas in one step in a fluidized bed gasifier. Both laboratory and process development scale (nominal 1 ton/day) gasifiers were used to test two different catalyst systems: 1) supported nickel catalysts and 2) alkali carbonates doped on the bagasse. This paper presents the results of laboratory and process development unit gasification tests and includes an economic evaluation of the process.

CATALYTIC STEAM GASIFICATION OF BAGASSE FOR THE PRODUCTION OF METHANOL

INTRODUCTION

Bagasse produced as an unavoidable by-product of cane sugar represents a significant energy resource. It is primarily used as a fuel; however, more efficient use of bagasse or conversion of it to higher value products is being considered.

One possibility is conversion of bagasse to methanol. Methanol can be produced from biomass materials such as bagasse via relatively simple gasification technology. Methanol is a valuable chemical in the international market used primarily as a feedstock for production of other chemicals, particularly formaldehyde. However, the primary new interest in methanol is its potential as a transportation fuel. It is already being used as a gasoline additive and neat in fleet vehicles and is being considered as a fuel for gasoline engines, diesel engines and gas turbines.

Since 1977 Pacific Northwest Laboratory (PNL) has been developing a process for the catalytic gasification of wood under sponsorship of the U.S. Department of Energy. The process uses steam, indirect heat, and a catalyst to produce methanol synthesis gas in a fluidized bed gasifier. This report details the results of a project, sponsored jointly by the Australian Sugar Research Institute and the Biomass Energy Technology Division of the U.S. Department of Energy to test catalytic gasification of bagasse for the production of methanol. The project included gasification tests in laboratory scale gasifiers and in a nominal 1 ton/day process development unit and an economic evaluation of the process.

The original intent of the project was to test gasification of bagasse in a nominal 1 ton/day fluidized bed process development unit (PDU) gasifier using nickel catalysts as had been done previously with wood. However, in the first test with bagasse in the PDU the catalyst deactivated rapidly. Laboratory studies were initiated to study catalyst deactivation and screen other catalyst systems. PDU studies were completed using K_2CO_3 as a catalyst. This report also includes the results of laboratory and PDU studies and an economic evaluation of the process using K_2CO_3 as a catalyst.

LABORATORY STUDIES

Laboratory gasification tests were initiated after the first Process Development Unit (PDU) tests with supported nickel catalysts showed rapid catalyst deactivation. Two different types of catalyst systems were evaluated in the laboratory: 1) supported metal catalysts, primarily nickel based, and 2) alkali carbonate catalysts which were impregnated on the bagasse feed materials.

Bagasse Analysis

Bagasse used for the gasification tests was supplied by the Sugar Research Institute and was shipped from Australia. The bagasse was supplied in three different forms: loose, baled, and pelletized. For laboratory gasification tests the pellets were ground to smaller than 1.4 mm (14 mesh).

Table 1 shows the analysis of the Australian bagasse pellets and some Hawaiian bagasse pellets used for comparison in some laboratory gasification tests. The ash and sulfur content of bagasse are significantly higher than wood. Otherwise the proximate and ultimate analyses are quite similar to hardwoods (Mudge 1983a). Bagasse is primarily cellulose (38%), hemicellulose (38%) and lignin (20%). This also closely resembles the composition of hardwoods (Shafizadeh 1982).

Description of Laboratory Gasifier

Two continuous-feed, fixed-catalyst-bed reactors constructed of quartz glass were used for these studies. The reactors, which are operated at atmospheric pressure are shown in Figure 1. The reactors and analytical equipment used have been described previously (Mudge 1983b).

The laboratory reactors are designed primarily for catalyst screening studies. The space velocity over the catalyst is similar to the space velocity in the PDU and past experience with wood has shown this system provides a good indication of catalyst performance in the PDU. Because of the differences in gas/solid contacting and residence time between the laboratory gasifiers and the PDU, the rate of gasification and overall carbon conversion can not be compared.

Table 1. Analysis of Bagasse Used for Gasification Tests

Source of Bagasse	Australia	Hawaii
Composition of Raw Bagasse (wt%)	—	--
Sugar		2
Fibre		43
Ash		7
Moisture		48
Proximate Analysis (wt% dry basis)	—	—
Volatile Matter		65
Fixed Carbon		22
Ash		13
Ultimate Analysis (wt% dry basis)	—	—
C	44.7	43.0
H	5.9	5.0
O	44.4	37.6
N	0.2	0.3
S ppm	300	--
Ash	4.8	13.3
Heating Value (dry basis)	—	--
kJ/kg	18,300	18,100
Btu/lb	7,870	7,780
Moisture Content (wt basis)	9.9	8.3
Form	pellets	pellets

