# IMPACT OF A CORN COB GASIFIER
# ON THE FUEL CONSUMPTION OF A DUAL FUELED DIESEL ENGINE

by

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ABSTRACT

# IMPACT OF A CORN COB GASIFIER ON THE FUEL CONSUMPTION OF A DUAL FUELED DIESEL ENGINE

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Corn cob fuel was used to operate an open top, stratified down draft gasifier, powering a 3.7 kw slow speed diesel engine. Three cob moisture levels; 5%, 15%, 18% wet basis, were tested at 3 engine speeds; 400, 500, and 600 rpm; in a randomized complete block experimental design. Engine speed and power were held constant while diesel fuel consumption was monitored to determine the combination that saved the most diesel fuel, for the given speed and power level. At all speeds the lowest moisture cobs produced the greatest savings in diesel fuel.

To assess the potential financial benefits from the substitution of corn cobs for diesel fuel, partial budgets, incremental net benefit streams, and financial internal rate of return calculations were done for various cob yields, cob prices, and diesel fuel prices; for the Sahel region of West Africa.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background

In recent years interest in alternative energy technologies has proliferated in developing countries (George,1980;Stassen,1980; Barnard,1982). Among the more promising techniques reviewed is the realm of biomass energy conversion. This appears to be a logical approach since the majority of rural populations in developing areas utilize some form of biomass (such as firewood or charcoal) as a major energy source. Indeed it is one of the oldest sources of energy known to mankind.

Even though petroleum prices have recently declined on the world market, consumers in many developing nations have continued to experience price increases. In 1985 the government of the Republic of Mali increased the diesel fuel price 16 percent (MFC, 1985) over the 1984 level. Government intervention by price setting is one reason for these distorted prices. Governments often obtain tax revenues on fuel, and while this is not a free market inflationary factor on pricing, the end result is the same for the consumer, inflated prices. There are also problems of irregular supplies and high transport cost to remote areas (OFDA,1978). These factors can push price levels far beyond the official (government) price.

In the Sahel region of Africa (figure 1.1), many consumers are located in areas that have only seasonal access by road. It is not unusual for these areas to be among the more agriculturaly productive in the country due to controlled water application by irrigation. The principal source of power for water lifting in these areas is the diesel engine. Surface water is pumped mainly from rivers like the Niger river (passing through Guinea, Mali, Niger and Nigeria) and the Senegal river bordering on Senegal and Mauritania (Figure 1.1). Diesel powered irrigation has been the quickest and surest approach for offsetting declines in crop production. Salinger and Stryker (1983) compared returns to irrigated versus dry land agriculture in the Senegal river basin, and found irrigated production to provide superior rates of return in Senegal and Mauritania.

Surface irrigation is the predominant technique used in the area. Two schemes are employed: one is referred to as small perimeters, the other, large perimeters. Small perimeters are operated in a cooperative manner by the members of a village. The average surface area is around 40 hectares,and is managed with practically no mechanised inputs other than the diesel powered irrigation pump. Large perimeters are owned and operated by the governments. The minimum size of these schemes is typically 500 hectares. They are characterized by a high level of mechanized inputs, and heavy bureaucracy.

# Africa political

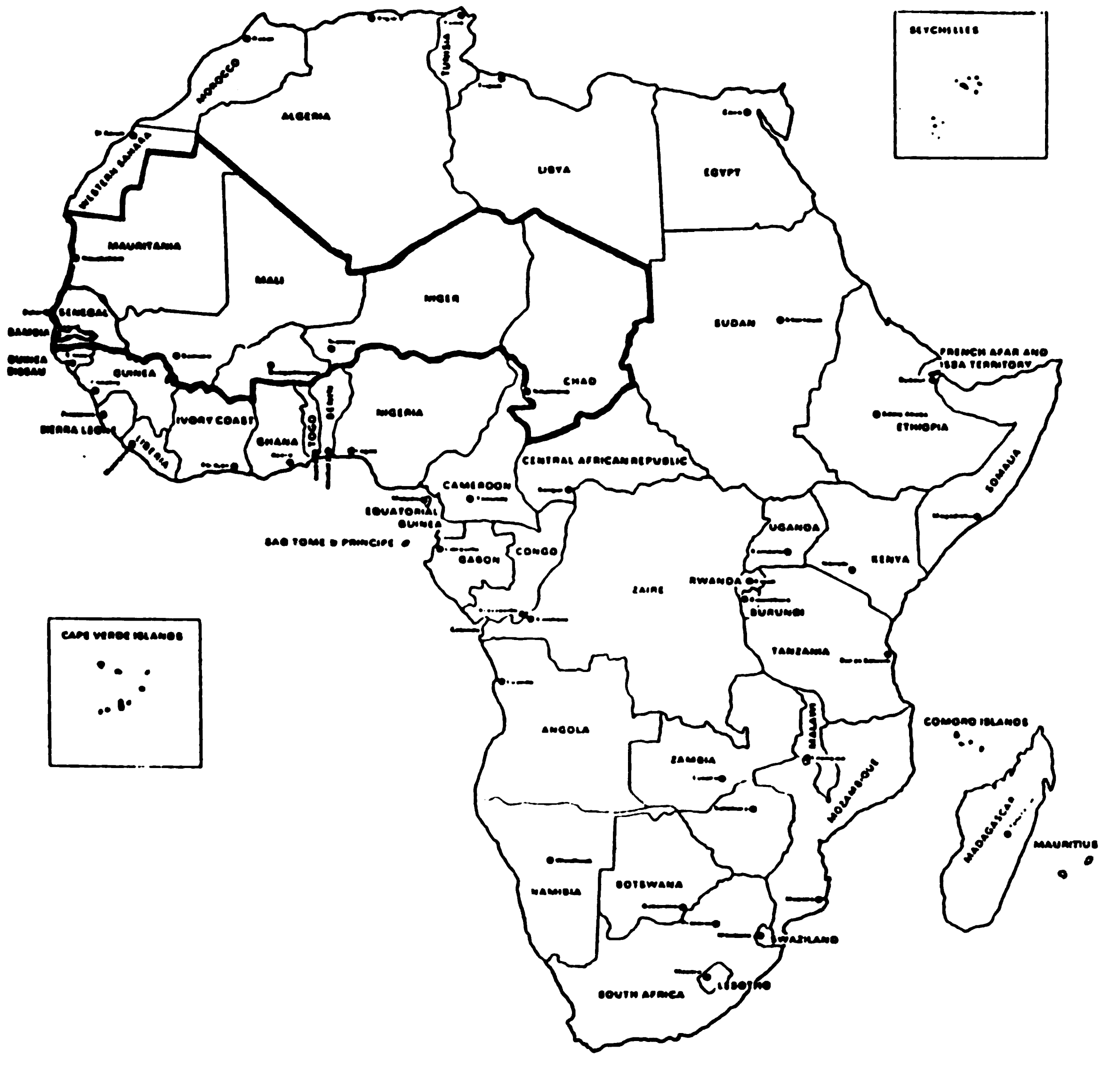



Figure 1.1 Map of the African Continent with an outline of the Sahel Zone. Source: CILSS, 1979

Diesel powered irrigation in the Senegal River Valley, had expanded from 2,000 hectares in 1977 to 20,000 hectares in 1982 (CILSS,1982). Future growth is projected at 2-3,000 hectares per year through the year 2000. This large increase in area irrigated has proportionally increased the demand for diesel fuel. Experience thus far indicate that fuel is the highest production cost of diesel powered irrigation systems in the Senegal river basin (Fieloux, 1980).

Since many nations are not producing their own petroleum fuel they must import it. Foreign exchange payments can be high to those nations that consume large quantities of fuel. In Mauritania, imports quadrupled over a 12 year period from 1959 to 1972. Petroleum products comprised a significant amount of the increase and the trend is continuing (OFDA,1978). Reducing the demand for petroleum by substituting alternative fuels would free foreign exchange for other purchases.

Gas producers are a potential response to the energy problems experienced by rural inhabitants in some of these countries. Gas producers or gasifiers, convert biomass into energy in the form of gas. The process is called gasification. Gasification occurs when biomass is burned with a limited supply of air. The products are carbon monoxide, carbon dioxide, hydrogen, and methane gases. The energy available from this gas mixture is suitable as a supplementary fuel for diesel engines.

There is substantial information available on using gas generators to power gasoline and diesel engines. The bulk of this information however, refers to the use of wood and/or charcoal as the biomass feedstock for the gas generator. This is suitable for countries with large forest resources. In other countries, forest resources are so limited that harvesting of wood on a large scale is not practical. Environmental transformation would be significant and most likely destructive. There is still the possibility that other sources of biomass, like crop residues, could furnish significant quantities of energy.

Gas generators are not without drawbacks and shortcomings. While it is a relatively inexpensive unit to build, the supply of biomass must be substantial to operate on a continuous basis. Considerable fuel preparation may be required for it to perform adequately ie. drying, sizing etc. The human element plays a major role in operational efficiency of the unit. High output by the gas generator unit demands that attention is paid to details. Leaks must be kept to a minimum, air/gas mixture precisely maintained, and cleaning of filters and piping done frequently.

Until recently, all of the low cost gas generators were of the closed batch type design. The open top stratified design may offer some new advantages due to its design simplicity.

# CHAPTER 2

## OBJECTIVES

The intent of this investigation is to obtain more specific information on the relationship of moisture in biomass fuel, to the power produced with biomass under gasification.

In this particular case the biomass is corn cobs. Three moisture levels were selected for analysis. They were in the ranges of 5, 15, and 25% wet basis. This range of moisture contents were selected based on the work of White et al (1984) and weather data for West Africa taken from the Food and Agriculture Organization (1980). At temperatures of 30-50 degrees celsius the equilibrium moisture content wet basis, of corn cobs peaks at just above 25% with 90 percent equilibrium relative humidity. The lowest moisture content is around 5% moisture wet basis, at a relative humidity of 30 percent.

Data from the FAO indicate that the mean daily relative humidity in humid zones of Africa is in the 70-80 percent range. In the more arid areas such as the Sahel, the mean daily relative humidity can drop as low as 30 percent during the dry season. On the basis of this data the range 5 to 25 percent moisture content wet basis was chosen for the experiment.

The method of determining power is the diesel engine.

The productivity of biomass fuel was measured by monitoring the amount of diesel fuel consumed, at a given speed and power level. This was done when the engine was operated in the dual fueled mode, running on both gas from biomass and diesel fuel. The hypothesis is that the energy provided by the biomass gas as moisture content is lowered, will increasingly replace and reduce diesel fuel consumption at a given speed and power level.

The experimental objectives then were to:

1. Determine which of the corn cob moisture levels ie. 5, 15, 25 percent nominal moisture content wet basis, produces the greatest reduction in diesel fuel consumption.
2. Determine if there is a significant difference between the amount of diesel fuel consumed at the 3 corn cob moisture levels.
3. Evaluate the relationship between the moisture content of the corn cobs and the temperature at the grate of the gasifier, and at the cooler entrance and exit.
4. Evaluate the feasibility of using corn cobs for energy in the Sahel zone of West Africa, by means of financial cost benefit analysis.

The engine speeds selected for the experiment were 400 500 and 600 rpm. This speed range is selected because in preliminary tests of the gasification system, satisfactory performance was unattainable at higher speeds with the 15 and 25 percent cob moisture levels. Also engines of the type used in these studies are typically slow speed diesels operating at less than 1,000 rpm. Such models are manufactured in India and the Peoples Repubic of China. Specifications of some models are available in the appendix.*

* Note: the mention of a particular manufacturers or suppliers products in this document does not constitute an endorsement of the product(s).

# CHAPTER 3

# LITERATURE REVIEW

Gasifiers have been used as sources of fuel since he 1800's. The earliest ones were made of fire brick. They were fueled with coal, charcoal, or wood and were used to heat blast furnaces in the steel industry (Donkin,1905). During World War II gasifiers or producer gas generators, as they were sometimes called, gained popularity as a fuel source for transportation in Europe (Griffen,1944; Nowakowska et al,1945). Many trucks,buses, and tractors were equipped with gasifiers and ran on wood or charcoal since fossil fuels were scarce during World War II. Once cheaper fossil fuels became available in the post war period, attention to gasification technology was largely abandoned, until the mid 1970's when higher fossil fuel cost generated renewed interest in alternative energy.

### 3.1.1 Gasifier Designs

Gasifiers, or producer gas generators, are available in 3 principal configurations (Reed, 1981) :

Updaft

Downdraft

Crossdraft

These terms refer to the direction in which the air stream flows through the gasifier as it feeds the combustion process and breaks the fuel down into the desired gases. Downdraft indicates that the air flow is in a downward direction, through the gasifier (fig 3.1). Crossdraft refers to a sideways or lateral path of air flow, and updraft refers to an upward direction of air flow.

Downdraft models are popular for applications involving internal combustion engines because they produce a cleaner gas. This eliminates the need for frequent cleaning of the filters, coolers and piping between the gasifier and the engine. It also permits the use of simpler and less costly filtering equipment. The disadvantage is that the gas produced has a slightly lower energy content than that of the other models.

### 3.1.2 Processes

Air gasifiers are those which combust fuel with a limited amount of air. The gas produced has an energy content of 5,600-7500 kj/m$^3$ (150-200 btu/scf). By contrast oxygen, hydrogen, and pyrolysis gasifiers produce gas with energy contents of 11,000-18,500 kj/m$^3$ (300-500 btu/scf,see Table 3.1). These higher energy system are more sophisticated and expensive than air gasifiers.(Reed 1981). For this reason the air gasification process is selected for study as a potential candidate for developing areas due to its simplicity and low cost.

The gasification processes yields a combustible gas

Table 3.1 Energy Content of Fuel Gases and Their Uses

| NAME | SOURCE | ENERGY RANGE (BTU/SCF) | USES |
|---|---|---|---|
| Low Energy Gas (LEG) | Air Gasification | 150-200 | Diesel and spark engines, crop drying, gas/oil boilers |
| Medium Energy Gas (MEG) | Oxygen Gasification | 300-500 | Regional industrial pipelines, synthesis of fuels and ammonia |
| Biogas | Anaerobic Digestion | 600-700 | Process heat, pipeline (w/scrubbing) |
| High Energy Gas | Oil/Gas Wells | 1000 | Long distance pipelines for general heat, power, and city use |

Source: Biomass Gasification - Principles and Technology, 1981.

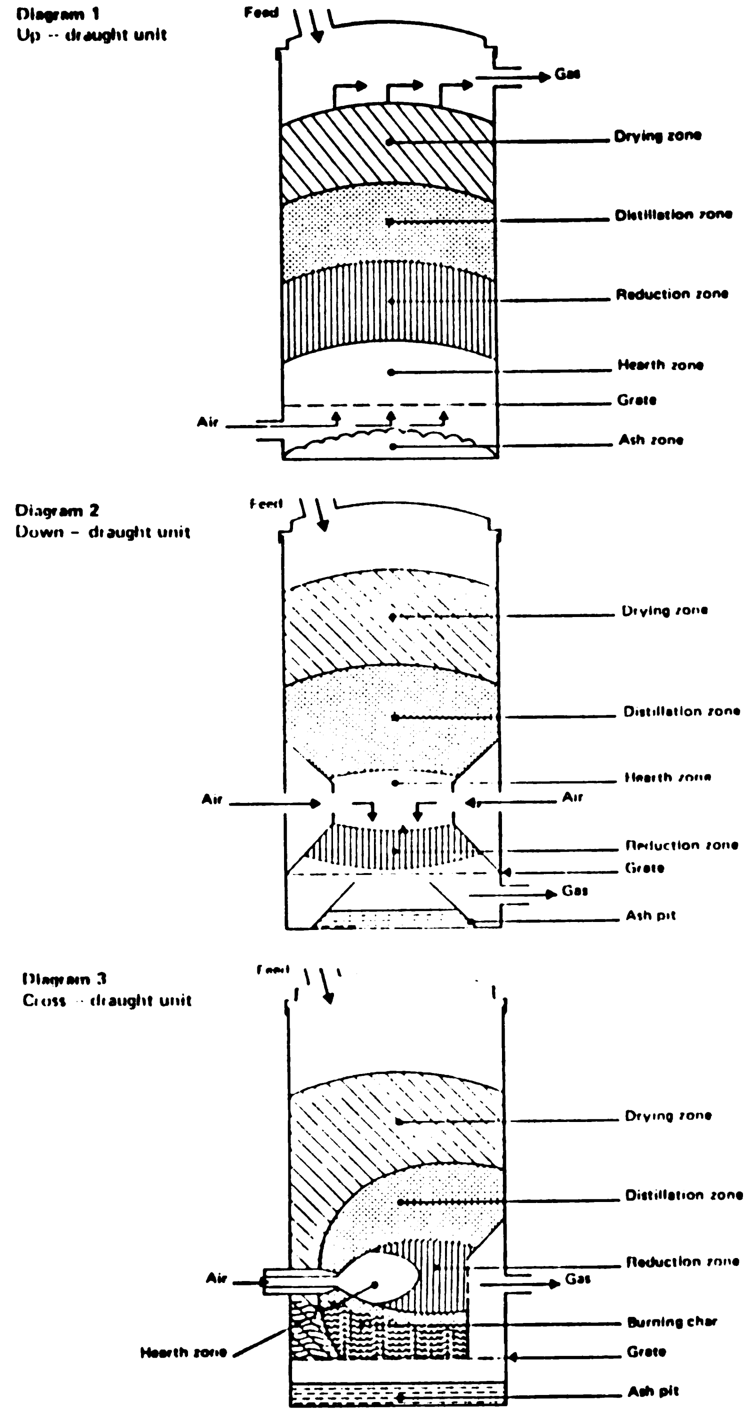



Figure 3.1 Various Gasifier types; Updraft, downdraft and Crossdraft. Source: Breag and Chittenden, 1979

from solid fuels such as coal, charcoal wood and crop residues. The fuel is ignited and fed with a stream of air to perpetuate combustion. The fuel reacts with air at at temperatures of 1,000$^{o}$C to produce a gas contaianing approximatly 20-30 percent carbon monoxide (CO),5-15 percent hydrogen (H), and up to 3 percent methane ($CH_4$) (Kaupp et al 1981,Reed 1981, Sakai et al 1978).

### 3.1.3 Wood Fueled Downdraft Gasifiers

There is substantial information on downdraft gasification of wood and charcoal fuels, but comparitively little on corn cobs, especially where the operation of IC engines is concerned. As such, much of the information that follows is related to wood or charcoal fueled gas producers coupled to IC engines.

Payne (1978) reports that the downdraft type gasifier design first appeared in 1924. It was developed by the Imbert company of West Germany. Downdraft units produce a cleaner gas product and thus are more suitable to power internal combustion engines. Downdraft refers to the direction of flow of the combustion air through the gasifier. Titl (1981) evaluated saw dust, bark and wood waste in gasifier diesel cogeneration system for electric power and process heat. Montgomery (1980) sucessfully operated an air blown gasifier to fire a boiler and generated process steam. McGowan and Jape (1981) did comprehensive studies on wood fueled gasifiers, and documented the performance of numerous gasifier types. From these studies data were obtained on pressure drops, flammability limits of producer gas, and combustion characteristics of selected fuel gases. Eoff and Post (1982) converted a six cylinder Chevrolet truck engine for operation on producer gas as a demonstration unit. Power output from the spark ignition engine was reported to be 50% that of pure gasoline.

Russell (1980) used a similar approach and converted a Chevrolet Malibu station wagon engine to run on producer gas from a downdraft gasifier. The unit was fueled with wood blocks of 15-25% moisture content wet basis. The vehicle was driven for 12,320 KM (7,700 miles) and no unusual wear or abnormalities were found in the engine.

Johansson (1980) tested spark ignition and compression ignition engines in trucks and tractors in Sweden. He obtained performance levels of 96% that of pure diesel fuel, when operating a truck mounted gasifier on wood with moisture contents of 12% wet basis. The tractor mounted unit acheived a diesel fuel substitution of 80%. These results are depicted in figures 3.2 and 3.3.