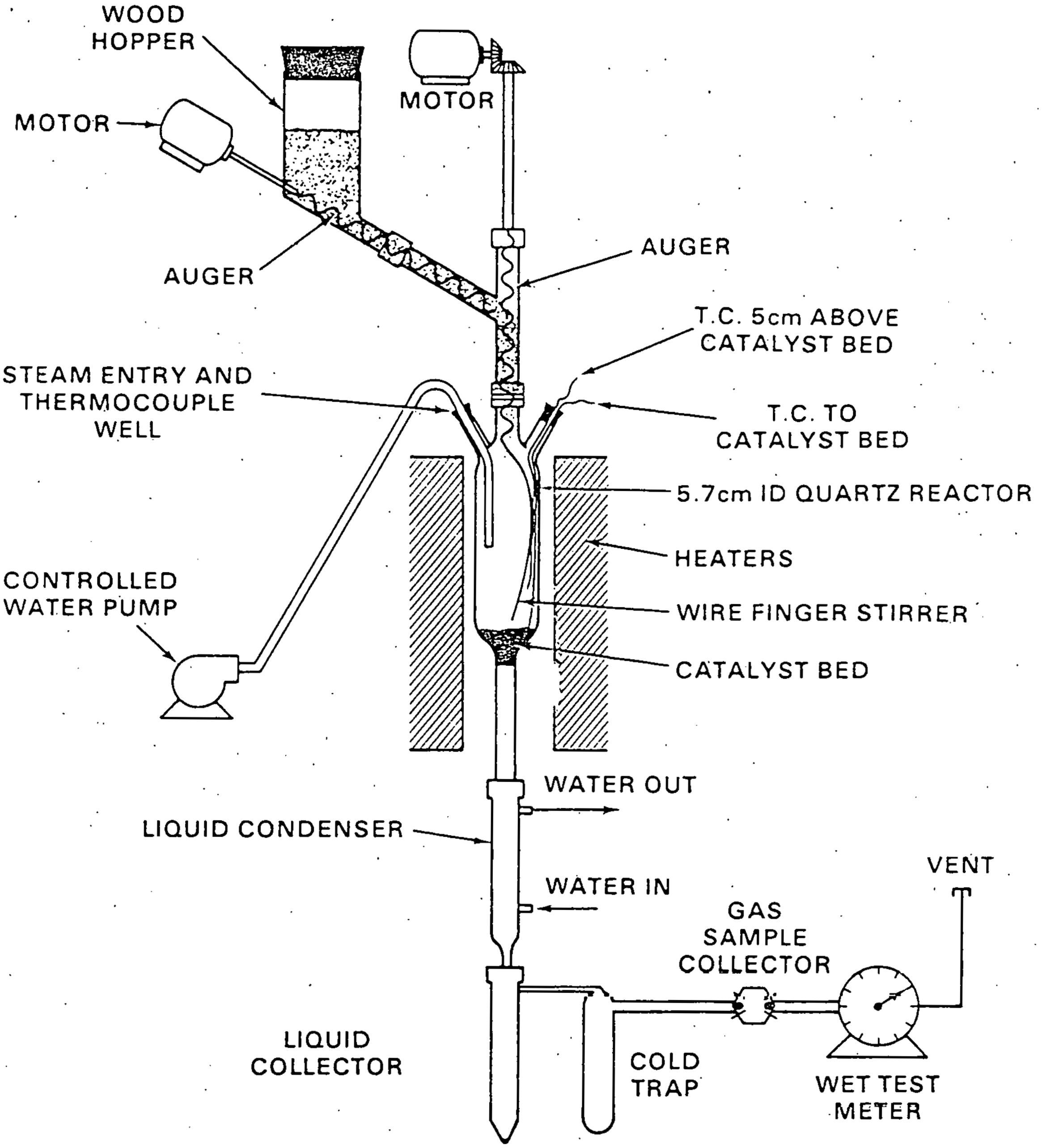

Figure 1. Laboratory Gasifier

Tests with Supported Metal Catalysts

Previous catalyst screening studies with wood as a feedstock showed supported nickel catalysts to be the most effective for the production of methanol synthesis gas. Some of the nickel catalysts tested showed rapid deactivation; however, several catalysts were identified which showed the potential for a long lifetime. These included a series of trimetallic catalysts, supplied by W. R. Grace, Inc. in a fluidizeable form (40-70 mesh spheres) (Mudge 1983, Baker 1982). A large batch of a Ni-Cu-Mo/SiO_2-Al_2O_3 catalyst was purchased from W. R. Grace, Inc. for PDU tests with wood and was also used for the bagasse studies. When this catalyst showed rapid deactivation in PDU tests with bagasse, laboratory studies were initiated to determine the cause of deactivation and identify other catalysts that could be used.

Test Results. Laboratory tests confirmed the early deactivation of the Ni-Cu-Mo/SiO_2-Al_2O_3 catalyst observed in the PDU. Loss of catalyst activity is apparent from the change in gas composition (Table 2) and by the appearance of tars in the condensate.

Several other nickel catalysts were tested with similar results. These included a high severity steam reforming catalyst and a NiMo desulfurization catalyst. We also tested a CoMo desulfurization catalyst and a SiO_2-Al_2O_3 cracking catalyst. These last two catalysts retained their original activity through the run but were not active enough at the start to be considered further.

Cause of Catalyst Deactivation. The usual cause of catalyst deactivation in our gasification tests is carbon deposition. The trimetallic catalysts made by W. R. Grace, Inc. maintained their activity in laboratory tests despite some carbon deposition. One of these catalysts reached a lifetime of 1470 g wood gasified/g catalyst without loss of activity. No long term tests have been made in the PDU.

The rapid loss of activity with the NiCuMo/SiO_2-Al_2O_3 catalyst with bagasse indicated the possibility of some other deactivation mechanism. Gas analyses showed 80-240 ppm H_2S was present in the laboratory gasifier and that it was being taken up by the catalyst. After the catalyst was saturated the H_2S content of the product gas rose to the level of the gas in the gasifier.

Samples of different feed materials and catalysts were also analyzed for sulfur. Bagasse contains 200-400 ppm sulfur and the deactivated catalysts had 800-3000 ppm sulfur on them.

That H_2S adsorption on the catalyst contributes to deactivation is suggested by several factors:

- H_2S is a known catalyst poison for nickel reforming catalysts in quantities as low as 2 ppm (Rostrup-Neilson 1975).

Table 2. Comparison of Gas Compositions Between Bagasse and Wood in Laboratory Gasification Tests with Trimetallic Catalysts

	Bagasse		Wood		
Vol %	Start	After 4 hours	Start	After 4 hours	After 1000 hrs
H_2	56	37	59	58	51
CO	19	22	27	28	24
CH_4	4	14	1	1	5
CO_2	21	23	13	13	19
C_2	-	4	-	-	<1
H_2S (ppm)	2	240	-	~25[a]	~25[a]
Tars Present in Condensate	No	Yes	No	No	No

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[a] Average of numerous measurements made with wood.

- There is a good comparison between the time that should be required to sulfide the catalyst (based on the amount of H_2S in the gas and the nickel surface area of the catalyst) and the time when deactivation occurs.

- Adding ZnO sulfur guard catalyst to the system extended the life of the NiCuMo/SiO_2-Al_2O_3 catalyst.

- A catalyst with more active surface area (Ni/Al_2O_3) takes longer to deactivate than NiCuMo/SiO_2-Al_2O_3. Just the opposite was true with wood where carbon deposition was the primary cause of deactivation.

Wood does have some sulfur, although it is lower than bagasse, and a similar catalyst ran for over 1000 hours in a laboratory test with wood without deactivating. Rostrup-Nielson (1975) in studies of chemisorption of hydrogen sulfide on steam reforming catalysts found the chemisorption of hydrogen sulfide on nickel to be reversible, the coverage on the catalyst being a function of the ratio pH_2S/pH_2. The amount of adsorbed sulfur in equilibrium with the H_2S in the gas increases with increasing H_2S concentration until constant fractional coverage of the surface is reached. It appears that the sulfur level in wood allows enough of the nickel on the catalyst to remain exposed and active.

Heavy deposition of carbon was also found on the catalysts, particularly those from the PDU. Figure 2 shows the accumulation of carbon on nickel catalysts used with bagasse. Carbon deposition was higher in the PDU than the laboratory and both are significantly higher than we have seen with wood. The NiCoMo/SiO_2-Al_2O_3 which ran over 1000 hours in the laboratory had only 5 wt% carbon on it at the end.

Based on the high carbon deposition on the catalysts used with bagasse one could conclude that the sulfided catalysts are more susceptible to carbon deposition which actually causes the loss of activity. However, it is generally agreed that sulfiding nickel reforming catalysts decreases carbon formation on the catalyst (Rostrup-Nielson 1975; McCarty 1981).

From our studies it is not possible to positively identify the mechanism for deactivation, but it appears that it is definitely a function of the sulfur content of bagasse. Coking may also play a part but the exact relationship between the sulfur adsorption and carbon deposition is not known.

Tests with Alkali Carbonate Catalysts

The application of alkali metal catalysts to coal gasification has been known for many years (Taylor 1921) and has been studied extensively in recent years (Cox 1974; McKee 1983; Walker 1983; McCoy 1983; Nahas 1983). These catalysts have also been studied for use with biomass (Mudge 1979; Hawley 1983; Sealock 1982).

Typically alkali metal salts are solution impregnated or dry mixed with the feed material to improve the kinetics of the reaction of char with steam, carbon dioxide, and other gases. In the course of our studies with wood we found that alkali catalysts also reduce the yield

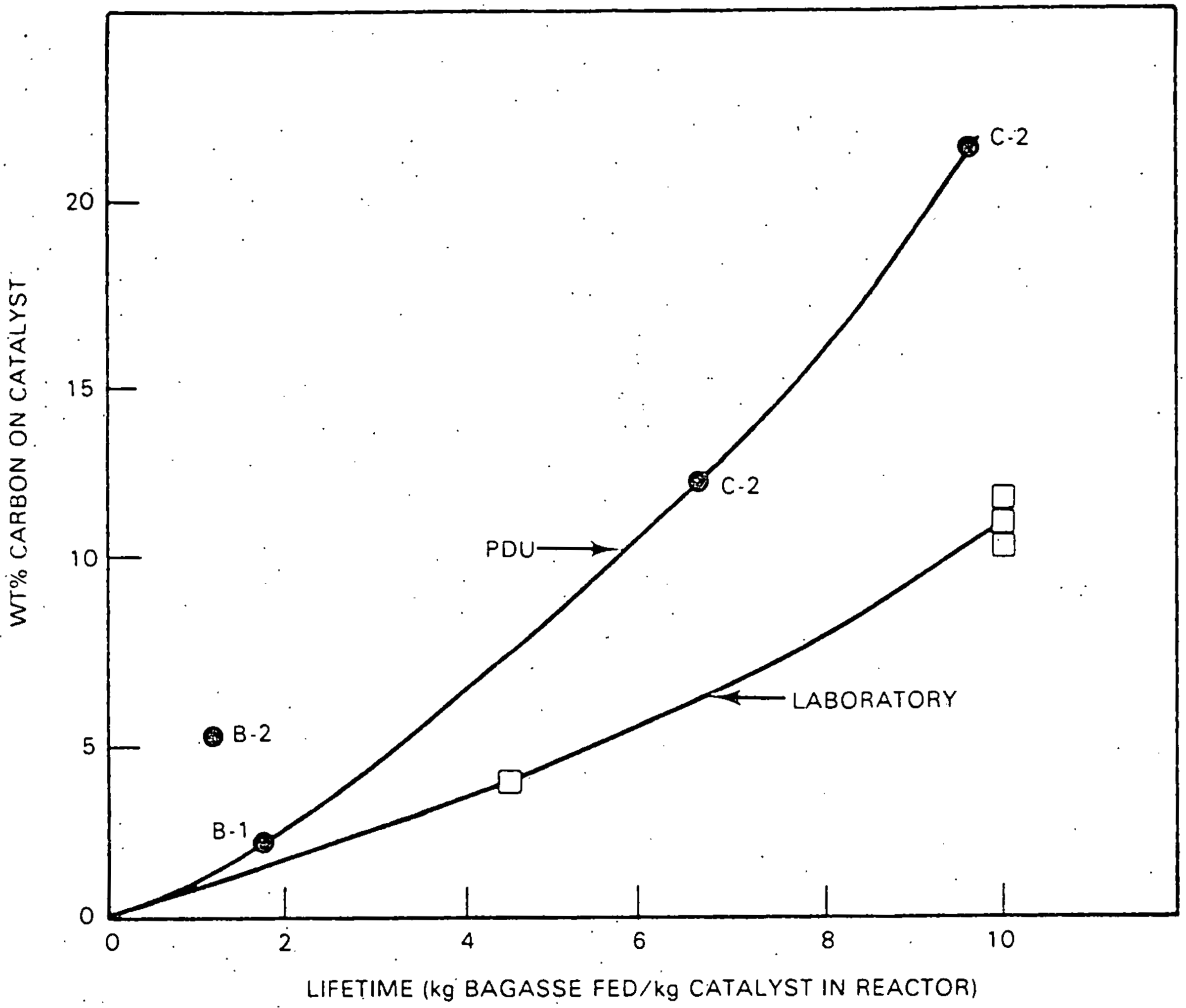

Figure 2. Carbon Accumulation on Nickel Catalysts

of tars, oils, and gaseous hydrocarbons and catalyze the water gas shift reaction making it possible to produce a high quality synthesis gas without the use of a secondary catalyst.

When it became apparent that we would be unable to find a long-lived supported nickel catalyst for bagasse gasification we switched our attention to the alkali metal salt catalysts. The alkali metal salts are not quite as active as fresh nickel catalysts in terms of synthesis gas yield, but because catalyst is being added continuously there is no loss of activity. The catalyst can be recovered from the char and recycled.

Test Results. Table 3 shows the results of laboratory tests with alkali metal salt catalysts. These tests showed the potential of this type of catalyst for the production of methanol synthesis gas from bagasse. There are many possible catalyst variations that can be studied including cation type (K, Na, Li, Cs, Ca) anion type (CO_3, OH, Cl), catalyst loading, and contacting method (solution impregnation or dry mixing). A complete investigation of these variables was not within the scope of this project. The selection of those catalysts tested was based on our previous work with wood (Mudge 1981) and data from the literature.

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We selected 10 wt% K_2CO_3 as a starting point for the bagasse studies. The results are about the same as we have seen for wood even at higher catalyst loadings. Run 19 with 5 wt% K_2CO_3 showed a significant increase in char and liquid yields.