Generally, improved indicated thermal efficierncy occurs with producer gas due to more complete combustion and a lower flame temperature (Ogunlowo 1979, Held and Koenig 1982). Kaupp (1980) revealed that low speed engines having a large inertial mass, large piston displacement and large combustion space have significant advantages over

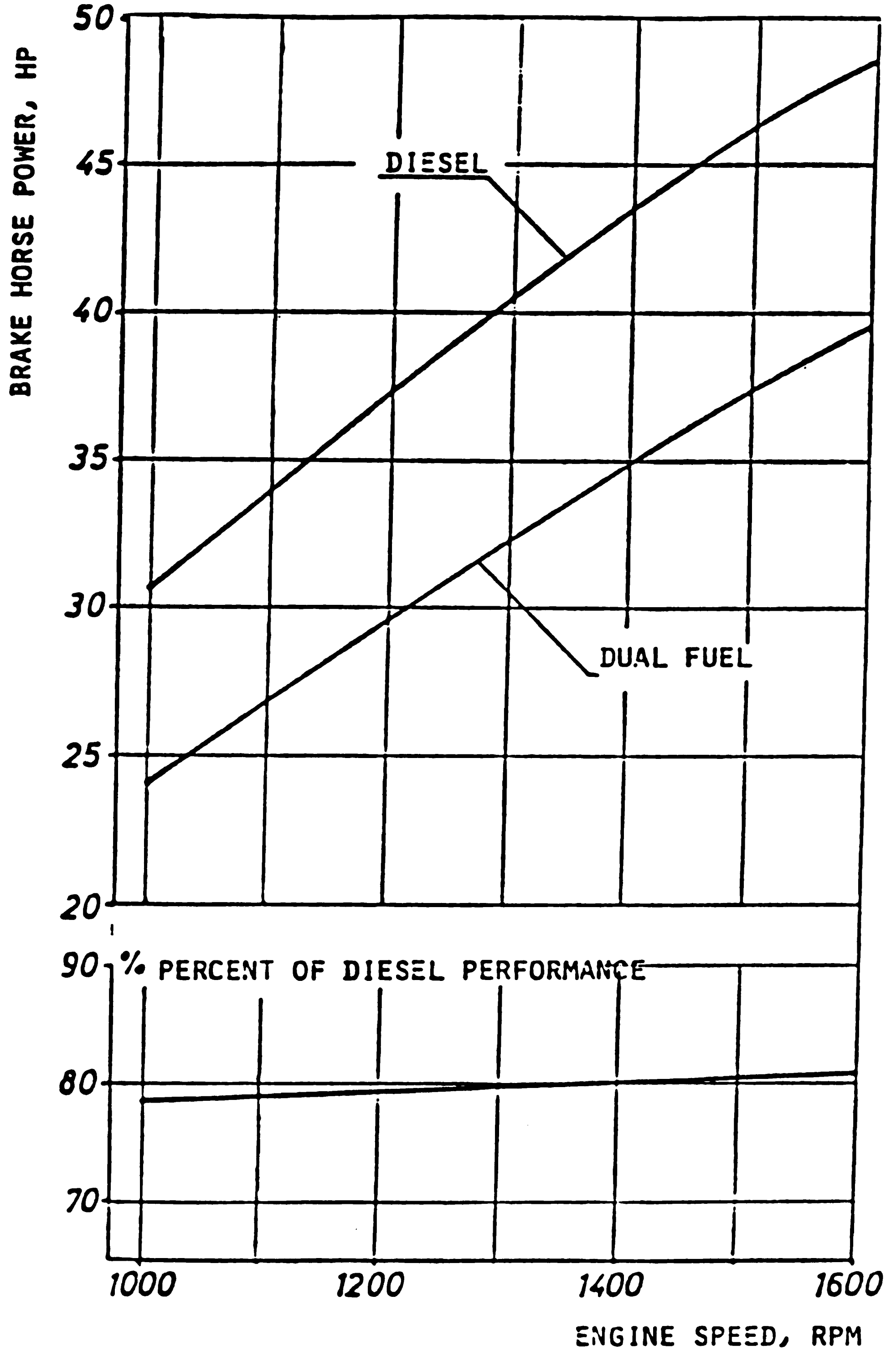



Figure 3.2 Maximum Power Performance at Diesel and Dual Fuel Operations. Diesel Engine, 3.5 liters cyl. displ., mounted in a tractor. Diesel fuel for ignition: 29g/$Nm^3$ producer gas Source: Johansson, 1980.

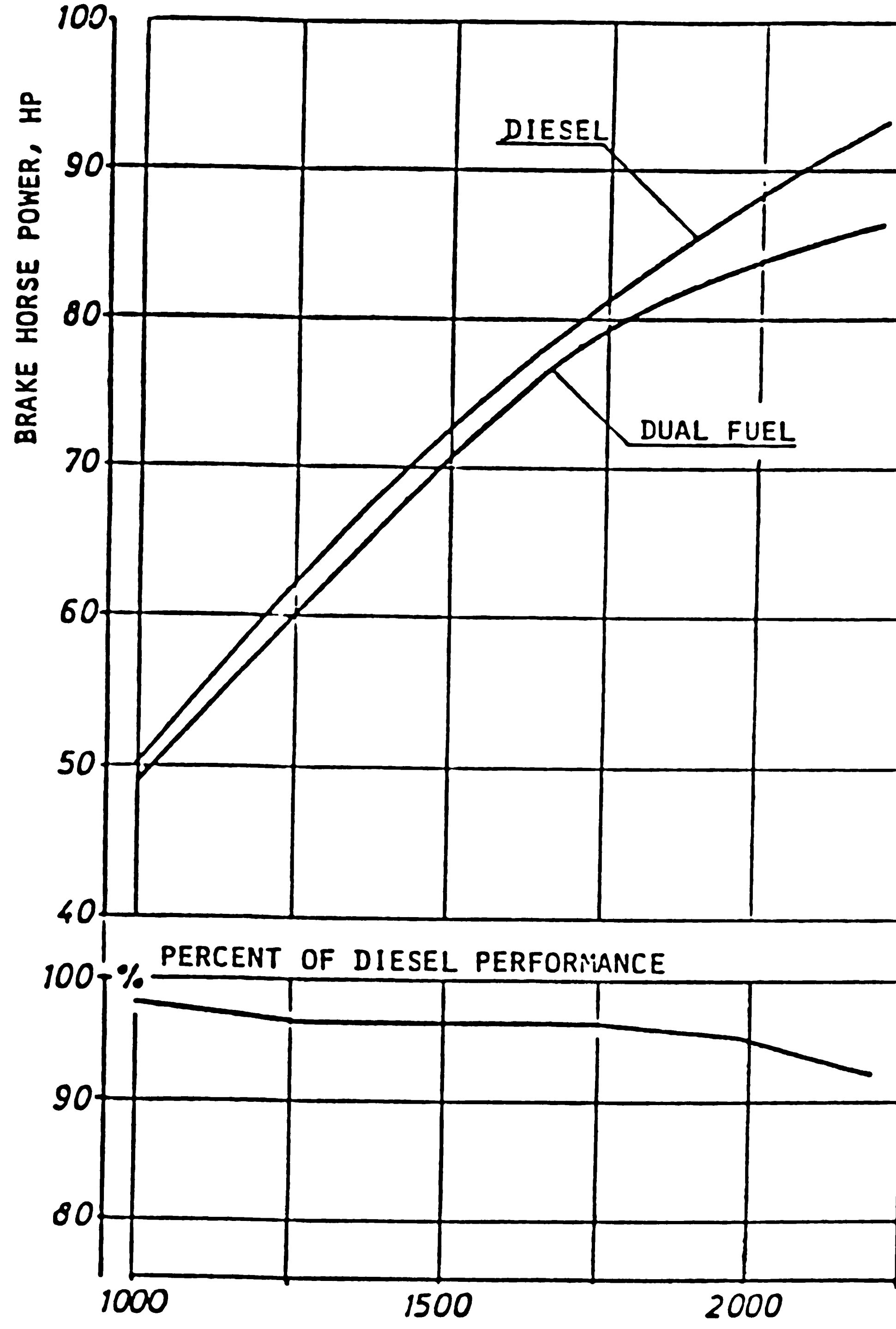



Figure 3.3 Maximum Power Performance at Diesel and Dual Fuel Operations. Diesel Engine, 6.2 liters cyl. displ., mounted in a truck. Diesel fuel for ignition: 12-19g/$Nm^3$ producer Gas. Source: Johansson, 1980.

compact, light, high speed engines. These advantages combined with large intake valves, appropriate opening timing and aerodynamic induction system make the difference between a poorly functioning engine and one with a power output very close to that of the normal fuel.

Nordstrom (1962) conducted thorough studies on various diesel engines operated with producer gas. He concentrated on gasifiers for mobile applications on trucks, tractors and buses. Significant among his work were the effects of increasing the pilot amount of diesel fuel injection for igniting the producer gas. He revealed that the gain in power increased at an increasing rate proportionally with engine speed. Also the effect of doubling the amount of the pilot injection only increases the power output over a range of 1-7% from low speed to high speed operation.

A reduction in diesel fuel consumption of 75% was reported by Shaw et al (1983) using a downdraft gasifier fueled with citrus wood, powering a six cylinder naturally aspirated 5.8 liter Perkins diesel. The engine developed 73% of its rated full power on diesel fuel when operated on the duel fuel mode. Johansson (1980) did similar studies and reported reductions in diesel fuel comsumption of 85-90% of the normal quantity, with tractor and truck engines of 3.5 liters and 6.2 liters displacement. Dennetiere et al (1980) worked with a super charged diesel connected to a 1000 KVA generating set at Duvant Moteurs in France. He obtained results showing an 80% reduction in diesel fuel consumpiton.

### 3.1.4 Biomass Gasification in Developing Nations

Producer gas powered internal combustion engines have seen growing applications in developing nations. In the Philippines Cruz (1980) conducted studies on single and multiple cylinder dual fueled diesel engines. His aim was to test the practicality of producer gas powered diesels for the Philippines agricultural environment. The gasifier design was a convertible type that would operate in either the updraft or downdraft configuration. Cruz found that the updraft mode was unmanageable due to the excessive tar production in this mode. Tests were conducted on charcoal, coal, coconut shell, wastewood, rice hulls, and corn cobs. A single cylinder 5 HP engine was used for these tests. He cited all fuels other than charcoal as posing a gas cleaning problem for the scrubber and filter system. This necessitated that the engine be disassembled and cleaned after 50 hours of operation. Table 3.2 contains the results of the trials performed with the 5 HP single cylinder engine.

Breag and Chittenden (1979) developed plans for a low cost crossdraft gasifier at the Tropical Products Institue in London, Egland. The unit had a power output of 3 KW and was intended for stationary applications. They concluded that biomass gasification systems were a serious alternative to steam for mechanical power in rural areas of

Table 3.2 Comparative Performance of a 3.7 KW (5 HP) Diesel Engine Run in (A) Dual Fuel Mode, and (B) Single Fuel (Diesel) Mode.
Source: Cruz, 1980

| Fuel | Mode | RPM | Brake HP | lb Fuel per BHP-HR Liquid | lb Fuel per BHP-HR Solid | % Diesel Saved |
|---|---|---|---|---|---|---|
| Charcoal | A | 1043 | 4.1 | 0.148 | 1.0 | 83 |
| Diesel | B | 1000 | 4.0 | 0.892 | 0 | - |
| Coal | A | 1288 | 4.8 | 0.246 | 1.3 | 80 |
| Diesel | B | 1246 | 4.9 | 1.261 | 0 | - |
| Coconut Shell | A | 1212 | 4.7 | 0.208 | 2.6 | 72 |
| Diesel | B | 1208 | 4.2 | 0.730 | 0 | - |
| Wastewood | A | 1221 | 4.1 | 0.357 | 2.8 | 62 |
| Diesel | B | 1237 | 4.1 | 0.950 | 0 | - |
| Rice Hulls | A | 1214 | 3.4 | 0.323 | 5.6 | 59 |
| Diesel | B | 1170 | 3.3 | 0.795 | 0 | - |
| Corn Cobs | A | 1287 | 4.5 | 0.516 | 1.0 | 31 |
| Diesel | B | 1222 | 4.2 | 0.752 | 0 | - |

developing nations. Also they contended that the introduction of gas producers must only occur where there are trained personnel to operate and service the units. They emphasized that each application must be considered individually in order to determine the suitability of a gas producer for that case.

Breag and Chittenden compared producer gas and steam power at small scale (<20 kw) outputs. At or below these levels producer gas had a higher efficiency than steam, 18% vs 3-5% per brake horsepower hour. Moreover, additional disadvantages of steam power on a small scale were high capital outlay, added cost of water treatment devices, and poor infrastructure for testing and maintaining high pressure vessels in developing nations.

Stassen and Zjip (1980) designed a downdraft gasifier at Twente University of Technology in the Netherlands. This unit was sent to Tanzania for testing under local conditions. The purpose of the exercise was (1) to evaluate the feasibility of gasification technology, for diesel driven corn shellers in rural villages of the Arusha district, and (2) derive a gasifier design suitable for manufacture in Tanzania.

The original prototype was designed, built and tested in the Netherlands. After its arrival in Tanzania, the gas producer was connected to a Petters PH-2 diesel engine and used to operate a corn sheller. The unit operated on charcoal for 200 hours, and achieved a reduction in diesel fuel consumption of 80%. The optimal engine thermal efficiency was obtained at 1200 rpm. Stassen and Zjip found that fuel consumption was dependent on the air-gas mixture ratio, the optimum being 1.05:1. They report that the engine produced more than adequate power to run the sheller even at 1,400 meters above sea level.

A tar accumulation problem was attributed to low quality charcoal. Better charcoal produced a tar free gas at engine speeds between 1,000 and 1,450 rpm.

The original design underwent modifications to create simpler and cheaper gasifiers for (1) easier operation by villagers and (2) easy local fabrication. All necessary materials were locally available except for refractory cement. Clay was substituted with partial success.

After extensive operation under village conditions Zjip and Stassen (1981) implemented further modifications to the gasification system. Improved gas cleaning equipment was employed to reduce the high amount of soot reaching the engine. Cob flow in the producer was enhanced with a stirring rod and by increasing the bunker diameter, to eliminate the deterioration of gas quality caused by bridging. Other changes such as a diesel fuel indicator, cast iron throat section, large capacity fuel hopper, elinination of gaskets at the reduction zone, addition of an ignition pipe for easy ignition of the biomass fuel, and elinination of the primary air heat exchanger due to manufacturing complexity. Five villages were scheduled to recieve and operate the modified units for one year.

### 3.1.5 Corn Cobs as a Gasifier Feedstock

Initial efforts to study corn cobs as a gasifier fuel were applied to grain drying energy concerns. Payne (1978) evaluated pyrolysis, gasification, and combustion of corn cobs as energy substitutes for propane in grain drying. Gasification was identified as the least costly of the three methods, though hardware needs improvement for ash and char elimination. Peart et al (1980) built a prototype gasifier- grain dryer and used the results of tests to develop an economic model for predicting drying costs of gasifier powered and conventional grain drying. The analysis endoresd the corn cob gasifier dryer as economical if cob handling equipment on the combine and the gasifier cost less than $30,000. Doering (1978) developed an elaborate computer simulation model of corn cob gasification for grain drying, and concluded that the decision in favor of cob gasification systems would depend on system cost, the value of the advantage of controlling a critical fuel supply, in addition to the extra management required along with safety and convenience considerations.

Richey (1983) fabricated and sucessfully tested an automatic cob feeding system on a pressurized downdraft gasifier. Methods for regulating the cob level, eliminating gas leakage and metering cob flow into the gasifier were incorporated into the design. This system was used to fuel a dryer for corn.

The particulate emissions of corn cobs in a rectangular downdraft gasifier were studied by Kutz (1983). He found a linear relationship between the gasification rate and the primary air flow rate. The moisture content of the cobs was identified as an important factor affecting the gasification rate. Increasing the moisture content caused a decrease in gasification rate for a constant air flow rate. This occured as a result of the energy consumed to evaporate water in the fuel. The range of moisture contents evaluated were 8.1%, 23.2%, and 32.0% wet basis.

Riggins et al (1980) compared the energy content of corn cobs and corn stalks at varying maoisture contents for the cobs, stalks, and kernels. This work showed that the lower the moisture in the cobs, the higher their energy content. A cob moisture prediction equation was developed based on the kernel moisture content. Equilibrium moisture characteristics of corn cobs are important due to the dynamic nature of the climate, and the need to keep cob moisture at acceptable levels. High humidity will cause adsorption of atmospheric water, and low humidity will cause desorption. These phenomena were the subject of a study by White et al (1984) on equilibrium moisture content and equilibrium relative humidity of corn cobs. The experiments were conducted at tempertaures of 10, 30, and

50$^{o}$C, while the moisture contents involved five levels in a range from 5.7%-27.5% wet basis. White compared the Henderson and Chung equations for their predictive behavior in regard to EMC and ERH. Both methods were found to adequately represent the experimental data, though standard errors were variable with both methods. White recommended selecting the method that best fits an application and had the lowest standard error. White derived desorption isotherms for corn cobs and that data is presented in figure 3.4 and 3.5.

Silva et al (1984) researched tar formation in downdraft and updraft gasifiers using corn cobs as a fuel source. A major conclusion of this research was that tar formation increased with increasing moisture content. The fuel was evaluated at 3 moisture levels; 8, 16, and 24 percent wet basis. Secondly, 3 air flow rates were analyzed along with moisture content. They were 16, 32, and 48 liters per minute. The outcome of this study is graphically displayed in figure 3.6.