A significant finding on these laboratory bagasse studies is that a much lower than expected steam to bagasse ratio is needed to achieve the 2 to 1 hydrogen to carbon monoxide ratio required for methanol synthesis. With wood and a nickel secondary catalyst a steam to wood weight ratio of 0.7 was required for a 2 to 1 hydrogen to carbon monoxide ratio. For bagasse with the alkali metal catalysts it appears that 0.4 to 0.5 kg of steam per kg of bagasse would be appropriate

Catalyst Recovery. Because of the cost of alkali metal catalysts and the loadings required it is necessary for economic reasons to recover the catalyst from the gasification residue (char, ash, catalyst). Previous studies with wood showed 90-95% of the potassium charged to the gasifier could be recovered by washing with large quantities of water (Mudge 1981). Exxon is currently planning on 90% recovery of the potassium used in their catalytic gasification process (Furlong 1978, Fant 1980).

The quantity of residues generated from a bagasse gasification run with 10% K_2CO_3 will range from about 0.2 kg/kg of dry bagasse at 90% carbon conversion to 0.25 kg/kg dry bagasse at 80% carbon conversion. The residue will be 40-50 wt% K_2CO_3 with the remainder being ash and char.

Four samples of residue from a laboratory gasification test were washed with smaller quantities of water and the solutions analyzed by atomic absorption. The results are shown in Figure 3. About 80% recovery was achieved with as little as 2 ml of water per gram of residue. Additional water did not significantly improve recovery.

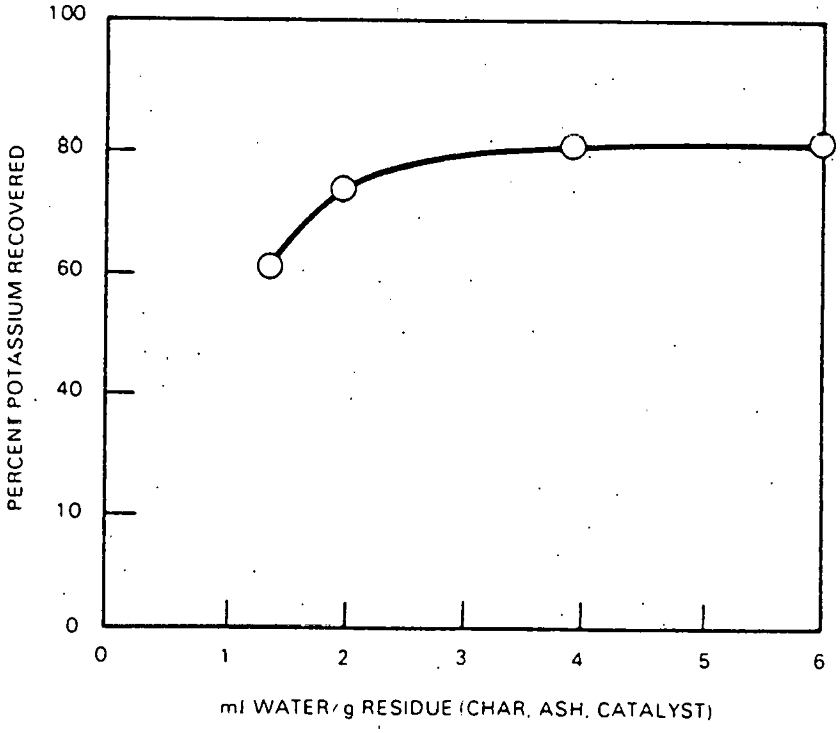

Figure 3. Catalyst Recovery From Gasification Residue

The remainder of the potassium probably reacts with mineral matter in the bagasse to form water insoluble compounds. Wood has very little ash so higher recoveries are possible. Exxon digests the char from their catalytic coal gasification process with $Ca(OH)_2$ to free additional water-soluble catalyst to increase their recovery to 90% (Furlong 1978; Fant 1980). This method could probably be used with bagasse char to increase the recovery of potassium.

PROCESS DEVELOPMENT UNIT STUDIES

The main objectives of the process development unit (PDU) studies are to determine the technical feasibility of producing a methanol synthesis gas from bagasse and to provide information on equipment and catalyst performance for further scale up.

PDU Description

The process flow diagram for the PDU is shown in Figure 4. Steam is superheated in the gas heater and contacts bagasse in the fluid bed gasifier. The gasifier is a nominal 1 ton/day unit with a reaction zone 20 cm (8 in.) in diameter. The bed is about 1.2 m (4 ft) deep when fluidized. Product gas and char exiting the gasifier are separated by a cyclone and filter. A heat exchanger condenses steam and organic compounds which are then separated from the gas in the demister. The gas can be recycled to the gas heater via the recycle compressor. Product gas is released through a letdown valve. A parallel off-gas system employs a venturi scrubber; however, it was not used. The PDU system has been described in detail previously (Mudge 1983a).

After a PDU test, preliminary results are determined using estimated compositions (moisture, ash, C, H, O, and total organic content). Then, when chemical analyses are complete, a final analysis of the test

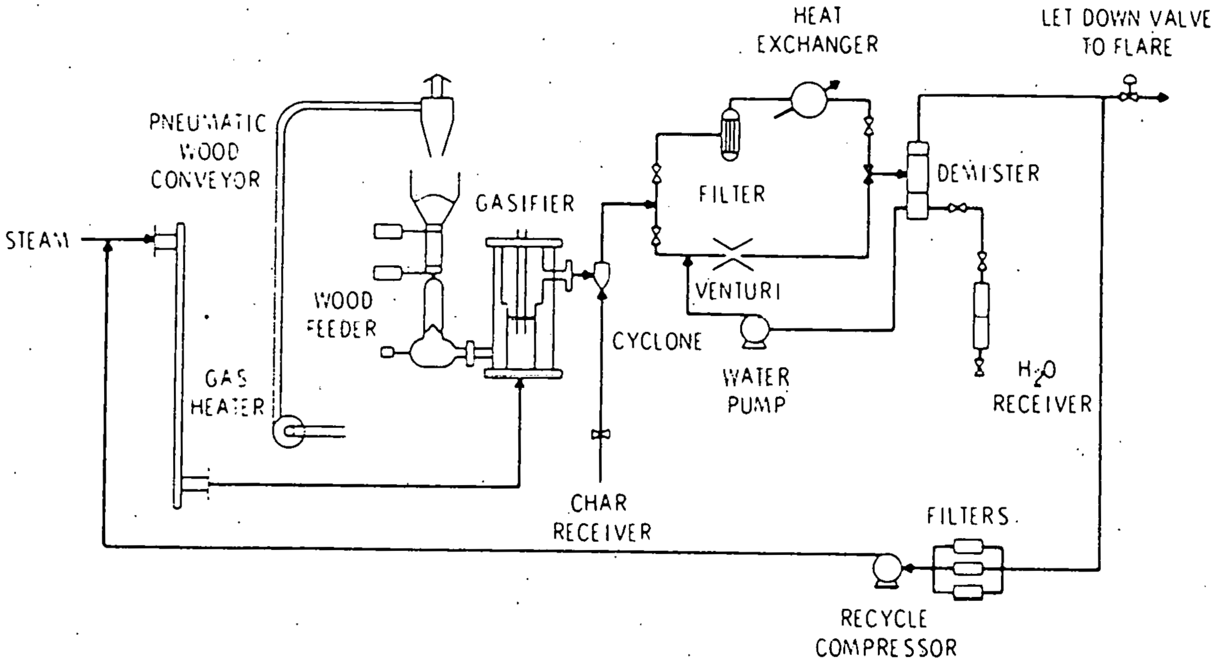

Figure 4. PDU Flow Diagram

is made using measured values. This analysis is programmed on a microcomputer. The calculated results include elemental mass balances, energy balances, conversions, and efficiencies.

Preliminary Feeding Tests

Three types of bagasse were supplied by Sugar Research Institute; Loose (as dried), baled, and pelletized (1.3 cm and 1.6 cm pellets). The loose bagasse consisted of fiberous chaff similar to long grass clippings. Occasional long fibers (up to 60 cm) were present. This loose material was shipped in large ($\sim 1\ m^3$) burlap bags. Forty bales of compacted material were received. The baled material was full of fines as well as long fibers. Pelletized material had been milled prior to pelletizing. Even the pelletized material showed a visible amount of fines.

Prior to making a run with bagasse it was necessary to calibrate the screw feeder. An attempt was made to feed the loose material directly. The injector screw compacted the loose bagasse and completely bound up after a short time. Calibrations with pellets were much better. Repeatable calibrations were obtained with bagasse both plain and impregnated with 10% K_2CO_3 catalyst. Overall feed rates that were derived from each run agree closely with original calibrations.

Loose material might be fed to a larger gasifier, but a novel approach possibly employing a different type of screw or a sloped injector would be required. Until further research can be done on roll compaction and other methods of densification and feeding it is recommended that pelletized material be used. When the pellets were impregnated with K_2CO_3 some breakdown of the pellets occurred but they still fed uniformly, indicating size reduction may be as important as pelletization. With a specially designed lock hopper and screw feeder it may be possible to feed loose material which has been reduced in size.

PDU Gasification Tests with Nickel Catalysts

Extensive laboratory testing with wood showed nickel based catalysts to be the most effective for production of synthesis gas. With an active catalyst the product consists primarily of H_2, CO and CO_2. Nearly all of the hydrocarbon gases, tars, and oils are reformed. Long catalyst lifetimes were shown in laboratory tests but had not been verified in the PDU.

Initial results from the PDU using nickel catalysts were quite encouraging. In the shakedown run and the early part of an extended run the results were similar to those achieved with wood. However, as the extended run progressed catalyst activity deteriorated rapidly. The run was eventually terminated after only one day. Catalyst deactivation was readily apparent from the CH_4 and H_2 content of the gas versus time as shown in Figure 5. Laboratory studies were initiated to determine the cause of catalyst deactivation and to search for other catalysts.

The PDU results with nickel catalysts, summarized in Table 4, showed bagasse pellets to be a good feedstock for fluid-bed gasification. With an active nickel catalyst the results were as good or better than those achieved with wood. Particularly encouraging was the high carbon conversion to gas, about 90% on the average for five runs. Carbon conversion to liquid products was quite low, 0.1% or less when the

Table 4. Summary of PDU Results with Nickel Catalysts[a]

Run Number Catalyst	B-1 Ni on Al_2O_3	C-1 Ni-Cu-Mo	C-2 Ni-Cu-Mo	B-2a Ni on Al_2O_3	B-2b Ni on Al_2O_3	Davy Base Case (Wood)
Bed Temp., (°C)	740	775	780	740	740	750
Feed Rate (kg/hr dry bagasse)	14.0	10.2	12.0	14.5	14.5	75,900
Steam Rate (kg/kg dry bagasse)	1.10	1.16	1.12	0.87	1.02	0.75
Gas Composition						
H_2	0.566	0.560	0.512	0.561	0.568	0.513
CO_2	0.242	0.198	0.223	0.218	0.203	0.174
CH_4	0.041	0.029	0.072	0.038	0.021	0.056
CO	0.151	0.210	0.179	0.183	0.205	0.257
C_2+	0	0.004	0.14	0	0.003	0
Dry nm^3/kg Dry Bagasse	1.66	1.54	1.04	1.90	1.82	1.57
Carbon Conversion (wt%)						
to gas	82.5	78.6	59.8	95.8	90.9	80
to char	12.9	8.0	9.5	6.8	12.9	20
to liquids	0.1	0.1	1.5	0.05	0.05	0
Carbon Balance, %	95.3	86.6	70.8	102.6	103.8	100
Total Bagasse Fed (kg)	50	75	78	30	59	

(a) The results are averaged over the entire steady state operating period. For Runs C-1 and C-2 the gas compositions deteriorated steadily with time as shown in Figure 5. For Runs B-1, B-2a, and B-2b the gas compositions were fairly constant.

catalysts were active. Unfortunately the NiCuMo catalyst quickly lost its activity and the yield of tars, oils, and light hydrocarbon gases (CH_4, C_2H_4, C_2H_6, etc) increased rapidly. The amount of the H_2 and CO produced was reduced accordingly. The Ni/Al_2O_3 catalyst maintained its activity longer in the PDU but laboratory tests showed that it also deactivated too fast to be considered for further tests.

Laboratory studies indicated the loss of activity was due to some combination of sulfur poisoning and carbon deposition. A brief catalyst