The gasification characteristics of 30 residue derived fuels used in downdraft gasifiers were presented in Jenkins (1980). His work focused on the variability in fuel quality that a gas producer would tolerate and still perform satisfactorily. The parameters of variability involved fuel form, fuel ash content, air flow rate, and fuel moisture content. The results he obtained stated that corn cobs of a 37 mm (1.5 inch) nominal size with low

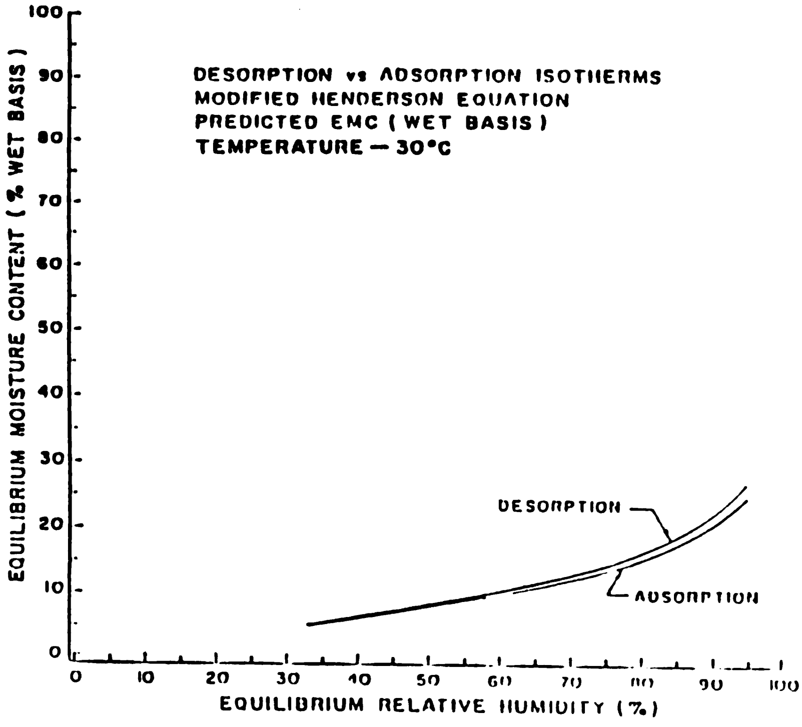



Figure 3.5 Difference in Wet Basis Desorption and Adsorption Isotherms at 30 C When Predicting EMC With Modified Henderson Equation. Source: White et al, 1984

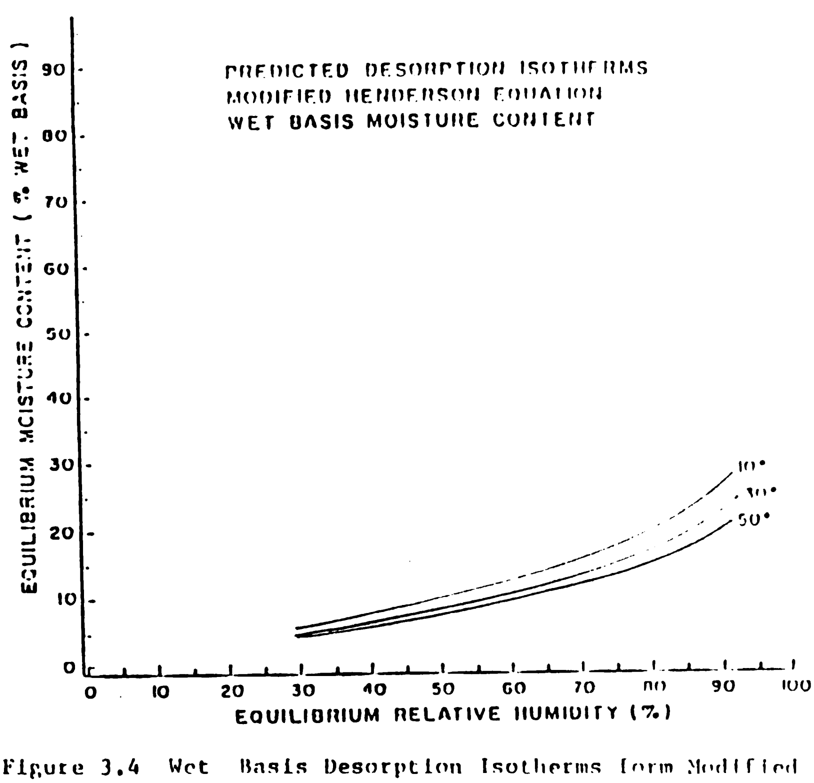



Figure 3.4 Wet Basis Desorption Isotherms form Modified Henderson Equation When Predicting EMC. Source: White et al, 1984

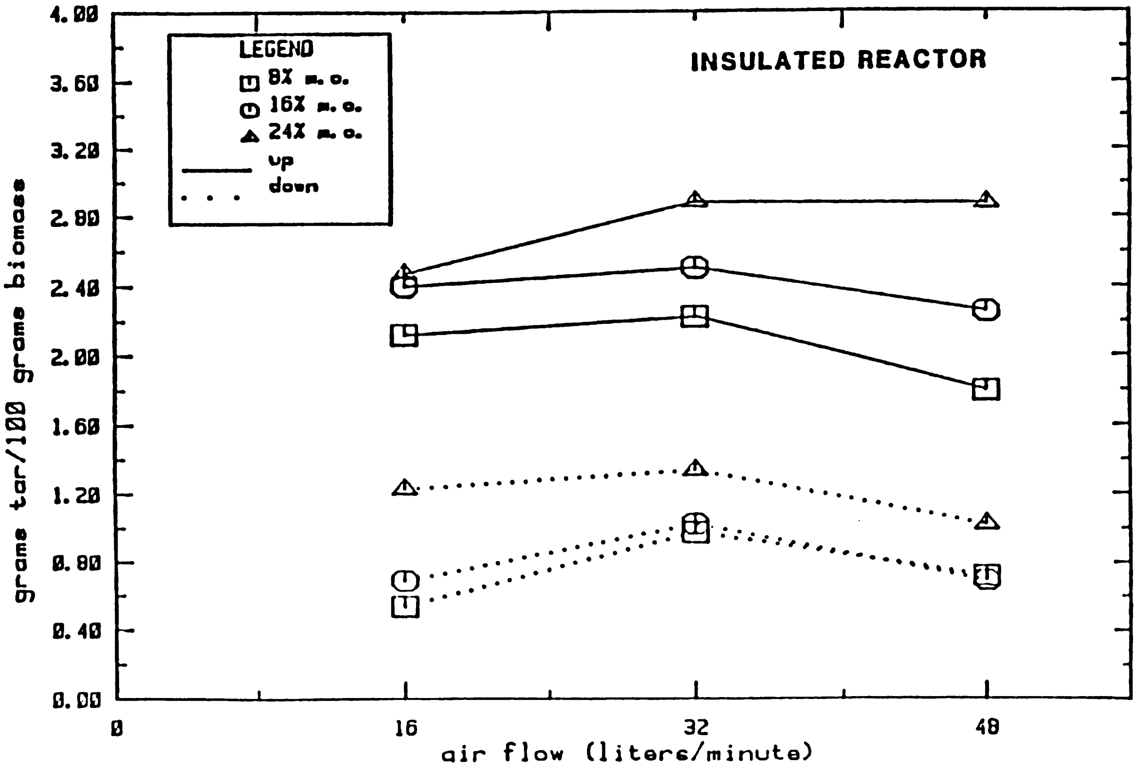



Figure 3.6 Tar From Corncob Gasification, Source: Silva, 1984

percentage of fines was a reasonably good fuel form for gasification. This judgement was made on a criteria that considers the tendency to "bridge" in the gasifier (poor flow characteristics that can cause large voids in the fuel hopper, and inhibit the flow of fuel into the firebox), the magnitude of pressure drops across the fuel bed (low being desirable), the quality of the gas over the duration of the test, and the bulk density refueling interval associated with the fuel type. Wood chips less than or equal to 5 cm square were rated excellent, as were fruit pits. Fine particles, small pellets, walnut shell and low density cubes and pellets of barley straw, cotton gin trash, and cotton stalks were rated poor.

Ash content was important because the ash contains mineral matter (such as silicon) which could melt and then form slag (fused ash) within the firebox of the gasifier. This occurence restricted fuel flow and caused a decrease in gas quality. Jenkins reports the fuels with ash contents lower than 6.0% by weight, did not form slag in the gasifier. Corn cob tests indicated an ash content of only 1.5% and no evidence of slagging.Input air flow rate tests were only reported for peach pits. The results however are applicable to any fuel used in a gasifier. Jenkins found that varying the air flow rate did not alter the air to fuel ratio (AFR) significantly. Increasing air flow rate by 125% increased AFR by 6.7%. Hot and cold gas efficiency increased slightly and reaction temperatures in the oxidation and reduction zones increased. The net heating value of the gas dropped slightly at increased flow rates while the power density (power output of cold gas divided by the fire box volume) increased substantially.

In regard to fuel moisture content, Jenkins work indicated that increasing fuel moisture content lead to an increase in the gas moisture content in addition to a drop in thermal efficiency, reduced firebox temperature, and reduced gas quality. The decrease in thermal efficiency occured due to the energy expended to vaporize the higher volume of water in the fuel. Since this energy is not recovered, efficiency decreases compared to lower moisture conditions. Water vaporization and poor ignition of wet fuel were responsible for the firebox temperature drop. Lower temperatures in the gasifier altered the gas composition and a less "burnable" gas resulted.

## 3.2 Economics of Biomass Gasification

### 3.2.1 Applications Meriting the Gasifier Alternative

From their conception through WW II, gas producers were widely used to operate stationary and mobile engines (Hiscox, 1919; Levin, 1910). In developing nations, the often numerous stationary engines used for grain processing, electrical power generation, and irrigation water pumping, promote interest in gasification as a potential fuel system. Barnard (1984) conducted an assessment for the World Bank and the United Nations Develpoment Program (UNDP), to identify applications in develpoing nations where gasification technology is feasible economic and suited to local needs. He concluded that enterprises and agencies in rural areas already possessing diesel engines, are the principal candidates for the reception of gasification technology. Such a system would be particularly suited to remote areas where electrical grids are non-existant and diesel and gasoline power are the typical options. Barnard reports that remote locations that experience interruptions in fossil fuel supplies might warrant high cost equipment to achieve fuel security.

The principal requirements cited for determining the suitability of a gas generation system were:

1. That the power demand is fairly steady
2. Qualified operators are available
3. A supply of biomass is available

Irrigation was one of the most frequent applications of diesel power in the Sahel. Boutillier (1980) reported that nearly 24,000 hectares of land (table 3.3) are irrigated in the Senegal river valley. This river supplies water to Senegal, Mali, and Mauritania. About 4,000 hectares (10,325 acres) of the total are small irrigation systems of 40 hectares or less. All of the area was fed with water lifted by diesel driven pumps.

Table 3.3 Land Area Under Irrigation with Full Water Control in the Senegal River Valley. Source: Boutillier, 1980 .

| Country | District | Area in Hectares |
|---|---|---|
| Senegal | Delta Perimmeters | 6,970 |
| | Senegal Sugar, Richard Toll | 6,400 |
| | Dagana Perimeter | 2,000 |
| | Nianga | 750 |
| | Podor | 1,640 |
| | Matam | 1,170 |
| | Bakel | 400 |
| Sub Total | | 19,330 |
| Mauritania | M'Pousie | 1,800 |
| | Delta Small Perimeters | 410 |
| | R'Kiz Zone | 390 |
| | Boghe Small Perimeters | 380 |
| | Kaedi Perimeter | 700 |
| | Gorgol Large and Small Perimeters | 335 |
| Sub Total | | 4,015 |
| Mali | Kayes Small Perimeters | 180 |
| Grand Total | | 23,525 |

Groenveld and Westerterp (1980) monitored the performance of a producer gas powered corn sheller and mill in Tanzania. Corn cobs were part of the output of the sheller and were used as an energy input to the engine that operates the sheller/mill. Mill operators were business people who owned their equipment and provided a service to the public.

### 3.2.2 Financial Cost

#### 3.2.2.1 System Cost

The capital cost of the gas generation system is an important variable affecting the outcome of the financial analysis. Van den Aarsen (1984) evaluated the effects of capital and operating costs on the economical feasibility, of small power plants using gasification as a fuel system. His study revealed that large systems have favorable economies of scale over small systems. The higher the power generating capcity the lower the capital cost per unit of power. That data included the cost of the engine.

The problem of comparability between different systems and the lack of a broad set of cost data handicaps any general assessment of economic feasibility of gas generators. In spite of this, progress has been made in obtaining a broad view of the suitability of gasifier technology in developing nations. Barnard (et al) collected information from manufacturers on system costs.

Considerable variation in capital cost was evident, and for this reason the data was divided into 3 cost ranges; low, medium and high. From these he selected an intermediate value in each range and defined this as the "typical" or average cost for the range. The following are his results:

Case 1. Low Cost Gasifier $75/KW

Case 2. Medium Cost Gasifier $200/KW

Case 3. High Cost Gasifier $800/KW

The low cost option represents a scenario in which a nation has significant manufacturing and servicing resources. Mass production of equipment would lower costs to the indicated level. Nations in this category would be India, Brazil, and the Philippines. The medium cost option is considered to be typical of custom made systems for wood or charcoal. The high cost option refers to the lowest cost wood/charcoal gasifiers manufactured in industrialized countries and imported to developing nations. These costs do not include the diesel engine.

3.2.2.2 Maintenance and Labor Cost

Barnard (et al) employs a figure of 10 percent of the capital cost as maintenance cost and adds a lubricant cost of twice that of a diesel. Van den Aarsen (1984) uses a rate of 5-6 percent of capital cost for maintenance. No provision was made for lubricant costs in his work. Groenveld et al indicates maintenance cost are 14 percent higher for the gasification system than without it, for the Tanzanian system.

Additional labor cost of $1,000/year for operating gasifier systems was cited by Barnard. Van den Aarsen shows a higher figure of $4,330/year for systems in the range 20 kva to 150 kva. Groenvelds' study reports that labor costs are the same with gasification and without.

#### 3.2.2.3 Diesel Fuel Cost

The price of fossil fuels has a direct impact on the economics of energy systems. The OPEC oil price increases of the mid 1970's inspired the interest in alternative fuels that followed. Barnard (et al) had performed sensitivity analysis on diesel fuel price versus overall power cost. His findings are presented in figure 3.7.

The 1985 price of diesel fuel in Mali was 213 francs per liter ($1 = 325 francs). Prices for petroleum products in Senegal, Mali, and Mauritania were controlled by their respective governments.

#### 3.2.2.4 Biomass Feedstock Costs

The biomass fuel source under consideration as a gasifier feedstock was corn cobs. Corn was grown under irrigation in the Senegal river valley area. Manteuffel and Tyner (1980) have reported yields of 3 tons per hectare. Wheat and rice are also grown but rice is the predominent crop of the three though it is grown in the wet season,

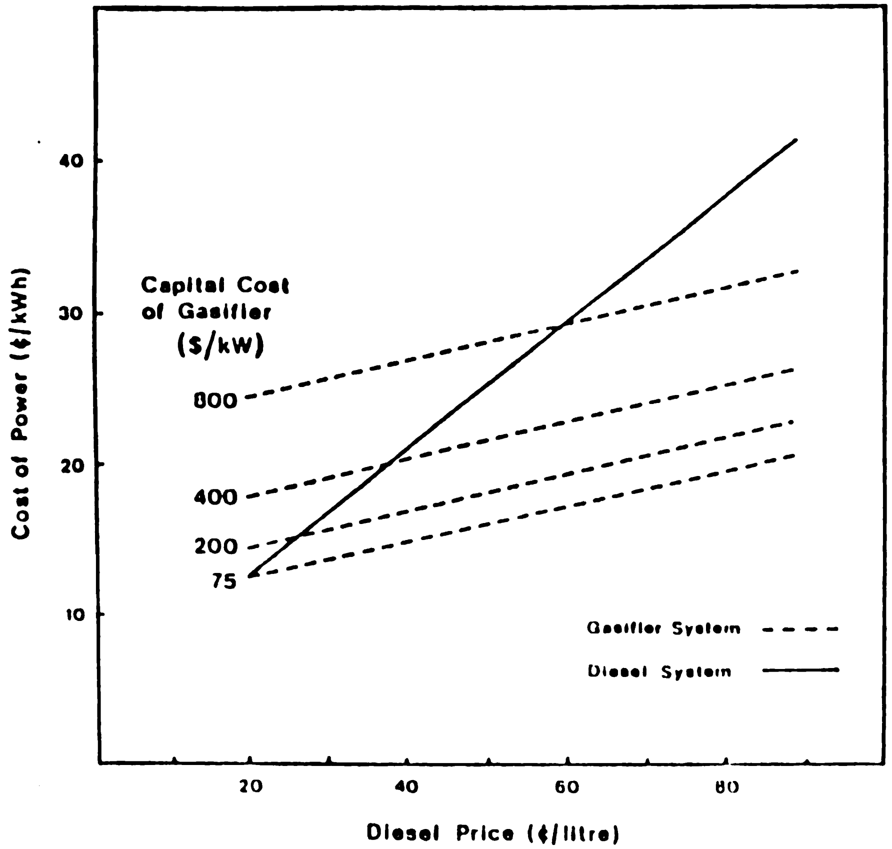



Figure 3.7 Effect of Diesel Fuel Price on Gasifier Economics
Source: Barnard, 1984

while corn and wheat are grown in the dry season. Corn cobs rank as a higher quality feedstock for gasification than either wheat or rice residues (Jenkins, 1980). Table 3.4 characterizes fuel suitability for power.

Based on the authors experience in the area, corn residues were employed as a feed input to livestock production, but not in a formal manner. That is, cobs were not gathered, stored, and fed to livestock to any significant degree. Rather the cobs were thrown out after the shelling operation and grazing animals may eat them when a better source of forage is not immediately available. Livestock typically graze on grass, low growing vegetation and standing crop residue remaining in the fields after harvest. Given this situation, the cost of corn cobs is assumed to be zero since little if any transportation is necessary and alternative uses were not significant.

A recent development in gasifier designs is the open top or stratified gasifier. As the name implies, the top of the gasifier is open, exposing the fuel bed. Air for the reaction in the firebox is drawn through the top of the unit and through the fuel bed. The advantages of this design are that (1) the simpler design permits lower construction cost, (2) the open top allows continous feeding of biomass into the furnace, (3) monitoring of the fuel level and condition are easier for the operator.

Tests conducted by Eoff (1985) produced data which

Table 3.4 Behavior Ranking of Various Fuel Forms
Source: Jenkins, 1980.

| Rank | Fuel Form |
|---|---|
| Excellent | 1. Fruit pits<br>2. Whole log chips of uniform size distribution ≤ 2 inches square |
| Good | 1. Blocks (cut up trim ends from saw boards, etc.) approximately 1" cubes<br>2. Hard, durable cubes (cubed alfalfa seed straw, corn stalks) approximately 1 1/4" x 1 1/4" x 1 1/2"<br>3. Cracked nut shells (walnut, almond shells)<br>4. Hammermilled corn cobs (1 1/2" nominal size and low fraction of fines)<br>5. Hard durable pellets ≥ 3/8" diameter (rice hulls) |
| Poor | 1. Loose, low density cubes or pellets (barley straw, cotton gin trash, cotton stalks, pelleted RDF)<br>2. Fine pellets (1/4" walnut pellets)<br>3. Fine particles<br>4. Hogged wood chips with length to diameter ratio ≥ 2 or large fraction of fines. |

described the minimum and maximum power outputs for a range of open top gas generator dimensions, using wood as a feedstock.

# CHAPTER 4

## 4.1 EQUIPMENT

### 4.1.1 Gasfication System Description

The open top stratified downdraft gasifier was of a cylindrical shape. It measured 20 cm outside diameter by 50 cm high. The interior walls were lined by 2 cm thick asbestos insulation. The fuel hopper was 10 cm in diameter, had a grate area of 45.6 cm2, that was positioned vertically in the interior chamber of the unit (figure 4.1).

The gas exit was at the side of the unit through a 6.2 cm round mild steel pipe, and into a 7.5 X 3.5 cm rectangular mild steel section. The gas then entered a cyclone separator which removed large dust and ash particles from the gas stream. The next stage of gas conditioning was via a polyester cloth filter that removed the smaller particles from the gas stream. The gas then proceeded to a cooler which was a 7.5 cm diameter X 12 meter nylon hose, immersed in a water bath. A 55 gallon oil drum contained the water for the bath. The hose ultimaetly was connected to the engine via a tee-type mixing valve, which had a throttle plate for metering air.