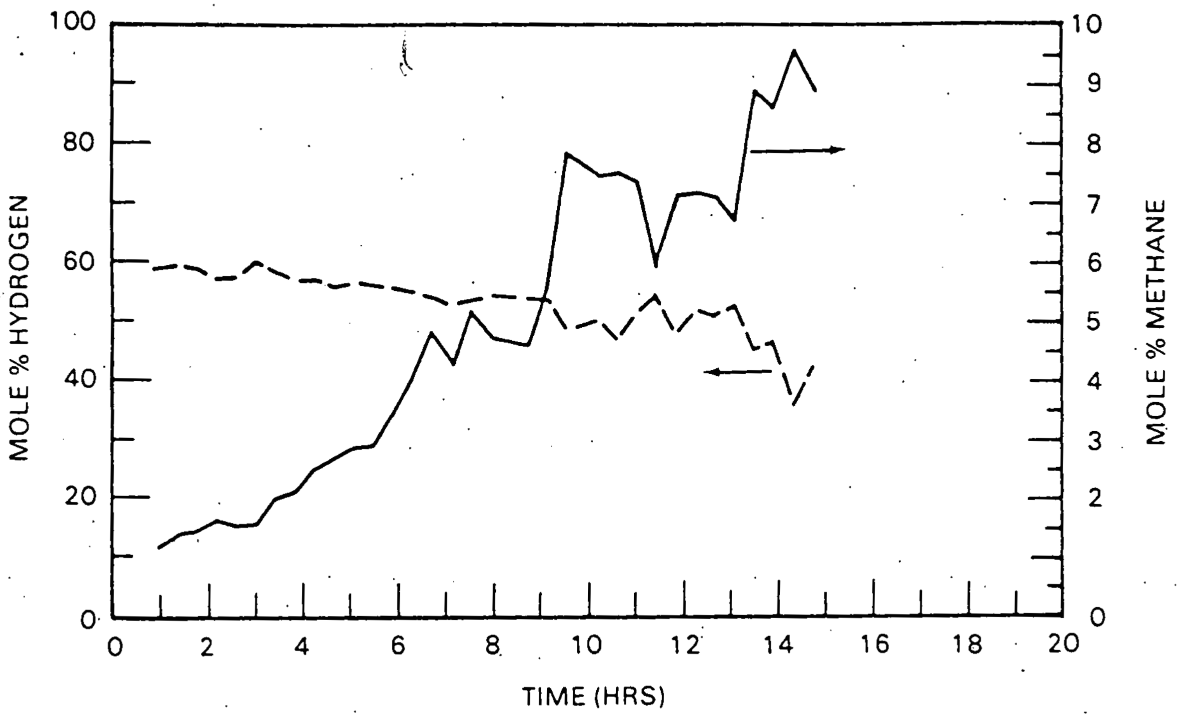

Figure 5. Product Gas Composition in Runs C1 and C2 Indicating Catalyst Deactivation

screening study indicated alkali carbonate catalysts doped on the bagasse would be an effective catalyst system for bagasse and the rest of the PDU tests were made with this type of catalyst system.

PDU Gasification Tests with Potassium Carbonate Catalyst

Based on the results of laboratory testing a catalyst system of 10 wt% K_2CO_3 impregnated on the bagasse was selected for testing in the PDU. This catalyst had previously been successfully tested with wood (Mudge 1983). Use of this catalyst in the PDU presented several technical problems compared to using supported catalysts in the bed including:

- preparing the feedstock,
- preventing agglomeration in the gasifier, and
- finding a suitable inert material for the fluid bed.

All of these problems were solved in the course of the PDU tests with K_2CO_3 and the results of these tests were quite encouraging.

In previous tests with wood the K_2CO_3 was dry mixed with wet wood chips. This worked quite well as the moisture in the wood absorbed the K_2CO_3. The chips were then dried prior to gasification. The bagasse pellets were too dry to use this method so a solution of K_2CO_3 had to be used. We were afraid that drying would result in pellet attrition so we had to use a minimum of water.

A 40 wt% solution of K_2CO_3 was mixed with the bagasse in a preliminary PDU impregnation test. Laboratory gasification tests with this feed material were good. A cement mixer and a spray wand were then used to impregnate about one ton of pellets with a 40 wt% solution of K_2CO_3. This resulted in a fairly even distribution on each pellet and a minimum of pellet attrition. The final composition of the pellets on a wet basis was about 9% K_2CO_3, 78% bagasse fibre, and 13% moisture.

Four PDU runs were made with K_2CO_3 impregnated bagasse at four different bagasse feed rates which corresponded to four different steam/bagasse ratios. The steam rate was held constant at the rate required to fluidize the bed. The length of the runs was limited by accumulation of residue (char, ash, catalyst) in the filter vessel. The residue from these runs is finer and is produced at a higher rate (due to the K_2CO_3) than we have experienced in the past. This puts a heavier load on the filter vessel. The filter vessel is not designed to be emptied during a run. When we attempted to empty the filter vessel while it was hot the char ignited and caused a small fire.

A summary of the results of each run is given in Table 5. The tests with K_2CO_3 impregnated bagasse in the PDU went quite well and showed the feasibility of using this type of catalyst system in a larger

Table 5. Summary of PDU Results with 10% K_2CO_3 Impregnated Australian Bagasse Pellets[a]

Run Number	C-3a	C-3b	C-4	C-5
Bed Temp., (°C)	760	760	730	720
Feed Rate (kg/hr dry bagasse + K_2CO_3)	14.3	19.6	24.5	30.6
Steam Rate (kg/kg dry bagasse)	0.95	0.70	0.62	0.58
Superficial Gas Velocity, m/s	0.45	0.45	0.38	0.52
Gas Compositions (mole %)				
H_2	54.5	55.3	51.4	46.8
CO_2	24.0	24.5	24.2	24.8
CH_4	3.6	4.0	3.0	3.9
CO	11.0	15.1	20.2	22.6
C_2^+	0.9	1.1	1.2	1.9
Dry nm^3 gas/kg dry bagasse	1.47	1.47	1.44	1.14
Carbon Conversion (wt%)				
Gas	83.0	81.7	87.4	76.5
Solid char	22.0	21.4	18.3	23.1
Liquids	0.19	0.05	0.57	0.74
Total	105.3	103.1	106.2	100.2

(a) The results are averaged over the entire run.

scale. The results were as good or better than laboratory gasifier results with the same catalyst and nearly as good as laboratory and PDU results with active nickel catalysts.

Carbon conversion to gas was good (77-87%) although not as high as achieved with nickel catalysts. This is consistent with results with wood in the PDU (Mudge 1983). Although K_2CO_3, is an effective catalyst for the steam/char reaction (which should increase carbon conversion to gas), at short residence times (less than 10 minutes) laboratory tests show an increase in char production with alkali carbonate catalysts (Sealock, 1982; Mudge 1981). This char is more reactive and will gasify faster than uncatalyzed char provided sufficient time is provided. The residence time in the gasifier is difficult to determine but the fact that carbon conversion is lower with K_2CO_3 indicates it probably is fairly short.

Carbon conversion appears to be more a function of gas velocity in the gasifier bed. Increasing the gas velocity as was done in Run C-5 increases the size of char particles which are carried out of the bed. This reduces their residence time and reduces carbon conversion.

A steam rate of about 0.5 kg/kg dry bagasse is required to produce a gas with a H_2/CO ratio of 2. Alkali carbonates appear to be a better shift catalyst than nickel catalysts so a lower steam rate can be used.

Clinker formation can be a problem with alkali carbonate catalysts; however, if good fluidization is maintained in the bed through the run and during the cooldown phase of shutting down, clinker formation can be avoided. The melting point of K_2CO_3 is 891°C and the K_2CO_3 is quite mobile at 750°C. Particles of K_2CO_3 agglomerate and gradually get larger until chunks are formed. Maintaining good fluidization prevents agglomeration and minimizes hot spots where agglomeration would be more severe.