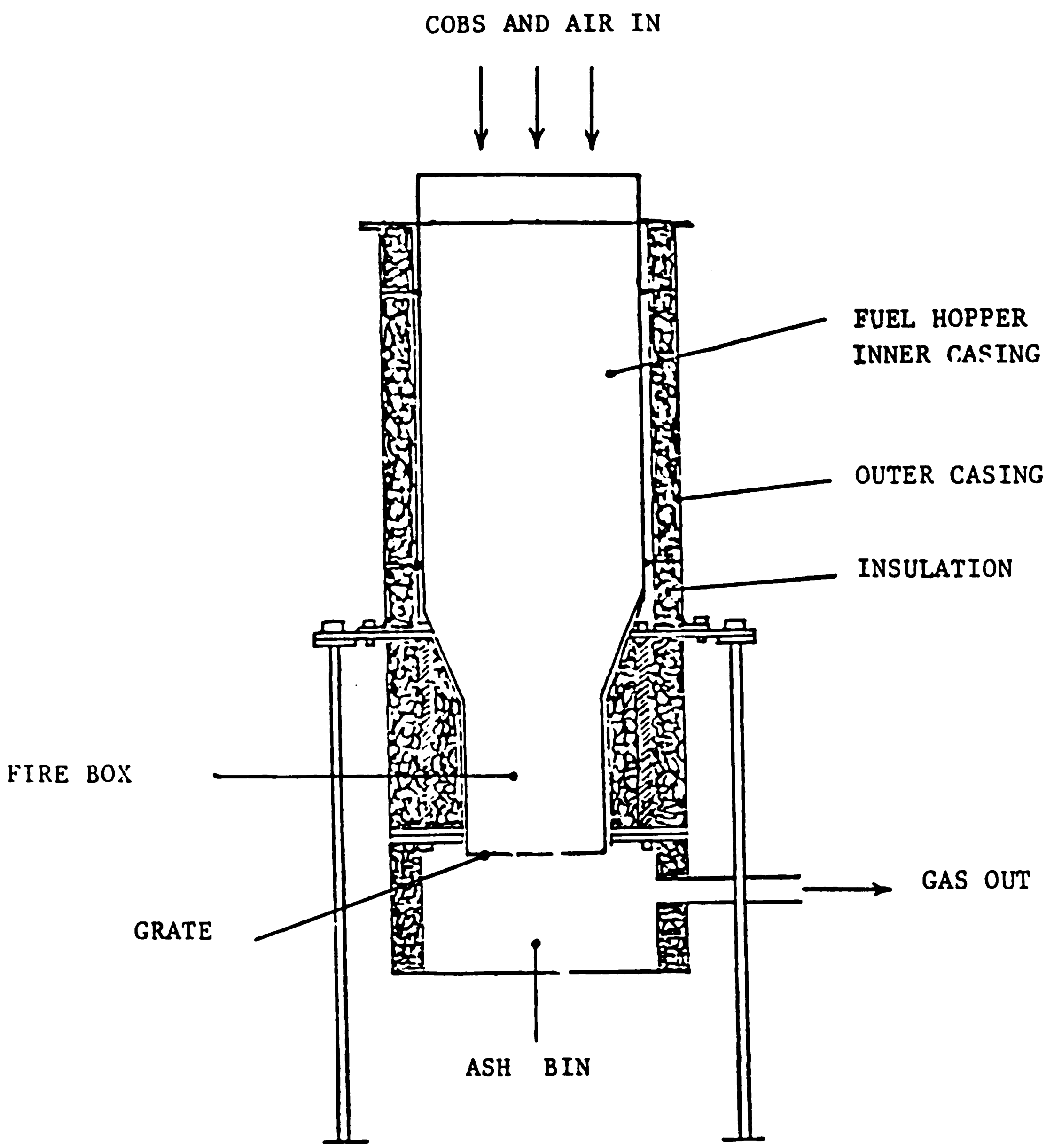



Figure 4.1 Open Top Gasifier Components

#### 4.1.2 Engine Characteristics

The engine used in the experiment was a single cylinder 5hp Stover pre combustion type diesel. It was water cooled, had a manual start and a maximum speed of 1,000 rpm. Stock performance specifications are cited in the Appendix. The Bosch injection pump was not modified to control the pilot amount of fuel injected for ignition of the gas. Instead the governing mechanism was used to control the quantity of fuel delivered to the combustion chamber. This permitted a quantity of fuel sufficient for idle speed operation and ignition of the producer gas, to be delivered to the combustion chamber at all times. When the engine was running at speed and producer gas was introduced to the engine, the combined energy of the two fuels caused the engine speed to increase. The governor reacted to the higher speed by diminishing the amount of diesel fuel injected into the combustion chamber, reducing the engine speed to the previous level. Figure 4.2 shows the layout of the gasifier and engine system.

#### 4.1.3 Analog to Digital Data Conversion Hardware

The above sensors fed analog voltage signals to the Starbuck 8232 data acquisition and control unit. The unit had 8 analog inputs, 8 digital inputs, and 8 digital outputs. This study uses 5 analog inputs as follows:

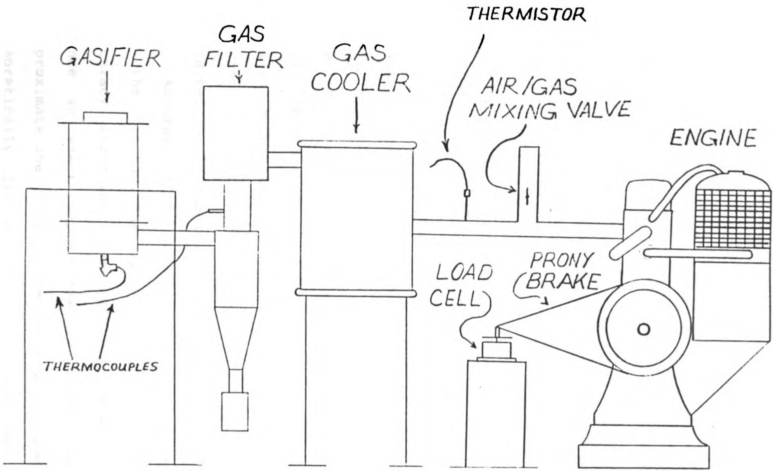



Figure 4.2 Gasifier System/Engine Arrangement

Channel 1 - magnetic pickup
" 2 - Load cell
" 3 - Linear thermistor 0-100$^{o}$C
" 4 - K- type thermocouple
" 5 - 2nd K-type thermocouple

The unit required a power supply of 9 VDC at 100 MA. This was provided by a 115 VAC to 9 VDC transformer.

The Starbuck 8232 analog to digital (A/D) and digital to analog (D/A) converter, produced an 8 bit digital signal from an analog voltage. This process was called quantization.

The quantization operation involved replacing the exact value of the analog signal with one of the quantized values. A signal was quantized by dividing the amplitude axis into levels which were assigned "N" numbers ie 0-255. When the interval between levels was defined, quantization could be carried out. The interval between levels was called a quantum (q). If the amplitude of an input signal vector lies within the interval (nq,(n+1)q) its value was obtained by the quantity nq.

Accuracy of the quantized signal depended on the size of the quantum. The smaller the quantum the higher the accuracy. Error was introduced in the quantization process since an exact input signal value was replaced by an approximate one. This occured because a signal range could theoretically divided into an infinite number of values, while quantization imposes a finite number of values for the same signal range. For digital information given in n bits to the base b, and a maximum input signal amplitude given by E, the quantum level is:

$$q = \frac{E}{b^n}$$

The relative error is given by the expression:

$$E = \frac{1}{b^n}$$

The full scale analog input votltage was 5.33 volts dc. With n = 8 bits and b = base 2 (digital signals) the peak digital signal was equivalent to a decimal value of 255 ($b^n$). Thus the 5.33 volt range was divided (quantized) into 256 equal parts. Each part represents 0.02 volts dc (quantum) of the 5.33 volt range. This value was also referred to as the resolution of the converter since 0.02 volts dc was the smallest analog signal difference the converter can detect. The quantization error for the Starbuck 8232 was plus or minus one least significant bit (LSB).

Initially data points were held in the on board Random Access Memory (RAM) of the A/D converter. The memory capacity of the unit was 1,975 data points. Calibration data and raw treatment data were downloaded to the Radio Shack Model 100 upon completion of each treatment run. The data was then transferred to magnetic cassette tape for permanent storage. The Model 100 had 32 kilobytes of RAM, 27 of which were available for temporary data storage.

The Model 100 contains a built in modem with software selectable communications parameters. It was connected to the A/D converter via serial type RS-232c connectors and standard ribbon type cable. The A/D connverter was capable of communicating to Data Terminal Equipment (DTE) or Data Communications Equipment (DCE). The DTE mode was used with the Model 100. No special hardware or equipment was necessary to interface the Model 100 to the A/D converter. The data acquisition hardware is represented in figure 4.3.

### 4.1.4 Engine Horsepower Measurement

Engine horespower is a function of enigine speed and applied load. When a prony brake was used to measure horespower, the length of the lever arm multiplies the load and was considered in calculating horespower. The expression for horsepower is:

$$HP = \frac{2 \quad L \times F \times N}{33{,}000 \text{ ft-lb/min}}$$

where: L = the length of the prony brake arm (feet)

F = the force measured at the tip of the prony brake (lbs)

N = the speed of the engine in rpm

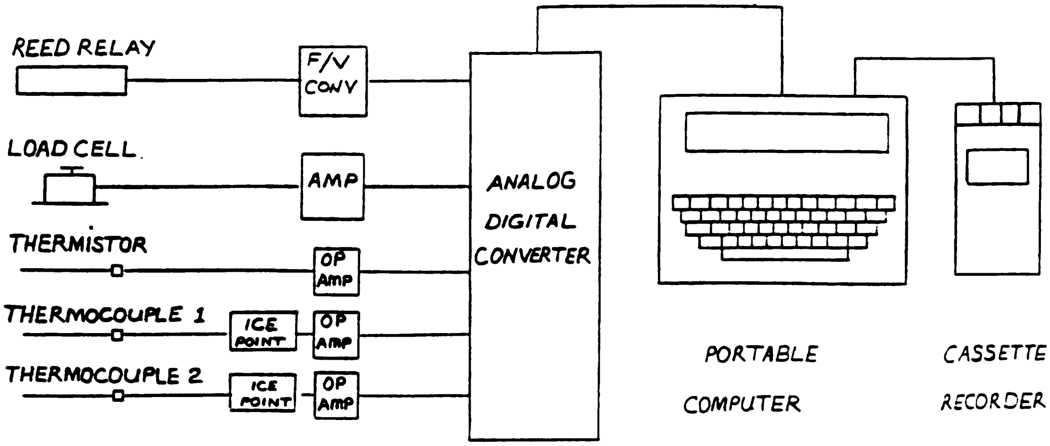



Figure 4.3 Digital Data Acquisition System

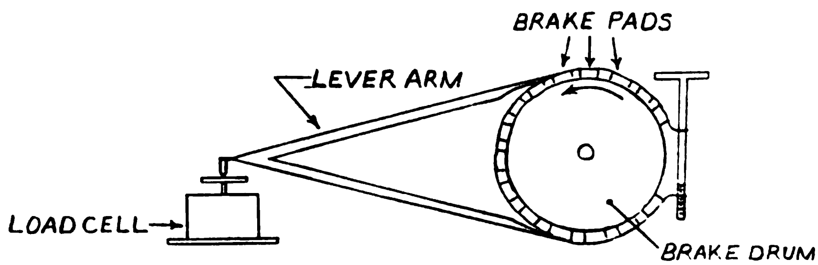



Figure 4.4 The Prony Brake Mechanism

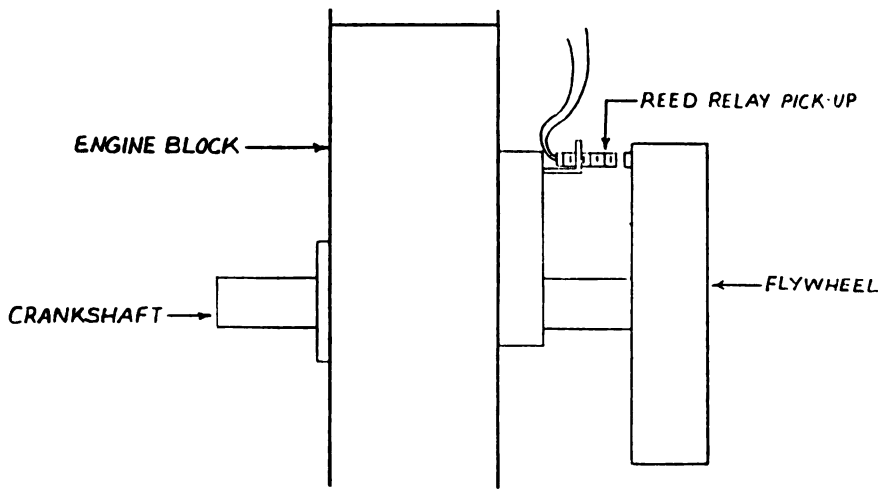



Figure 4.5 Reed Relay Pick-up Position

In these experiments a reed relay pick-up and triggering magnet was used to obtain readings on engine speed. The relay switch was rigidly mounted to the engine block and a single 12 mm diameter permanent magnet was glued to the inside face of the engine flywheel (figure 4.5). A voltage source was connected to the leads of the normally open relay. As the flywheel rotated the magnet passed the relay causing it to momentarily close. This closure allowed current to flow in the relay circuit. The rapid opening and closing of the relay created countable pulses that correspond to a frequency in cycles per second (Hertz). One pulse was generated per revolution of the crankshaft with one magnet. If for example 10 revolutions occured per second 10 pulses were generated each second. The engine speed in revolutions per minute (RPM) was:

$$\text{Engine Speed} = \frac{10 \text{ revs}}{\text{sec}} \times \frac{60 \text{ sec}}{\text{min}} = 600 \text{ RPM}$$

The frequency was then translated into engine speed electronically via a frequency to voltage converter. Basically, the frequency to voltage converter was a signal processing circuit that produces an analog DC voltage output proportional to the input frequency. The higher the frequency the higher the output voltage. The frequency voltage circuit for this experiment produced 90-100 mv per 100 rpm change in speed in the range 400 to 600 rpm.

The overall accuracy of the engine speed detection system was a function of the accuracy of the calibration instrument and the accuracy of the measurement system. The A/D converter had an accuracy of $\pm 1$ least significant bit. With a full scale (FS) input range of 5.33 volts dc, 1 bit was equivalent to 0.0208 volts. Thus the accuracy of the A/D converter was $\pm 0.0208$ volts at 5.33 volts FS. The strobe tachometer had scale graduations of 20 rpm. Readings could be made to the nearest 10 rpm ie 1/2 graduation. The highest calibration factor encountered was 174.9 rpm/volt. The maximum accuracy then:

$$\frac{(5.33 + 0.0208) \times (174.9 + 10) - (5.33 \times 174.9)}{5.33 \times 174.9} = 0.06136$$

or 6.136%.

The prony brake was made of a cast iron drum 35 cm in diameter with a contact surface was 12.7 cm wide. The lever arm was 75 cm long and was attached to a brake shoe composed of a steel strap carrier with 19 brake pads. The brake pads were simple wooden blocks 4.0 x 2.0 x 11.0 cm. A threaded T-handle rod clamped the arm and shoe assembly to the drum. As the engine turned the drum, the drum tried to turn the lever arm. The brake pads permitted some slippage allowing the lever arm to remain stationary, but transmited some force from the rotating drum. A weighing scale or other force measuring device was placed under the tip of the lever arm, to obtain the magnitude of the force transmitted by the prony brake mechanism. The brake mechanism is diagramed in figure 4.4. A Daytronics model 152A-25 lb LVDT load cell was employed to sense the load transmitted by the prony brake. The LVDT (linear varibale differential transformer) load cell was a force transducer. This device produced an electrical signal (voltage) proportional to the applied force. It functioned on the principles of cantilever beam deflection. When the beam within the device was loaded, a deflection of the beam occured which was proportional to the load (force). The deflection of the beam displaced the armature of the variable differential transformer. As the armatures postion changed, the distribution of the magnetic flux field changed. This change in magnetic flux altered the voltage induced in the transformer. In this manner each load had an associated deflection and output voltage (Seippel 1983). The LVDT was supplied with an input AC voltage as a source of elecrical energy.

The load cell was connected to a Daytronics Model 300 signal transformer/amplifier. The amplifier amplified the analog voltage originating from the load cell. This signal was calibrated to produce an output equal to 0.5 volts DC per pound. The output of the amplifier/transformer was directed to the analog to digital converter for futher processing. These readings were required to determine the horspower produced by the engine.

The accuracy of the force measuring system was accounted for by the accuracy of the A/D converter and the accuracy of the weights used as reference loads. The accuray for the A/D converter was $\pm$0.0208 volts in 5.33 volts FS. The reference weights had an error of 12 grams in 4,540 grams. The calibration factor for the load cell was 0.84 kg/volt. The maximum accuracy for the force measuring system was equal to:

$$\frac{(5.3508 \times (0.84 + 0.012)) - (5.33 \times 0.84)}{5.33 \times 0.84} = 0.0182 \text{ or } 1.82\%$$

4.1.5 Gas Temperature Measurement Instrumentation

Temperature information was needed from the fire box zone of the gasifier to monitor the effect fuel moisture content had on the reaction temperature. Temperatures inside the gasifier unit typically reached peak of around 1,000$^{o}$C. A sensor for this application must tolerate oxidizing and reducing environments, and withstand high temperatures for extended periods of time. Response time was not a critical factor because the temperature levels were relatively stable for all treatments.

In the gas circuit between the gasifier and the gas cooler, temperatures in the 300-400$^{o}$C range occured. A sensor for this application must have characteristics similar to those indicated above though toleration of oxidizing and reducing environments was not important here. For both of the above applications temperature sensors of the thermocouple type K were suitable.

A thermocouple was a thermo-electrical device that converts temperature to a corresponding electrical signal. The principal of operation behind the thermocouple involves the Seebeck Effect (discovered by Thomas J. Seebeck). Two wires, each composed of dissimilar metals, were fused together on both ends forming a loop. When one of the connections (junction) was heated, an electrical current flows form one wire to the other (Sippel 1983). Thermocouples produce electrical signals in millivolts. The higher the temperature the larger the millivolt signal. Downstream from the gas cooler temperatures will be much lower, in the 30-70$^{o}$C range. The sensor must withstand temperature peaks up to 100$^{o}$C and be capable of functioning at 70$^{o}$C for extended periods. In addition the sensor must penetrate a closed pipe to sense the temperature of the gas within. It must therefore be designed in a way that will facilitate mounting and positioning it in a pipe, and also be resistant to the chemical composition of the gas. Given these requirements a thermistor type sensor with stainless steel sheath and a compression type fitting were most appropriate.

A thermistor was a thermoelectric device fabricated from semiconductor materials such as oxides of cobalt, manganese, and nickel. This device had a characteristic behavior such that as temperature increased, its resistance (to electric current) decreased. This was referred to as the Faraday Effect (Seippel,1983), and the thermistor had a negative temperature coefficient since resistance decreased as temperature increased. Temperature information was obtained by exciting the device with a power supply such as a small battery and measuring the voltage that exits the thermistor at various temperatures. Since the thermistor had a negative temperature coefficient, the voltage at relatively low temperatures was high, and was lower at higher temperatures.

Temperature sensors were used at 3 points in the gasifier system (figure 4.2):

1. At the firebox within the gasifier
2. At the gas cooler inlet
3. At the gas cooler outlet

At the firebox and the gas cooler inlet Omega Type K thermocouples were used. The firebox was fitted with a 14 gage K type element with an Omegatite 300 1/2" O.D. X 5/16" I.D. X 12" long ceramic protection tube. The thermocuple assembly was inserted through the bottom of the gasifier and protrudes upward stopping just below the grate of the firebox. This permitted the sensing of the temperature of the incandesent fuel in the fire box.

The cooler inlet was fitted with a stainless steel protected K-type thermocouple for extruders No. CF-090-K-4-60-1 also from Omega emgineering. The compression fitting on the thermocouple assembly attached to a corresponding riser on the inlet pipe. The depth was adjusted to place the tip of the thermocouple in the center of the gas stream.

Each thermocouple was connected to an Omega MCJ-K electronic ice point with a temperature reference setting of $0^{o}C$. K-type thermocouple wire was employed to extend the connections to the electronic ice points. The electronic ice point effectively replaced the external reference junction needed for measuring the output voltage of thermocouples and therefore temperature. The electronic ice point converted thermocouple outputs to $0^{o}C$ referenced voltages. In this way the voltage reading from the thermocouple corresponded to a temperature based on $0^{o}C$ as a starting point. The electronic ice point was fully compensated so copper wire could be used to connect the ice point to the data acquisition unit. Slightly downstream from the cooler a linear output thermistor was used to sense the cooled gas temperature just prior to entry into the engine.

As with the other instruments, the accuracy of these devices depended on that of the reference instruments and of the A/D converter. The referfence tables were used for the thermocouple temperatures. These tables were provided by the manufacturer of the devices, and correspond to standrads established by the American National Standards Institute (ANSI). The error limit cited for type K thermocouples was $\pm$ $2.2^{o}C$ in the range 0 - $1250^{o}C$. The maximum calibration factor for the high temperature thermocouple was 176.98°C/volt. Maximum error for this device then was 1.64% using the same procedure as above.

The accuracy for the low temperature thermocouple (channel 5) was likewise calculated. The calibration factor in this instance was 89.24°C/volt. The resulting maximum error value was ±2.865%.

In the case of the thermistor (channel 3), a mercury filled glass thermometer was used as a reference. The thermometer had graduations of 1°C. Readings were possible to 0.5°C. The largest calibration factor attained was 6.62°C/volt. The maximum accuracy in this case was 7.97%

4.1.6 Data Acquisition Software

The Starbuck 8232 A/D and D/A converter contained instruction sets for: (1) selecting sampling rates, (2) allocating RAM to each channel, (3) starting the acquisition of data, (4) displaying the acquired data, (5) displaying the channel pre-set status and (6) clearing the channel settings. These instructions were combined with BASIC language commands from the Radio Shack Model 100 , in this way, instructions were sent to the A/D converter using a BASIC language program in the Model 100.

When the system was operating, the sensors, transducers and their signal conditioning circuitry, provided continuous dc voltage input signals to the Starbuck 8232 A/D connverter. This input signal was not continuously recorded by the A/D converter, samples were taken at regular intervals, and the average of these samples was taken as the reading for the treatment. The sampling rate was an important factor in the precision of data acquisition. If the dimension being sensed behaved or responded in a non-steady state manner, a low sampling rate may miss important data points during the interval period between samples. At the other extreme, very high sampling rates generated large data sets, much of which was redundant and required massive memory space in the equipment that holds the data. The ideal rate was one which provides the necessary information and was compatible with the available data storage devices.

There were two channels in the system that exhibited signal fluctuation warranting relatively high sampling rates; channel 1 (reed relay pick-up) and channel 2 (load cell). Trials were run at rates of 2 Hz, 1 Hz, 0.5 Hz, and 0.25 Hz. These trials indicated that 0.5 Hz provided sufficient information.

The sampling rate for channels 1 and 2 was 2 seconds. The interval for channels 3 and 4 was 15 seconds, and channel 5 had an interval of 5 seconds.The treatment run period was 10 minutes giving 300 data points for each of the first two channels, 40 data points per channel for channels 3 and 4, and 120 data points for channel 5. The total number of data points collected per treatment was 800.

Configuration of the A/D converter for the sampling rate, channel memory, and the "start acquisition" command was accomplished with a BASIC language program. This initiated data acquisition within the A/D converter and acquisition ceased when the channel memory area was full. When all channel memories were full another routine downloads the raw data from the A/D converter to the Model 100. The raw data was held in a RAM data file for subsequent storage on magnetic cassette tape. The raw data was then routed to a subroutine that determined the mean and the standard deviation for the treatment. These were also held in a RAM data file for later storage on magnetic tape.

When all treatments had been executed an analysis of variance program was used to calculate the test statistic for the treatment classes. Flow charts of the configuration program, and downloading program are presented in figures 4.6 and 4.7.

## 4.2 Sensor and Instrument Calibration

Calibration was the process of indexing the output of measurement devices to physical quantities that were of interest to the investigator. Without calibration one cannot be certain of the magnitude of a particular dimension, the sensors output represents.

Since all measurement devices in this experiment produced direct current voltage signals in the range 0-5.0

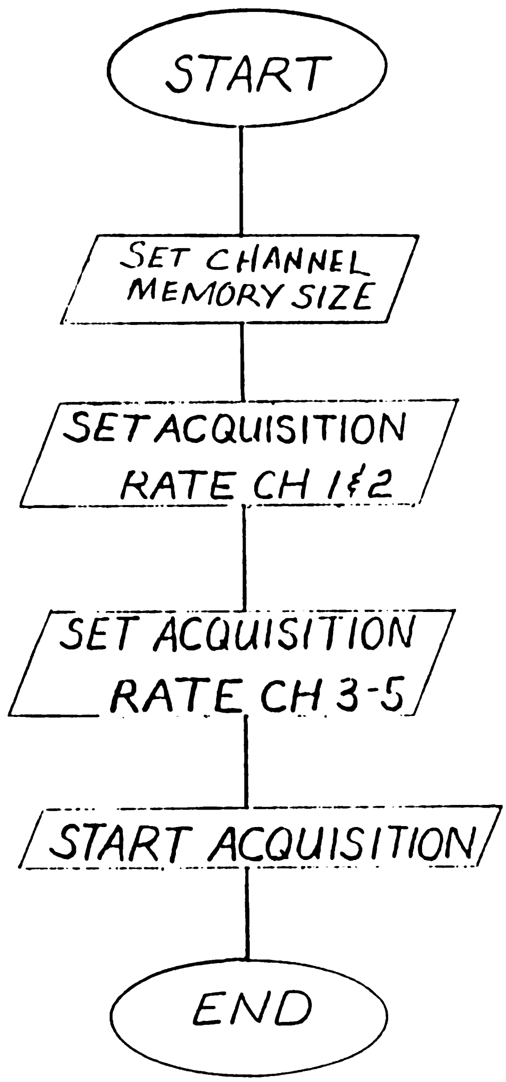



Figure 4.6 Flowchart for A/D Converter Channel Sampling Parameters

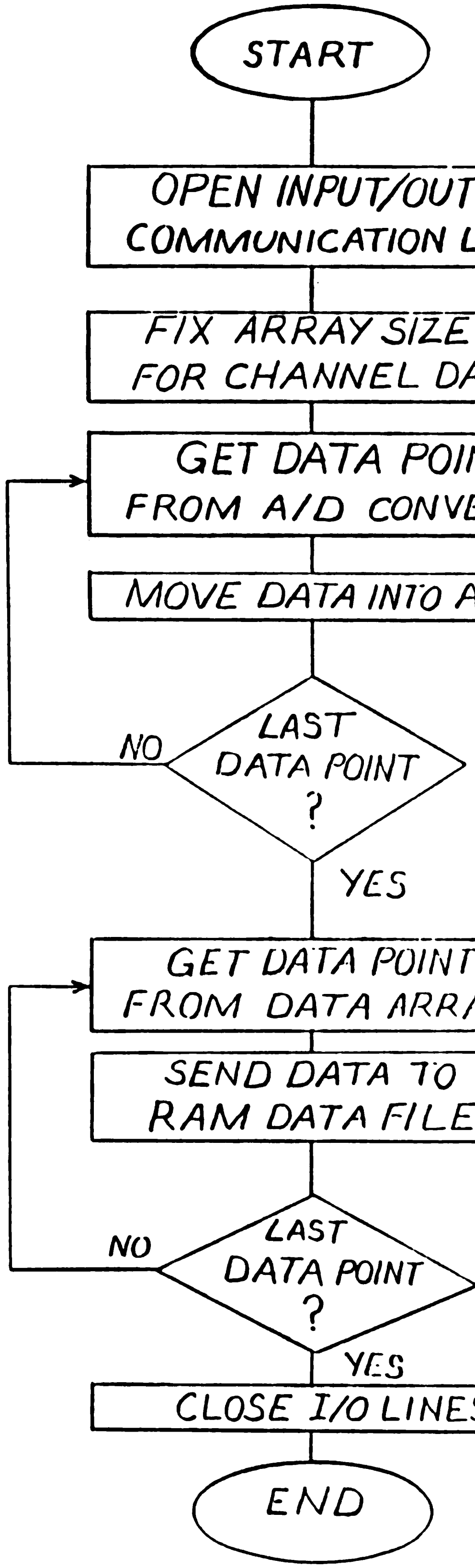



Figure 4.7 Flowchart of the Downloading Program to Transfer Data from the A/D Converter to the Portable Computer

volts, the real world physical dimensions corresponded to a voltage in this range.

### 4.2.1 Engine Speed

The engine speed in revolutions per minute (RPM) was provided by a reed relay pick-up and triggering magnet. The output pulse signal was conditioned, counted and converted to a voltage by electronic circuitry. The circuit was referred to as a frequency to voltage converter.

To determine the output voltage at various speeds, an analog strobe type tachometer was employed. This device operated on reflected light signals recieved from reflective tape placed on the rotating flywheel of the engine. In essence the number of reflections recieved in a given time period were directly converted to speed.

Two pieces of reflective tape were placed equidistant on the flywheel to provide a more accurate reading of the engine speed. With this arrangement the strobe tach reading was divided by 2 to obtain the actual engine speed.Readings were taken in steps of 100 rpm beginning with 400 rpm and extending up to 600 rpm. This process was repeated three times and the values averaged to obtain an output voltage at the given speed.

Table 4.1 shows the data points taken during the calibration runs. Readings were repeated three times and averages calculated for each speed.

TABLE 4.1 ENGINE SPEED CALIBRATION DATA

| ENGINE SPEED | REP 1 | REP 2 | REP 3 | MEAN |
|---|---|---|---|---|
| 400 | 3.25 | 3.23 | 3.215 | 3.23 |
| 500 | 3.35 | 3.35 | 3.33 | 3.34 |
| 600 | 3.44 | 3.43 | 3.42 | 3.43 |

A linear regression equation was derived from the averages and used to produce a calibration curve for engine speed. The curve is plotted in figure 4.8. The regression equation was employed in the data conversion and analysis computer program for horespower determination. The equation had a correlation coefficient ($r^2$) of 0.997 indicating strong linear relationships.

4.2.2 Load Cell Calibration

The load cell senses the force exerted by the engine through the prony brake. This device was of the linear variable differential transformer type (LVDT). The output was linear for loads within its operating range of 0-11.34 kg (0-25 lbs).

Calibration was performed using weights in 454 gram increments in the range 454 grams to 4,540 grams (1 lb to 10 lbs). The load cell and amplifier were allowed to warm up for 30 minutes prior to calibration. The load cell was fitted with a rubbing block for the prony brake arm, before being adjusted to zero output. The load cell was subsequently loaded to 4,540 grams in steps of 454 grams.

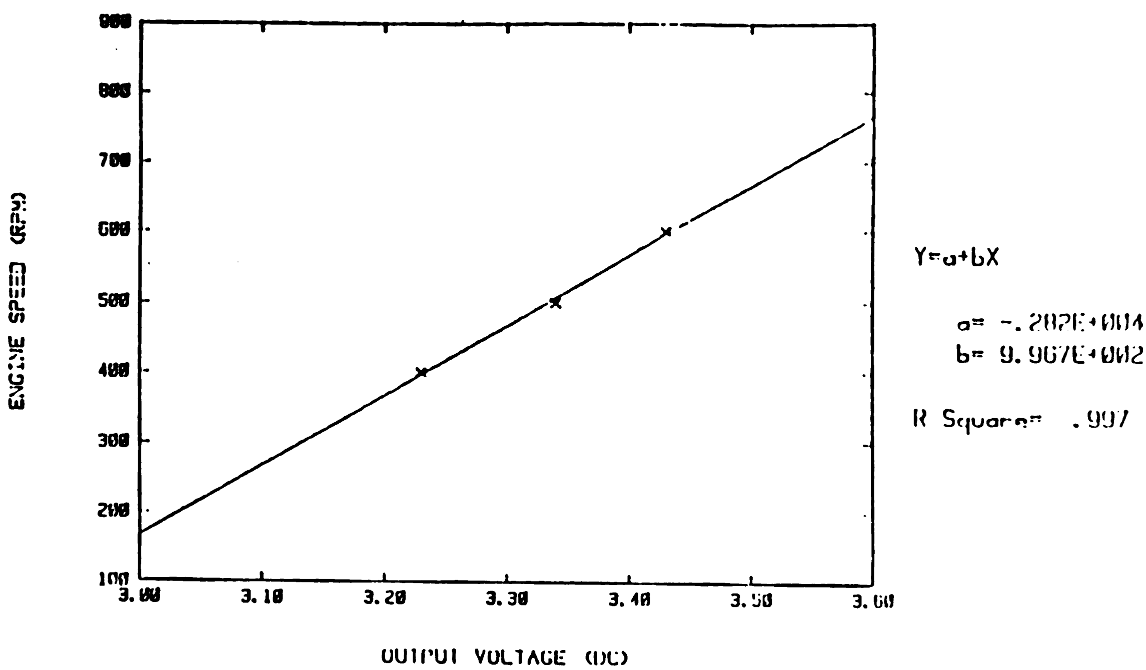



Figure 4.8 Engine Speed Calibration Curve
Data points from Table 4.1

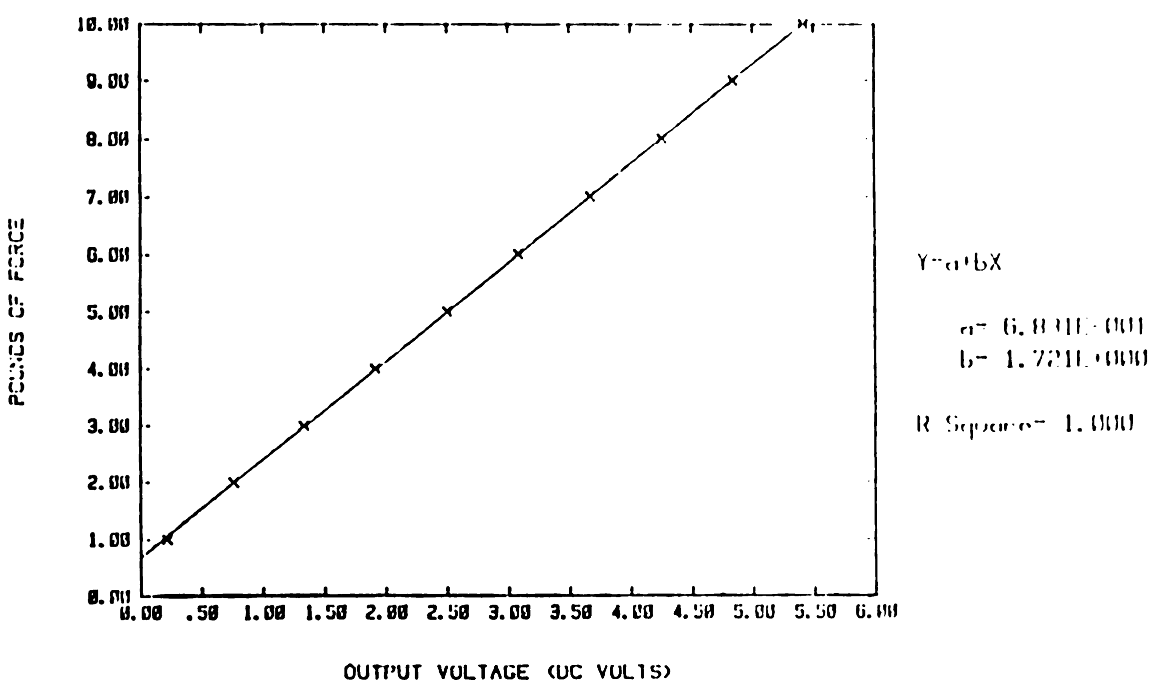



Figure 4.9 Load Cell Calibration Curve - using data points from Table 4.1

Then it was unloaded in the same manner to reveal if any hysterisis effects were present. The process was repeated 2 times for loading and unloading the load cell.

The values obtained were averaged and used to fit a linear regression curve. The raw data points from the calibration exercise are in tables 4.2 and 4.3. The calibration curve is presented in figure 4.9. The regression equation for the load cell data was contained in the computer program for horse power determination. As expected the data exhibited extremely high linearity as judged by the correlation coefficient of 1.000.

TABLE 4.2 LOAD CELL CALIBRATION DATA - INCREASING FORCE

| FORCE GRAMS | REP 1 | REP 2 | MEAN |
|---|---|---|---|
| 454 | 0.22 | 0.23 | 0.225 |
| 908 | 0.75 | 0.77 | 0.760 |
| 1362 | 1.32 | 1.34 | 1.330 |
| 1816 | 1.88 | 1.92 | 1.900 |
| 2270 | 2.50 | 2.50 | 2.500 |
| 2724 | 3.08 | 3.10 | 3.090 |
| 3178 | 3.67 | 3.68 | 3.675 |
| 3632 | 4.26 | 4.26 | 4.260 |
| 4086 | 4.84 | 4.85 | 4.845 |
| 4540 | 5.42 | 5.43 | 5.425 |

TABLE 4.3 LOAD CELL CALIBRATION DATA - DECREASING FORCE

| FORCE IN GRAMS | REP 1 | REP 2 | MEAN |
|---|---|---|---|
| 4540 | 5.42 | 5.42 | 5.420 |
| 4086 | 4.84 | 4.83 | 4.835 |
| 3632 | 4.25 | 4.25 | 4.250 |
| 3178 | 3.66 | 3.66 | 3.660 |
| 2724 | 3.08 | 3.07 | 3.075 |
| 2270 | 2.49 | 2.48 | 2.485 |
| 1816 | 1.92 | 1.90 | 1.910 |
| 1362 | 1.34 | 1.32 | 1.330 |
| 908 | 0.77 | 0.75 | 0.760 |
| 454 | 0.24 | 0.22 | 0.230 |

### 4.2.3 Thermistor Calibration

The thermistor was a temperature sensing device. In this application it has sensed gas temperatures in the 30-50°C range as the gas exits the cooler. The thermistor probe was calibrated using a mercury filled thermometer with 1°C graduations.

The method used involved immersing the thermistor and the thermometer into cold water and taking readings as the water warmed up to room temperature. The same procedure was used with hot water allowed to cool to room temperature. The process was replcated three times and averages calculated for the levels of readings acquired. As was done previously, the averages were used to derive a calibration curve using linear regression. Table 4.4 contains the data readings and the averages while figure 4.10 is a plot of the calibration curve.

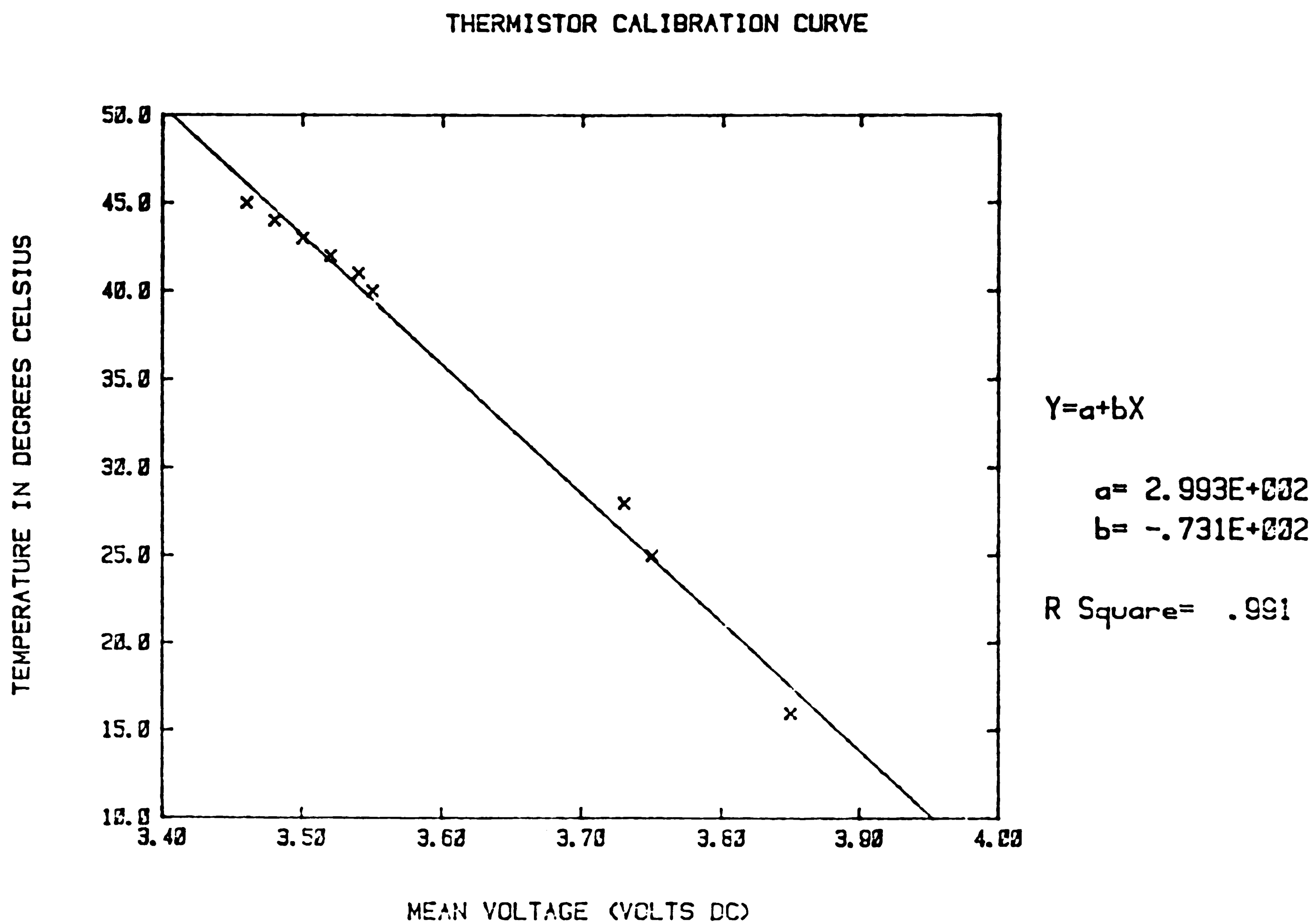



Figure 4.10 Thermistor Calibration Curve using sample data from Table 4.4

TABLE 4.4 THERMISTOR CALIBRATION DATA AND AVERAGES

| TEMP$^{O}$C | REP 1 | REP 2 | REP 3 | MEAN |
|---|---|---|---|---|
| 16 | 3.86 | 3.85 | 3.84 | 3.85 |
| 25 | 3.75 | 3.75 | 3.75 | 3.75 |
| 28 | 3.73 | 3.73 | 3.73 | 3.73 |
| 40 | 3.54 | 3.56 | 3.55 | 3.55 |
| 41 | 3.53 | 3.55 | 3.54 | 3.54 |
| 42 | 3.52 | 3.52 | 3.53 | 3.52 |
| 43 | 3.50 | 3.51 | 3.49 | 3.50 |
| 44 | 3.48 | 3.49 | 3.47 | 3.48 |
| 45 | 3.46 | 3.46 | 3.46 | 3.46 |

### 4.2.4 Thermocouple Calibration

The thermocouples detected the highest temperatures encountered in the experiment. As thermocouples produce very small output signals (millivolts), the output must be amplified. The amplified signal will correspond to the temperature sensed by the thermocouple.