PROCESS EVALUATION

Based on the results of the laboratory and PDU gasification tests a design basis for economic calculations was developed. A process flow diagram was developed, and heat and material balances were calculated to determine the ultimate yield of methanol from bagasse. This was combined with cost information, supplied primarily by Davy McKee Engineers and Constructors for wood based plants, to calculate the required selling price of methanol. The effect of variables such as plant size, capital cost, financing method, and bagasse cost on the final cost of methanol were evaluated.

Process Development

The process developed to convert bagasse to methanol is based on:

- PDU and laboratory investigations of catalytic gasification of bagasse for the production of methanol synthesis gas, and

- a detailed feasibility study of methanol production via catalytic gasification of wood done by Davy McKee Engineers and Constructors for PNL (Mudge 1981).

The design basis is shown in Table 6. The gasifier operates at 750°C and 1000 kPa (150 psia) and 90% of the carbon in the bagasse is converted to gas. Operation of the gasifier at 1000 kPa significantly reduces downstream compression costs. In PDU tests with wood carbon conversion and gas yields were slightly higher at 1000 kPa compared to atmospheric tests. Gas compositions were similar when a catalyst was used (Mudge 1983). Carbon conversion to gas ranged from 77-87% for the bagasse PDU tests. With a properly designed system operating at 1000 kPa (150 psia) we believe 90% carbon conversion to gas can be achieved with bagasse and this was used for the design basis. Figure 6 is a process flow diagram for converting bagasse to methanol. The yield of methanol is 0.47 kg/kg dry bagasse and the overall thermal efficiency is 56%.

Cost Studies

Evaluating the economics of producing methanol from bagasse was accomplished by adapting previous studies utilizing wood as a feedstock

Table 6. Design Basis for Conversion of Bagasse to Methanol

Plant Capacity- 800 ton/day (727 t) dry bagasse
Storage Required - 8 months feed
Operating Factor - 330 days/year

Gasifier Operation

Pressure - 1000 kPa (10 atm)
Temperature - 750°C
Steam Rate - 0.4 kg/kg dry bagasse (assumes ~10% moisture in bagasse feed
Catalyst - 10 wt% K_2CO_3 (0.11 kg/kg dry bagasse)

Gas Production (dry basis) - 1.4 nm^3/kg dry bagasse
Gas Composition - (vol %)

H_2	49.5
CO	24.5
CO_2	19.0
CH_4	5.0
C_2^+	2.2
N_2	0.5
H_2S (ppm)	13.0

Residue Production - 0.2 kg/kg dry bagasse (90% carbon conversion to gas)

Catalyst Recovery - 80% with 2ℓ H_2O/kg residue

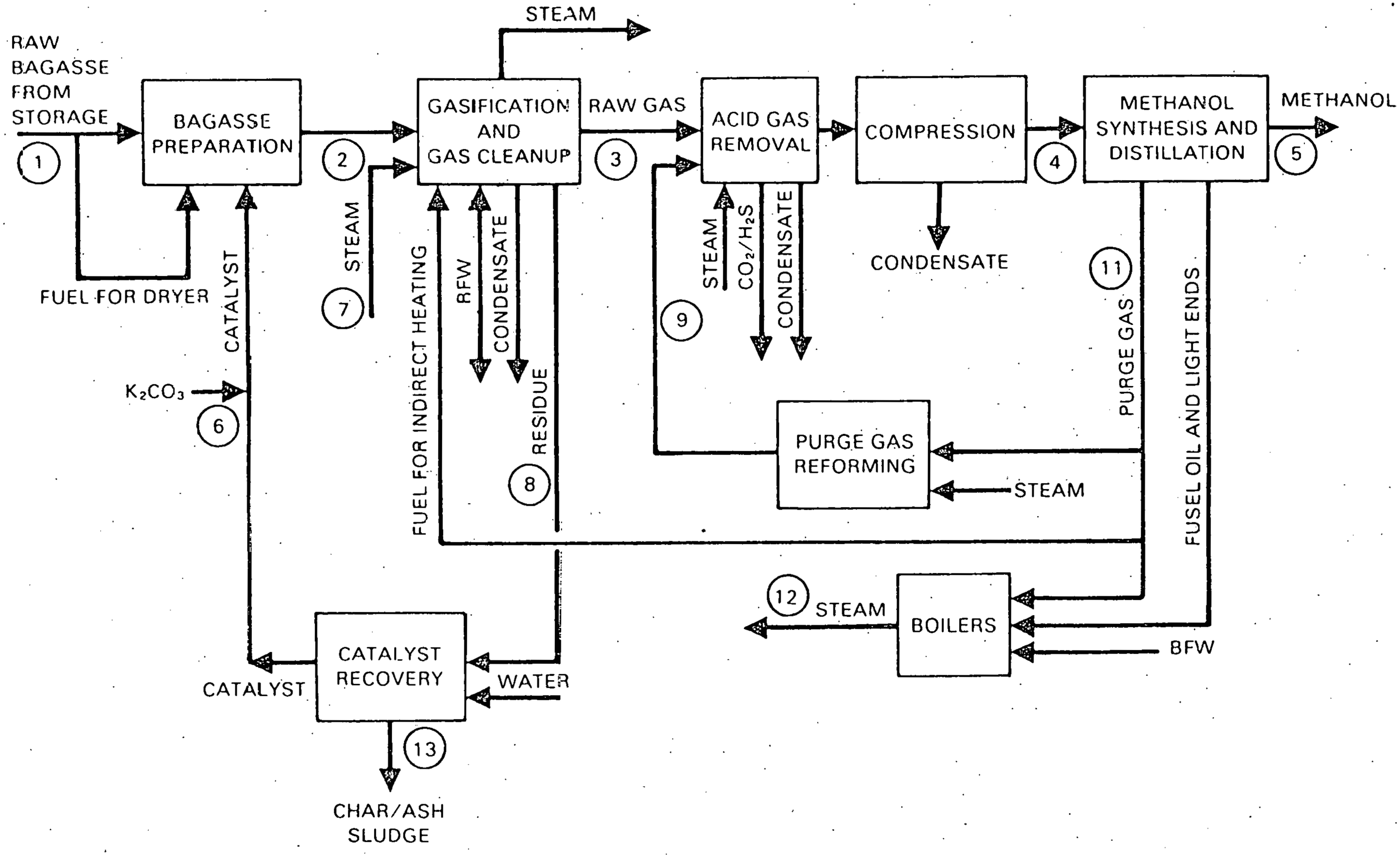

Figure 6. Process Flow Diagram for Converting Bagasse to Methanol

(Mudge et al., 1981, 1983). We have computerized the entire economic analysis onto a large spreadsheet type program. Many of the process variables (bagasse cost, plant size, yields, labor costs, etc.) can be changed and a complete recalculation using these new values can be done rapidly. The simulation predicts the final selling price of methanol from bagasse required to make the process economically attractive.