The calibration of the thermocouple was accomplished using a propane torch as a heat source, and using a digital voltmeter to read the unamplified output. The A/D converter was used to obtain the amplified output signal level.

Readings were taken in increments of 0.5 mv (12$^{O}$C) in the range 367-673$^{O}$C for the high temperature thermocouple, and from 98-221.5$^{O}$C for the low temperature thermocouple. Sample observations were replicated at least three times. The means of the observed output levels are shown in Tables 4.5 and 4.6. These mean values were used to obtain linear regression equations which are plotted in figures 4.11 and

4.12. Both sets of data displayed very strong linear relationships as noted by correlation coefficients of 0.999897 for the high temperature thermocouple,and 0.9998 for the low temperature thermocouple at the cooler inlet.

The high temperature thermocouple was outfitted with a ceramic protection tube to protect it from contamination. The protection tube had a slight insulating effect on the the thermocouple and thus the output signal level was lower than an unprotected thermocouple. The magnitude of the difference was measured using two thermocouples. One with ceramic protection and one without the protection. The two thermocouples were simultaeneously heated with a propane torch and the output signal observed. The result of the observations indicated that there was a difference of 6 mv between the two, with the unprotected unit being higher. After amplification this represents 0.71 volts. This difference was allowed for in the data conversion program for the high temperature thermocouple.

Table 4.5 Hi Temperature Thermocouple Calibration Data

| REP 1 VDC | REP 2 VDC | REP 3 VDC | REP 4 VDC | TEMP °C | $V_{AVG}$ |
|---|---|---|---|---|---|
| 1.958 | 1.958 | 1.958 | 1.958 | 367 | 1.958 |
| 2.0208 | 2.0208 | 2.0208 | ----- | 379 | 2.0208 |
| 2.0833 | 2.0833 | 2.0833 | 2.0833 | 391 | 2.0833 |
| 2.1667 | 2.1667 | 2.1667 | ------ | 402 | 2.1667 |
| 2.2292 | 2.2292 | 2.2292 | ------ | 414 | 2.2292 |
| 2.2917 | 2.2917 | ------ | ------ | 426 | 2.2917 |
| 2.375 | 2.3333 | ------ | ------ | 438 | 2.3541 |
| 2.4167 | 2.4167 | 2.4167 | 2.4167 | 450 | 2.4167 |
| 2.4792 | 2.4792 | 2.4792 | 2.4792 | 461 | 2.4792 |
| 2.5417 | 2.5417 | 2.5417 | ------ | 473 | 2.5417 |
| 2.5833 | 2.6042 | 2.5833 | ------ | 485 | 2.5903 |
| 2.6667 | 2.6667 | 2.6875 | ------ | 497 | 2.6736 |
| 2.750 | 2.750 | 2.750 | ------ | 508 | 2.750 |
| 2.8125 | 2.8125 | ----- | ------ | 520 | 2.8125 |
| 2.875 | 2.875 | 2.875 | 2.875 | 532 | 2.875 |
| 2.9375 | 2.9375 | ----- | ----- | 544 | 2.9375 |
| 3.0 | 3.0 | 3.0 | 3.0 | 555 | 3.0 |
| 3.0833 | 3.0625 | ----- | ----- | 567 | 3.0729 |
| 3.125 | 3.125 | ----- | ----- | 579 | 3.125 |
| 3.1875 | 3.2083 | 3.2083 | ----- | 591 | 3.2014 |
| 3.25 | 3.25 | 3.25 | 3.2708 | 602 | 3.2569 |
| 3.3333 | 3.3333 | 3.3333 | 3.3125 | 614 | 3.3250 |
| 3.3958 | 3.3958 | 3.3958 | 3.3958 | 626 | 3.3958 |
| 3.4583 | ------ | ------ | ------ | 638 | 3.4583 |
| 3.5208 | 3.5208 | 3.5208 | 3.5208 | 649 | 3.5208 |
| 3.5833 | 3.5833 | 3.6042 | 3.6042 | 661 | 3.5937 |
| 3.6667 | 3.6667 | 3.6667 | ------ | 673 | 3.6667 |

TABLE 4.6 LOW TEMPERATURE THERMOCOUPLE CALIBRATION DATA

| TEMP oC | REP1 VDC | REP 2 VDC | REP 3 VDC | REP 4 VDC | REP 5 VDC | REP 6 VDC | REP 7 VDC | $V_{AVG}$ |
|---|---|---|---|---|---|---|---|---|
| 98 | 1.125 | 1.1042 | 1.125 | ----- | ----- | ----- | ----- | 1.1181 |
| 110 | 1.25 | 1.271 | 1.25 | 1.271 | ----- | ----- | ----- | 1.2605 |
| 122 | 1.39 | 1.437 | 1.39 | 1.375 | ----- | ----- | ----- | 1.3935 |
| 134 | 1.521 | 1.542 | 1.542 | ----- | ----- | ----- | ----- | 1.5350 |
| 147 | 1.688 | 1.667 | 1.688 | 1.688 | 1.688 | ----- | ----- | 1.6833 |
| 159 | 1.792 | 1.813 | 1.792 | 1.833 | 1.792 | 1.792 | 1.813 | 1.8036 |
| 172 | 1.958 | 1.917 | 1.958 | 1.958 | 1.917 | ----- | ----- | 1.9417 |
| 184 | 2.083 | 2.104 | 2.063 | ----- | ----- | ----- | ----- | 2.0833 |
| 197 | 2.229 | 2.229 | 2.229 | 2.229 | ----- | ----- | ----- | 2.2292 |
| 209 | 2.354 | 2.333 | 2.354 | ----- | ----- | ----- | ----- | 2.3472 |
| 222 | 2.520 | 2.479 | 2.500 | ----- | ----- | ----- | ----- | 2.4997 |

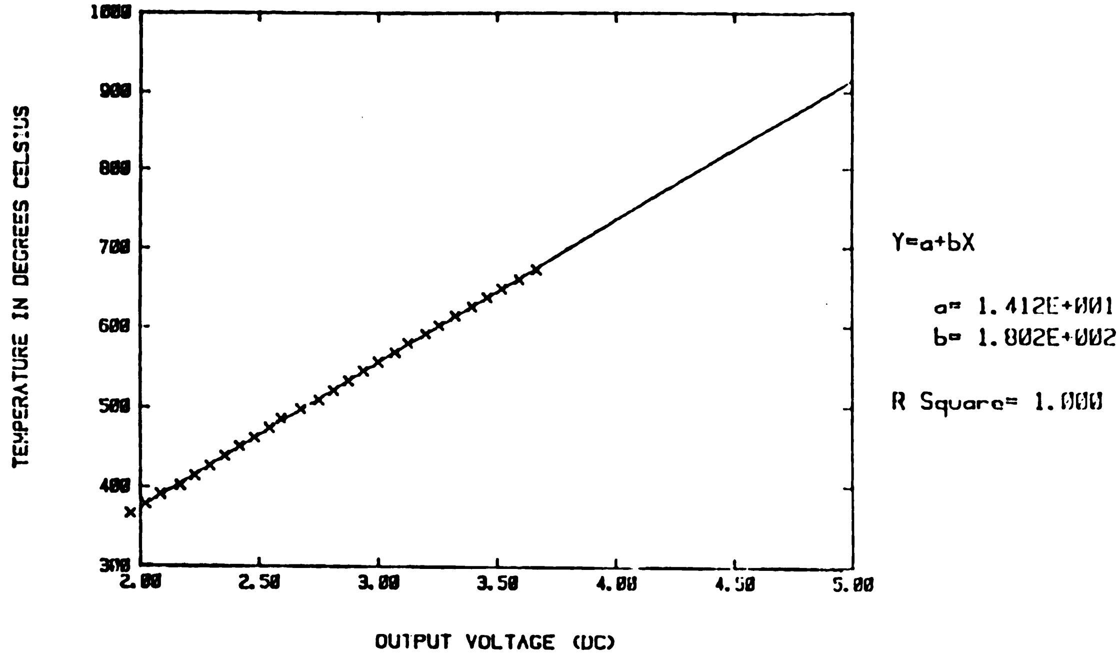



Figure 4.11 High Temperature Thermocouple Calibration Curve - data from Table 4.5

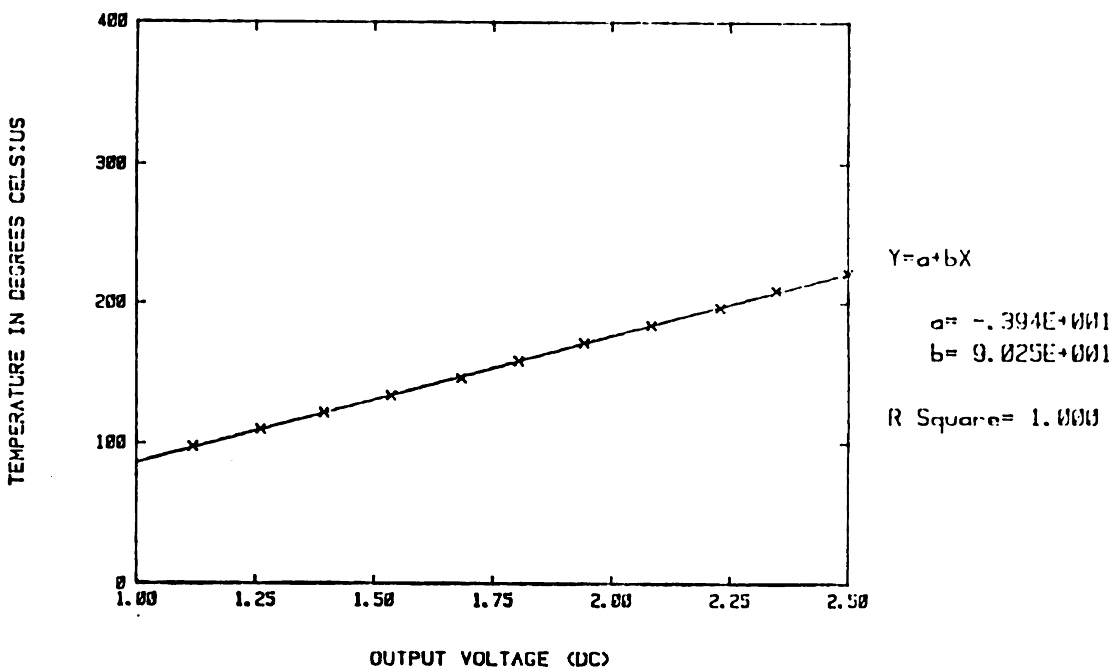



Figure 4.12 Low Temperature Thermocouple (Gas cooler inlet) Calibration Curve - data from Table 4.6

CHAPTER 5

# METHODS AND PROCEDURE

## 5.1 Experimental Design

### 5.1.1 Considerations

The objective of the investigations undertaken in the experiment was to assess the effect of fuel moisture content when gasification was used to power a diesel engine. Specifically, the task was to :

1. Measure the degree to which the cob moisture levels reduces diesel fuel consumption.
2. Deduce if there was a significant difference in diesel fuel consumption between the 3 fuel moisture contents.
3. Determine to what degree cob moisture affected the equilibrium grate temperature.
4. Evaluate the financial implications of gasification with the aid of cost benefit analysis.

The preceeding objectives involve two independent variables; moisture content and engine speed, each tested at 3 different levels. The moisture levels were 5%, 15%, and 25% wet basis. The engine speeds were 400, 500 and 600 rpm. The optimum level of each variable was sought, in addition to the relationship between the two independent variables and the dependent variable, diesel fuel consumption.

Statistical principles provide for an experimental design that accommodates the information desired from this experiment. The design was called a factorial experiment (Steel and Torre, 1980). Factorial designs were valuable for exploratory work where optimum levels of factors were sought or where the objective was to determine which factors were important.

A factor was simply one of the independent variables. However, each factor supplies several treatments to the experimental design. Each treatment represents a given level of the factor.

### 5.1.2 Treatment Selection

This experiment contains two factors; fuel moisture content and engine speed. Both factors had three levels or treatments. Three levels of each factor were chosen since it was important to determine if the nature of the response to the treatments was curvilinear.

Factorial experiments consist of all possible combinations of the three levels of the two factors. This combination yields 3 X 3 or nine treatments.

The term treatment refers to the procedure whos' effect was measured and compared with other treatments. A treatment was applied to an experimental unit, which was the material under evaluation in the experiment. For this case the experimental units were corn cobs.

### 5.1.3 Experimental Error

Variation that exists among observations on experimental units treated alike was called experimental error (Steel and Torre, 1980; Cochran and Cox, 1976). It had two main sources: (1) inherent variability that exits in experimental material to which treatments were applied, and (2) variation resulting from lack of uniformity in the physical implementation of the experiment. Such variation, if large, weakens the strength of the inferences made about the experiment. The weakness was manifested by long confidence intervals about the mean (and or variance) and low power of the test. The principle methods of controlling experimental error are:

1. Handling the experimental material in a way that reduces the effects of inherent variability.
2. Employing refined experimental technique

A detailed discussion of the use of these controls is given in subsequent sections.

### 5.1.4 Replication and Blocking

Replication implies repetition of something. In statistical procedures, replication involves repeated appearances of a treatment (Steel and Torre,1980). Replication was a means of increasing the sensitivity of an experiment by, reducing the standard deviation of the treatment mean. When more replicates were used, estimates of population means were more precise, since more observations were used to obtain that mean. Experimental error and confidence interval information were obtained from replication. Experimental error in the form of the error mean square, was necessary for tests of significance. Without replication one cannot determine if observed differences were due to the difference between treatments (real differences) or the difference between experimental units (inherent variation).

## 5.2 Experimental Procedure

### 5.2.1 Treatment Preparation

In July 1986, approximately 70 KG of corn cobs were obtained from an elevator in Weberville, Michigan. The cobs came from the 1985 crop. The variety of the corn was unknown. After delivery to the Agricultural Engineering Department on the Michigan State University campus, the cobs were cleaned. The cleaning process involved the removal of corn husks, and stalk pieces. Following this the cobs were placed in a sieve with 8 mm X 8 mm openings, to remove corn kernels, cob fines, and dust. Finally the cobs were graded using a 30 mm X 30 mm wire mesh screen. The grading yielded 2 classes of cobs. One class was of whole cobs 53 mm in diameter and 75 to 125 mm long. The second class contained slightly smaller cobs, 30 mm in diameter and 30 to 125 mm long. This class also contained split and broken cobs plus small cob pieces. The latter class of cobs were used in the experiment because there was less void space.

Three moisture levels were prescribed in the factorial experimental design. The initial corn cob moisture level was determined to be 4.8 to 5.2 percent wet basis. Thus to achieve the higher moisture levels of 15% and 25%, moisture was added to the corn cobs. A problem arises in obtaining and maintaining a precise moisture level by adding water. The volume of material was considerable, and some moisture loss could occur over time. Measures taken to reduce this variation involved (1) preparing a volume (batch) that was adequate for completing one replication and (2) keeping the cobs in moisture proof containers. Three batches of cobs were pepared for each replication. Each batch represents 1 of the 3 moisture levels in the experiment. Additionally, the moisture added must be absorbed by the cobs.

Moisture was added according to the procedure described by White et al (1984). With this method the cobs were repeatedly sprayed with water during a 48 hour period and stored at 4-5$^{\circ}$C. After each spraying the cobs were mixed and stored again. The appropriate moisture level was determined by drying a sample to obtain the initial moisture content wet basis. Using this information, the weight of the water required to achieve the specified moisture level was derived. The weight of the water plus the initial weight of the batch of cobs gave the total weight of the treatment. Water was sprayed on the cobs until this treatment weight was reached. Once the moisture addition was complete the cobs were held in a 4$^{O}$C cold storage for 4 days, allowing them to reach equilibrium. Prior to using the cobs in the experiment, the cobs were removed from the cold storage and allowed to warm up to ambient air temperature. At this point three samples were taken from the treatments to preciesly obtain the cob moisture content at the time of use.

### 5.2.2 Treatment Application

The diesel engine was warmed up for approximately 30 minutes before any treatments were applied. Start up of the gasifier involves igniting a small quantity of corn cobs with the help of charcoal lighter fluid. The cobs were allowed to burn until the lighter fluid was exhausted , at which time the cobs had acquired a glowing red color similar to charcoal in a barbeque grill.

The delivery hose was then attached to the engine intake manifold creating a vaccum through the gasifier system. The smoldering cobs were poured into the fuel hopper and regular cobs were added on top of the smoldering ones. The air/gas mixing valve was adjusted so that combustion of the cobs was promoted. Once the cobs were burning well enough to produce a suitable gas the air/gas mixing valve was again adjusted to draw the maximum gas to the engine without choking for air. After 15 minutes of operation at this level the system achieves a pseudo eqilibrium.

The speed of the engine was adjusted, as was the load on the prony brake, for the requirements of that particular treatment. For the purpose of comparing the amount of diesel fuel consumed under each treatment, the same load was applied to the engine for a given engine speed, ie 2.7 kgs of load was applied to the engine for all tests at 400 rpm, 3.2 kgs at 500 rpm, and 3.9 kgs at 600 rpm. After the correct speed and load were obtained, more cobs were added to the fuel hopper and data acquisition was subsequently initiated.

Diesel fuel consumption and ambient air temperature were monitored simultaeneously. A 250 ml graduated cylinder was filled with diesel fuel and a siphon hose was attached via a tee fitting to the engines fuel supply line. When data acquisition was started, the main fuel tank was shut off and the siphon was opened. Visual readings were taken at the beginning and the end of the runs.

All treatments were applied in a random manner. Each block was randomized separately. Ramdomization was accomplished by writing the nine treatment combinations on nine pieces of paper. The papers were folded and put into a cup. One paper at a time was drawn without replacement. Treatment combinations were noted in the order drawn, and excuted as such beginning with block 1. The order of the treatments were shown in table 5.1. The randomization process was done three times, once for each of the three blocks.

Treatment combinations were designated by two mumbers separated with a hyphen. The first number was precent moisture content, the second was engine speed in rpm.

Experimental conditions were kept as constant as possible for the duration of the experiment. Gas filtering material was changed once every three treatments, in addition to emptying ashes from the ash pan and char from the cyclone gas cleaner. Water vapor condensate was also emptied from the gas cooler unit after every three treatments. The gasifier throat was emptied of residual material after each treatment run. The grate was also cleaned of any slag.

TABLE 5.1 TREATMENT RAMDOMIZATION RESULTS

| ORDER | BLOCK 1 | BLOCK 2 | BLOCK 3 |
|---|---|---|---|
| 1 | 25-600 | 5-600 | 5-500 |
| 2 | 15-500 | 5-400 | 25-400 |
| 3 | 25-400 | 15-400 | 15-600 |
| 4 | 5-400 | 25-400 | 15-400 |
| 5 | 15-500 | 5-500 | 25-500 |
| 6 | 5-600 | 25-600 | 5-600 |
| 7 | 5-600 | 15-600 | 25-600 |
| 8 | 5-500 | 25-500 | 5-400 |
| 9 | 25-600 | 15-500 | 15-500 |

At the engine, motor oil changes were done and the injector nozzle cleaned before each block of treatments were run. Intake and exhaust valve lash was also checked. The engine was cooled using a thermo siphon raditor system. Radiator leaks requierd frequent filling of the radiator to maintain the water level. Engine temperature was not monitored in this experiment.

# CHAPTER 6

# RESULTS AND DISCUSSION

## 6.1 Overview

The execution of the experiment was accomplished without any major difficulties, though there were few conditions that required attention as far as the analysis was concerned. The conditions were the folowing: 1) variation in moisture content of the corn cobs, 2) engine speed variation, and 3) horsepower variation. Inspite of measures taken to control these parameters variations did occur. Taking this into account, additional analytical procedures were employed to obtain unbiased estimates of the statistics.

The variation in corn cob moisture content was the most significant of the variations encountered. The average moisture content wet basis was shown in table 6.1 for the range of engine speeds and the "nominal" moisture contents of 5,15, and 25%. The highest moisture loss occurred with the 25% material. Losses occurred during handling while running the experiment and for the period of time the material was kept at ambient air temperature.

Table 6.1 Wet Basis Cob Moisture Data

| Nominal Moisture | Actual Moisture | | | |
|---|---|---|---|---|
| Content(WB) | Block 1 | Block 2 | Block 3 | Mean |
| 5% | 4.7 | 5.14 | 5.145 | 4.995 |
| 15% | 14.38 | 13.1 | 12.25 | 13.24 |
| 25% | 18.54 | 13.45 | 22.0 | 17.996 |

The overall average moisture contents wet basis were low for the 15% nominal value by 1.75 points at 13.24. The 25% nominal level was lower by 7.0 points. Thus plots of temperature profiles found in this chapter involve the moisture content means found in table 6.1.

The engine speed variation occurred as a result of 1) varying load at the prony brake drum, 2) changes in the sensitivity responsiveness and calibration of the engine speed detection instrumentation. The speed sensor required 3 calibration curves by the end of the experiment, due to changes in the instruments output signal for a given speed.

Engine speed data for the three blocks of the experiment were presented in Table 6.2. The 400 rpm nominal tests were consistently below four hundred rpm. Some of this was due to the prediction equation which under predicts speed at the low end of the range. At the 500 rpm nominal speed, the prediction equations had betttter correlation and these results were closer to the nominal

Table 6.2 Engine Speed Treatment Data in RPM

1st Letter : L = Low Speed M = Medium Speed H = High Speed
2nd Letter : L = Low Moisture M = Medium Moisture H = High Moisture

| | LL | LM | LH | ML | MM | MH | HL | HM | HH | Totals |
|---|---|---|---|---|---|---|---|---|---|---|
| Block 1 | 372 | 342 | 379 | 485 | 445 | 512 | 558 | 565 | 628 | 4286 |
| Block 2 | 364 | 378 | 364 | 516 | 496 | 511 | 610 | 590 | 606 | 4435 |
| Block 3 | 395 | 382 | 380 | 517 | 493 | 492 | 571 | 564 | 576 | 4370 |
| Totals | 1131 | 1102 | 1123 | 1518 | 1434 | 1515 | 1739 | 1719 | 1810 | 13091 |
| Means | 377 | 367 | 374 | 506 | 478 | 505 | 579 | 573 | 603 | 484.67 |

Table 6.3 Engine Speed Means Across Blocks and Treatments

| | Low Speed | Medium Speed | High Speed |
|---|---|---|---|
| Low Moisture | 377 | 506 | 579 |
| Med Moisture | 367 | 478 | 573 |
| Hi Moisture | 374 | 505 | 603 |
| Overall Means | 373 | 496 | 585 |

value. The 600 rpm nominal speed had results above and below the nominal speed, differing by as much as 42 rpm. The engine speed results of the three blocks were averaged across blocks for like treatments. The block/treatment averages are contained in Table 6.3. These mean engine speed figures were included in a linear regression curve fitting. These results were elaborated elsewhere in this chapter.

The final component of variation was engine power. This component had the smallest variation of those mentioned thus far. It was necessary to minimize power variations to obtain fuel consumption results that were directly comparable, between moisture levels. Table 6.4 contains the power results for blocks 1,2 and 3 of the experiment. Variation in power output originated from the same sources as it did for engine speed, namely, the speed detection system and the force measuring apparatus.

The block means for engine power are contained in Table 6.5. These means were used to obtain fuel consumption figures per unit of power in a subsequent section of this chapter.

## 6.2 Grate Temperature Data

The high temperature thermocouple on channel 4 sensed the temperature just below the gasifier grate. Forty data points were collected for each treatment run. Temperature

Table 6.4 Engine Power Treatment Data in Kilowatts

1st Letter : L = Low Speed M = Medium Speed H = High Speed
2nd Letter : L = Low Moisture M = Medium Moisture H = High Moisture

| | LL | LM | LH | ML | MM | MH | HL | HM | HH | Totals |
|---|---|---|---|---|---|---|---|---|---|---|
| Block 1 | 0.613 | 0.553 | 0.626 | 0.902 | 0.872 | 0.984 | 1.34 | 1.31 | 1.55 | 8.75 |
| Block 2 | 0.581 | 0.611 | 0.585 | 0.962 | 0.962 | 0.984 | 1.47 | 1.45 | 1.46 | 9.065 |
| Block 3 | 0.626 | 0.619 | 0.619 | 0.947 | 0.980 | 0.902 | 1.387 | 1.36 | 1.39 | 8.83 |
| Totals | 1.82 | 1.783 | 1.830 | 2.811 | 2.814 | 2.870 | 4.197 | 3.94 | 4.40 | 26.465 |
| Means | 0.607 | 0.594 | 0.610 | 0.937 | 0.938 | 0.957 | 1.399 | 1.313 | 1.467 | 0.98 |

Table 6.5 Engine Power Means Across Blocks and Treatments (in kilowatts)

| | Low Speed | Medium Speed | High Speed |
|---|---|---|---|
| Low Moisture | 0.607 | 0.937 | 1.399 |
| Med Moisture | 0.594 | 0.938 | 1.313 |
| Hi Moisture | 0.610 | 0.957 | 1.467 |
| Totals | 1.811 | 2.832 | 4.179 |
| Overall Means | 0.604 | 0.944 | 1.393 |

data for like treatments were averaged across blocks (replicates). The averages are plotted in figures 6.1 to 6.3. In general the temperature profiles were lower as cob moisture content increases.

High moisture cobs however, were considerably more difficult to gasify than lower moisture material. Wet cobs tended to bridge easily inside the fuel hopper, thus producing erratic flow conditions into the fire box zone. This characteristic necessitated frequent monitoring of the fuel in the hopper, in order to manually assist cob flow.

Igniting the wet fuel proved to have its difficulty. Wet cobs were slow burning and easily extinguished themselves before reaching a sustainable level of combustion. To overcome this problem the drier 5% moisture cobs were used to start the combustion reaction. The heat produced by the dry fuel was used to ignite the wetter cobs and build up a sustainable incandesent mass capable of consuming the wet cobs. The high moisture cobs were slowly added, and once they had decended into the fire box data acquistion was started.

### 6.2.1 Temperature Profiles for high Moisture Cobs

The initially high temperatures depicted for the high moisture profiles in figures 6.1 to 6.3, were likely due to the use of the drier cobs as starter fuel for the wet cobs. The temperature profile decreases over time reaching an equilibrium toward the end of the treatment test. This was

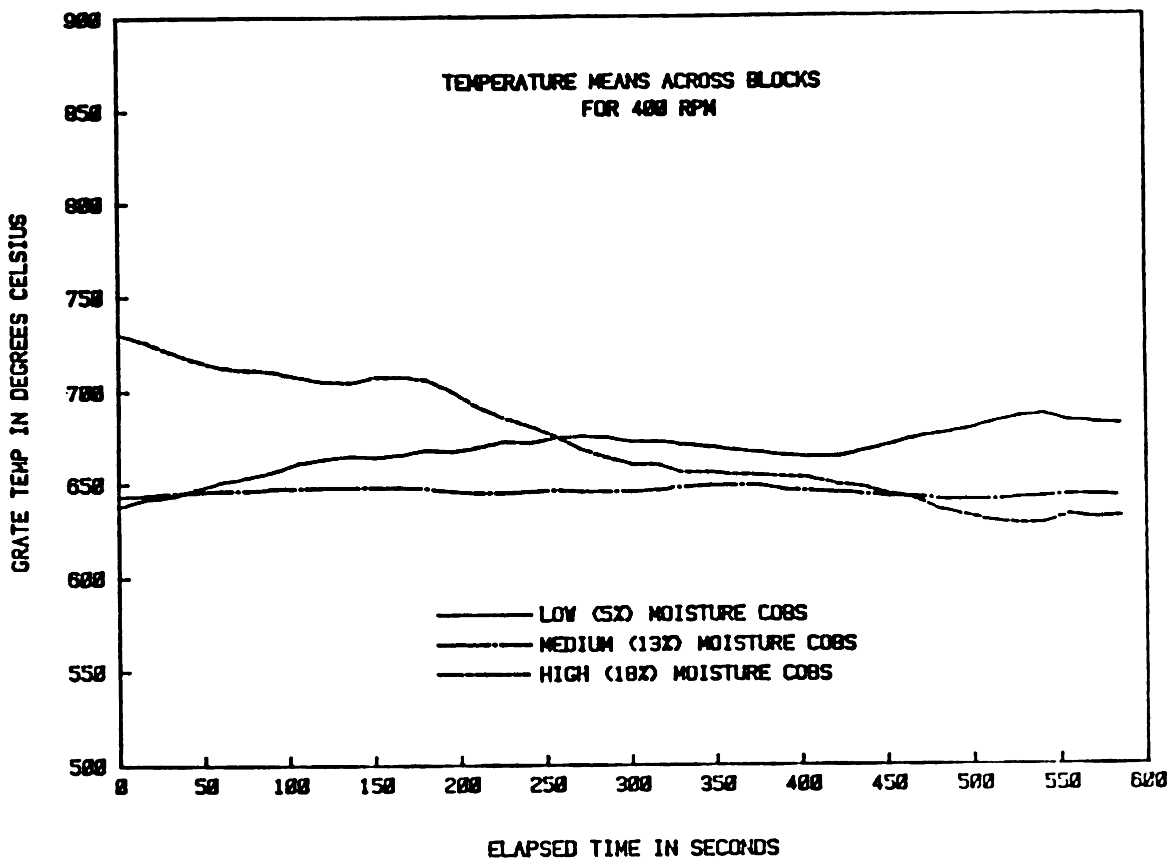



Figure 6.1 Gasifier grate temperature profiles at 400 rpm engine speed. The curves represent averages over the 3 blocks for the 10 minute length of the test.

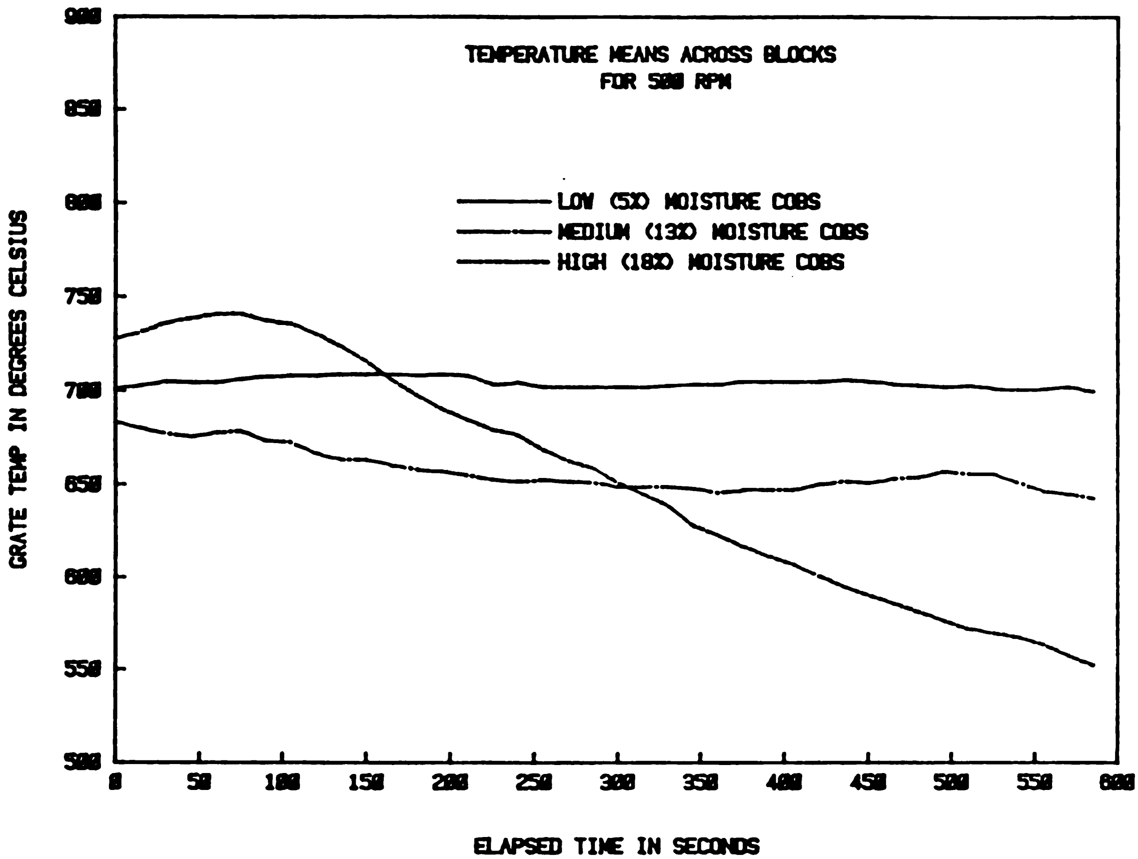



Figure 6.2 Gasifier grate temperature profiles at 500 rpm engine speed. the curves represent averages over the 3 blocks for the 10 minute length of the test.

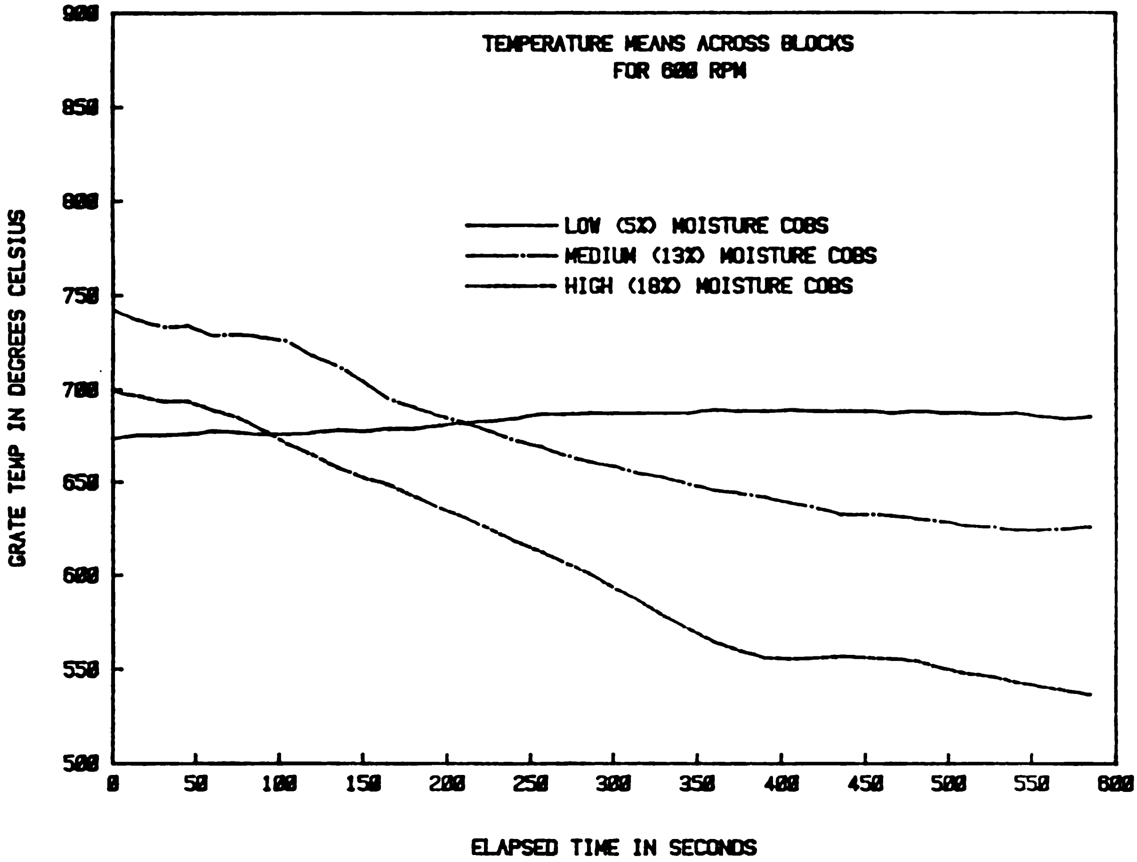



Figure 6.3 Gasifier grate temperature profiles at 600 rpm engine speed. The curves represent averages over the 3 blocks for the 10 minute length of the test.

the case at all of the engine speeds examined and was consistent with expectations and results of other investigators.

### 6.2.2 Temperature Profiles for the Medium Moisture Cobs

The medium moisture fuel behaved similar to the high moisture fuel in that dry cobs were required to get the combustion process started. When the cobs reached full combustion, the medium moisture cobs were added on top of the burning mass.

The results of the medium moisture cob temperature data place this moisture level at a near steady state temperature higher than that of the high moisture cobs, as expected. Steady state conditions were indicated by a flatened curve displaying nearly constant temperatures. Psuedo steady state conditions appeared at the very start of the test for the 400 rpm treatments, 300 seconds into the run for the 500 rpm treatments and 425 seconds into the run for the 600 rpm treatments. Prior to the steady state conditions temperature was decreasing due to the consumption of the dry cobs, and they're replacement with the wetter medium moisture cobs.

At all engine speeds, the medium moisture cobs show steady state temperatures higher than the high moisture cobs and lower than that of the 5% moisture cobs. Oven dried samples of the medium moisture cobs averaged 13.2% moisture wet basis.

### 6.2.3 Temperature Profiles for the Low Moisture Cobs

The low moisture corn cobs were gasified easily. Igniting the cobs and obtaining a self-sustaining combustible mass was achieved without complications.