The base capital and operating cost data with wood feedstocks were developed by Davy McKee Engineers and Constructors (now DM International) in 1980. The process design for converting bagasse to methanol varies somewhat from the wood based process, so a new basis was developed. The differences are primarily in storage, feed preparation, and catalyst recovery. For storage and feed preparation, cost information obtained from Sugar Research Institute and equipment vendors was combined with the information on wood developed by Davy. Catalyst recovery costs were based on a cost estimate by Exxon for their catalytic coal gasification process which uses K_2CO_3 (Fant 1980; Furlong 1978). The rest of the equipment from the gasifier downstream to and including the methanol synthesis unit was costed based on the Davy study. Relative sizes of the equipment were adjusted to account for the small differences between bagasse and wood (e.g. less steam is required for bagasse).

Economic Evaluation. Once the plant capital requirements and operating costs have been determined the required methanol selling price can be calculated. For a plant located in the US the following economic basis was used:

Private Financing

- project life - 20 years
- depreciation method - 16 years sum-of-digits method
- % equity capital - 100%
- rate of return - 12% DCF
- income tax rate - 48%

Utility Financing

- project life - 20 years
- depreciation method - 5% per year straight line
- debt/equity ratio - 75/25
- interest - 10%
- return on equity - 15%
- income tax rate - 48%

In the United States most of the sugar cane is grown in Hawaii, Florida, Louisiana, and Puerto Rico in that order. The average size suger mill produces anywhere from 50 to 800 ton/day of dry fibre (Boyd 1980). Four cases, representative of the bagasse supply, have been evaluated to determine the price of methanol necessary to make this process competative. Plant capacities range from 200 to 800 ton/day of dry fibre. Bagasse costs were varied between 10 and 40 $/ton. Table 7 shows the total installed capital cost and the calculated required methanol selling price for each case considered.

Table 8 shows a breakdown of the capital cost for a plant feeding 800 ton/day of dry bagasse. Bagasse storage, gasification, and methanol synthesis are the three largest cost areas. Capital costs are the most

Table 7. Summary of Economic Evaluation

Case	Plant Size Ton/Day	Capital Cost $ million	Bagasse Cost $/dry ton	Methanol Cost Utility	Methanol Cost Private
1	800	97.5	10	0.91	1.22
2	800	97.5	40	1.13	1.44
3	200	32.1	10	1.30	1.75
4	200	32.1	40	1.52	1.97

Table 8. Total Capital Required for a Plant Feeding 800 ton (727 t)/day Dry Bagasse Fibre (dry basis)

Cost Component	US $ Millions
Bagasse Storage and Preparation	20.1
Bagasse Drying	5.3
Gasification and Gas Cleanup	14.1
Shift Conversion	0.6
Acid Gas Removal	3.5
Compression	3.5
Methanol Synthesis and Distillation	9.9
Purge Gas Reforming	0.5
Utilities, Offsites, Miscellaneous	8.5
Direct Equipment Costs (DEC)	66.1
Field Indirects	13.9
Professional Services	15.9
Other	1.6
Total Installed Cost (TIC)	97.5
Funds During Construction	11.0
Start-Up Costs	4.0
Working Capital	2.4
Total Capital Required	114.9

significant contributor to the final methanol selling price. The capital costs are higher for bagasse than wood primarily due to the large amount of storage required (8 months) and additional costs for catalyst recovery because the K_2CO_3 catalyst was used. The rest of the capital costs are actually somewhat less for bagasse. The large storage costs will be a problem for any year-round process using bagasse as a feedstock.

Table 9 lists the operating costs for the same plant. Operating costs other than the cost of bagasse are based on the original Davy study with wood. Labor costs are the largest single operating costs.

Table 9. Projected Annual Operating Costs for a Plant Feeding 800 ton (727 t)/day Dry Bagasse Fibre

Cost Component	US $ 1000/yr
Bagasse @ $ 10/dry ton	2,640
Gasification Catalyst	1,824
Other Catalysts and Chemicals	437
Utilities	2,261
Labor	4,879
Administration and General Overhead	2,928
Supplies	2,354
Taxes and Insurance	2,700
Total Gross Operating Costs	20,026

If the cost of bagasse exceeds $20/ton it becomes the dominant operating cost. As shown in Table 7 the plant size also has a significant effect on the final cost of methanol. This results from economies of scale primarily for the downstream equipment after the gasifier, particularly compression and methanol synthesis. A central location receiving bagasse from several mills is more economic than a small plant at a single mill even if transportation costs significantly increase the cost of bagasse.

The calculated cost of methanol produced from bagasse is significantly higher than the current cost of methanol. A previous economic evaluation with wood showed the required selling price of methanol was competitive with the market price of methanol (Mudge 1981). The following factors make this latest analysis less favorable:

- Capital costs are higher
- Construction costs have inflated 20% since 1980
- Capital costs for bagasse are somewhat higher than for a wood based plant.
- The previous evaluation used a larger plant size than is feasible with bagasse which resulted in significant economies of scale.
- The market price of methanol in the U.S. has dropped 44% in the last six months to $0.45/gal ($0.12/ℓ).

Production of methanol from bagasse may still be profitable in the long term if a shortage of transportation fuels occurs and prices increase significantly. The cost of bagasse is primarily a function of capital costs and so the future price will be determined primarily by the inflation of the cost of materials and labor for construction.

CONCLUSIONS

Based on laboratory, PDU, and economic studies the following conclusions on catalytic gasification of bagasse for the production of methanol are offered.

- Pelletized bagasse fibre has significantly move sulfur and ash than wood but is a good feedstock for fluidized bed gasifiers.
- Nickel catalysts used in the gasifier for production of methanol synthesis gas were rapidly deactivated in both laboratory and PDU gasification tests.
- Catalyst deactivation appears to be a function of sulfur poisoning and carbon deposition.
- Alkali carbonates doped on bagasse are an effective catalyst system for production of methanol synthesis gas.
- The fluid-bed PDU gasifier can successfully handle high ash biomass feeds and feeds doped with alkali carbonates without agglomeration or clinker formation.
- Conversion of bagasse to methanol is currently not economic due primarily to the recent large drop in methanol prices.

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