Psuedo steady state conditions were rapidly achieved and continued for the duration of the tests. At steady state conditions the temperature of the 5% moisture cobs was in all cases higher than both the medium and the high moisture tests. This outcome was confirmed by literature which relates that the wetter the biomass fuel the lower the reaction temperatures in the gasifier fire box. This is due to the endothermic process of vaporizing the water contained in the cobs (biomass). The result was a lowering of the reaction temperature and, as is explained later, a decline in gas quality - ultimately producing less energy from the gas.

### 6.2.4 Summary of Temperature results at 400 RPM

Low Moisture Cob Averages (5%) - Initial temperatures were at the 650$^{o}$C level and rose to 675$^{o}$ at the end of the test. The temperature rise was probably due to starting data acquisition prior to achieveing steady state conditions. In the steady state range, these temperatures were 25$^{o}$ higher than the medium moisture test profile and 30$^{o}$ higher than the high moisture test profile. These were the smallest differences between the various moisture levels of the three engine speeds tested. The reason for this was attirbuted to the likelyhood of some moisture loss from the medium and high moisture material, and a lower air velocity through the gasifier given the slow engine speed.

Medium Moisture Averages (13%) - This higher moisture material also began with temperatures of 650$^{o}$C but maintained this level for the duration of the test. This profile was 5-10$^{o}$ higher than the high moisture cobs.

High Moisture Averages (18%) - This treatment average had the highest inital temperature of the three moisture levels. This again, was due to the initiation of data acquisition while some residual 5% moisture material remained in the gasifier. The profile however showed continous decline in temperature until a psuedo steady state was achieved at 635$^{o}$C. This temperature level was very close to that of the medium moisture cobs. A much lower temperature level was anticipated for this treatment.

### 6.2.5 Summary of Temperature Results at 500 RPM

Low Moisture Cobs (5%) - This was another test which shows steady state conditions for the entire test. Grate temperatures were in the 700-705$^{o}$C area, highest of the three moisture levels. This temperature was also very close to that of the 5% moisture test at 400 rpm.

Medium Moisture Cobs (13%) - This treatment had initial temperatures of 680$^{o}$C. Decreasing temperatures occurred in a continuous manner for 300 seconds. Thereafter the temperature stabilized in the 650-660$^{o}$ range. This level was 40-50$^{o}$ lower than that of the 5% moisture cobs tested at this speed and roughly the same as the medium moisture test at 400 rpm.

High Moisture Cob Averages (18%) - The high initial temperatures were again due to the employment of dry cobs to start combustion and beginning data acquisition before this material was exhausted. The profile shows continuous decline in temperature throughout the duration of the test. The slope of the curve remains negative at the end of the test indicating that further decreases in temperature were probable. The final temperature was slightly below 550$^{o}$C. This was 85$^{o}$ lower than the high moisture test at 400 rpm. Comparing it with the other moisture treatments of 500 rpm the final temperature was 150$^{o}$ lower than the 5% moisture test and 100$^{o}$ lower than the medium moisture test.

6.2.6 Temperature Results at 600 RPM Engine Speed

Low Moisture Cobs (5%) - Rising temperatures characterize this test, with an initial level of 675$^{o}$C that moved up to 700$^{o}$ at the mid point of the test. Steady state conditions arrived at the 700$^{o}$ level, though the profile of this treatment was a few degrees lower than the 5% moisture test at 500 rpm but equaled the 5% moisture results at 400 rpm.

Medium Moisture Content Cobs (13%) - The highest initial temperature level occured with this treatment average, again due to factors mentioned earlier. A constant decline was obvious to about 425 seconds into the test. The temperature stabilized slightly below 650$^{o}$C, and stayed in this area for the remainder of the test. This level was practically equal to that of the medium moisture cobs examined at 500 rpm.

High Moisture Content Cobs (18%) - Distinguishing this treatment average from the others at this moisture level was the low initial temperature of 700$^{o}$(figure 6.3). This indicated that the data acquisition began later in the cooling down period than it did in treatments at other speeds. The profile shows an extremely constant negative slope for 400 seconds. At this point the curve flattens somewhat but continued in a negative direction. This treatment average did not achieve a steady state before the end of the test. The temperature at the end was near 530$^{o}$, the lowest temperature of any test at any of the engine speeds.

## 6.3 Gas Cooler Inlet Temperature Results

The temperature data for the thermocouple at the cooler inlet (channel 5) was averaged across blocks for like treatments. These averages were plotted in figures 6.4, 6.5, and 6.6. Raw data used for the averages was listed in Appendix 2. In general the outcome of the results for this sensor mimicked those of the grate temperature sensor covered in previous sections of this document. However these averages exhibited a moderate

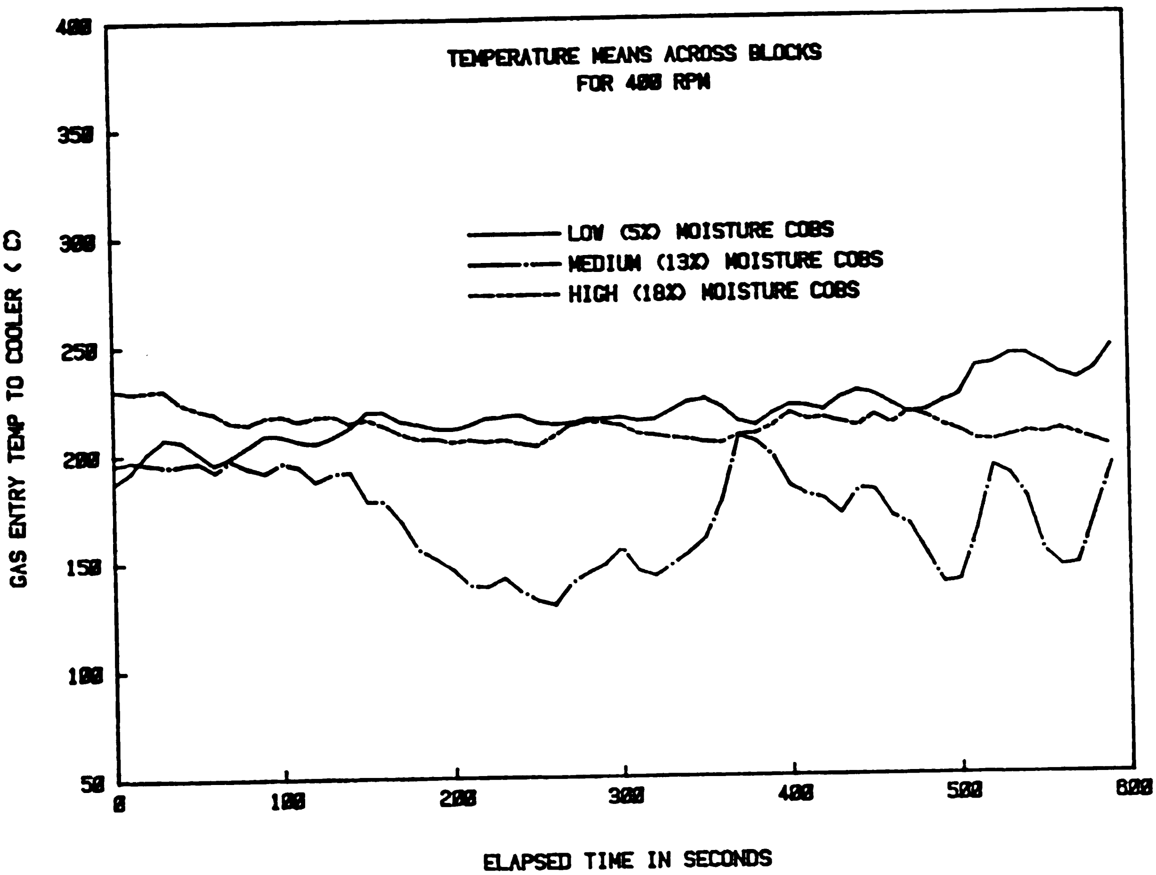



Figure 6.4 Gas temperature profiles at the cooler entrance for 400 rpm. Averaged across 3 blocks for the 10 minute length of the test.

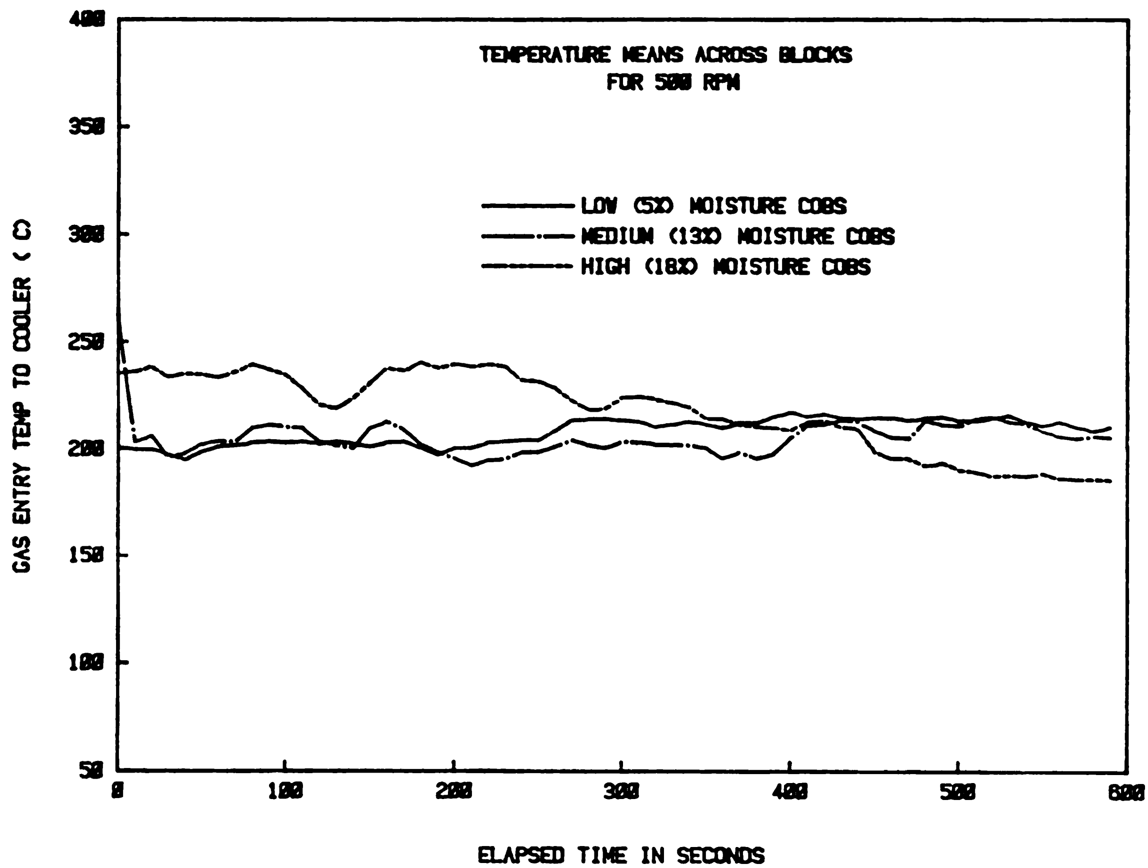



Figure 6.5 Gas temperature profiles at the cooler entrance for 500 rpm. Averaged across 3 blocks for the 10 minute length of the test.

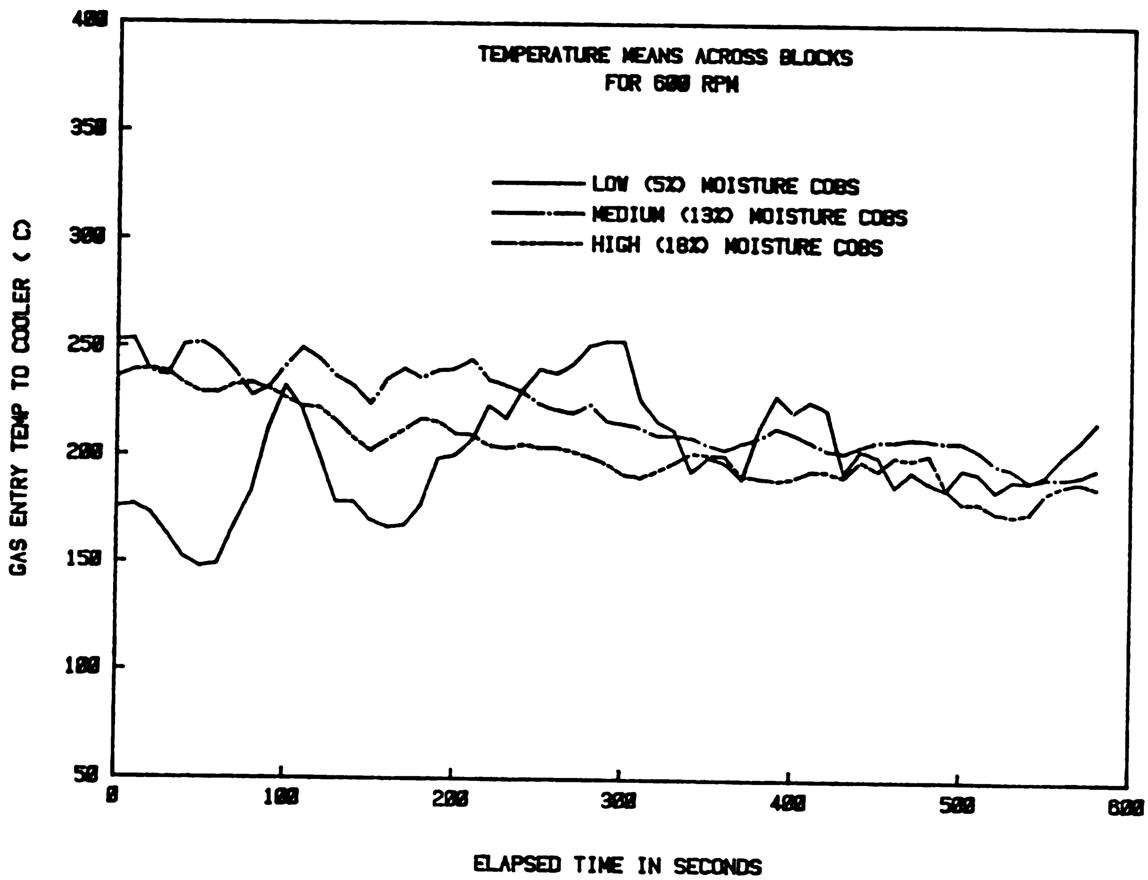



Figure 6.6 Gas temperature profiles at the cooler entrance for 600 rpm. Averaged across 3 blocks for the 10 minute length of the test.

amount of fluctuation. This was especially evident in the 400 rpm test for the medium moisture cobs (figure 6.4) and in the 600 rpm test for the low moisture cobs (figure 6.6).

Much of this fluctuating tendency was attributable to the sensor circuitry employed to amplify the signal. Preliminary calibration tests revealed that the thermocouples' output would randomly fluctuate above and below the actual temperature level. The reasons for this were not precisely known but were believed to be due to faulty components in the amplification circuitry. Since this was a secondary measuring device, it was decided to implement the experiment without corrrecting the fault, in an effort to complete the experiment prior to the program deadline.

Other potential sources of disturbance were the reversion pulses of the single cylinder diesel engine. the lack of insulation on equipment downstream from the gas producer and backfiring occurring in the gas producer.

Reversion was a reversal of the direction of flow of the incoming gas and air mixture. This reversal occurred because the suction produced by the engine was intermittant rather than constant. Suction only occurs when the intake valve was open, and the valve only opened once for every two revolutions of the crankshaft. This condition permitted cooler gas downstream from the sensor to reverse direction and flowed backward toward the sensor.

The gasifier furnace was insulated with asbestos on the inside of the outer casing. No other parts of the apparatus were insulated, and except for the cooling hose and delivery hose, all components were mild steel. The tests were conducted indoors but with the doors open to ventilate the area. In this environment gusts of wind and irregular breezes might have impacted the output of the sensor on occasion. Since the temperture gradient was high ($18-24^{o}$ vs $150-250^{o}$) some fluctuation in temperature could occur.

Finally, backfiring within the gasifier could also be a factor. The author does not believe it was a significant one since no backfiring was observed during data acquisition. However, strong bacfiring was evident on most tests prior to initaiting data acquisition. Backfiring occurred when pockets of combustible gases were produced above the firebox, and were drawn through or pushed into the burning mass of fuel, causing them to detonate. This detonation monetarily increased pressure inside the system pushing hot gases in all directions of least resistance. There were two such directions in this gasifier system and one of them leads to the thermocouple in question, the other leads out of the gasifier and into the surrounding atmosphere. Such detonation could momentarily raise temperatures in the vicinity of the thermocouple at the cooler inlet causing a spike in temperature. This spike would not be detected at the grate thermocouple because temperatures there were much higher and the effect of detonation on temperature was less obvious if at all.

### 6.3.1 Cooler Inlet Temperature Results at 400 RPM

The moisture test averages yielded a steadily increasing temperature profile. This was also the highest temperature regime of all tests at 400 rpm. This treatment average never truly achieved a near steady state condition. End of run temperatures were in $240^{o}$-$250^{o}C$ range.

Very erratic behavior and an uncharacteristically low temperature profile was the result for the medium moisture test. Temperatures were steady for the first 2 minutes of the test, but then repeatedly drop and rise in $50^{o}$ swings for the duration of the experiment. This outcome was likely due to one of the disturbances discussed earlier in this section. Review of the grate temperature profiles show that nothing in the gasifier temperature profile could explain this occurrance at the cooler inlet. The end of test temperature was in the $190^{o}$ area only $5^{o}$ lower than that of the medium cob moisture tests.

Except for the medium moisture profile the profiles of the cooler inlet temperature sensor were consistent with those of the grate temperature sensor.

### 6.3.2 Cooler Inlet Temperature Results for 500 RPM

The tests at this speed provided outcomes that the author considered typical for the experiment. All tests had relatively steady profiles, with the low cob moisture level being the warmest and the high cob moisture level the coolest.

In this treatment averge the low cob moisture level displayed an increasing temperature profile, but reached a fairly steady state 400 seconds into the test. At this point in the test it had the highest temperature of all moisture levels, as expected, though the medium moisture profile was only a few degrees lower (figure 6.5). The pseudo steady state temperature at the end of the test was $220^{\circ}$,roughly $30^{\circ}$ lower than the 400 rpm test.

A fairly steady state profile was also evident in the medium cob moisture level test (figure 6.5). After a steep decline in the first few seconds of the test, the profile closely followed that of the 5% cob moisture level. It hovered in the $200^{\circ}C$ area for much of the test before rising to the $220^{\circ}$ just as the 5% cob moisture averages did. At the end of the profile the temperature was $215^{\circ}$,a scant $4^{\circ}$ lower than that of the 5% cob moisture averages and $25^{\circ}$ higher than the high cob moisture averages.

The high cob moisture averages began at a high level ($235^{\circ}C$) and gradually decreased continually thereafter. During the final four minutes the temperature dropped below those of the low and medium moisture averages. At the end of the test the temperature was $190^{\circ}$, $25^{\circ}$ lower than the medium cob moisture averages and $30^{\circ}$ lower than the 5% cob moisture averages. The slope of the profile maintained a negative direction throughout the run, though some flattening was apparent at the end. Interestingly, the temperature at the end of the high cob moisture profile at 400 rpm was only 7.0°C higher than this one.

All of the temperature average profiles at the cooler inlet thermocouple at 500 rpm were consistent with those of the grate temperature profiles (see figures 6.2 and 6.5). This was the only speed for which all cooler inlet profiles were consistent with all grate temperature profiles.

6.3.3 Cooler Inlet Temperature Results for 600 RPM

One of the profiles at 600 rpm displayed wide fluctuations in temperature levels which were assumed to have been caused by disturbances described earlier, namely: reversion, lack of insulation down stream for the gas producer, and backfiring in the gas producer. The profile in question was the 5% cob moisture average. Noticable in figure 6.6, the temperature for this treatment begins at about 175°C. Immediately it dropped by 25°, then rose by 75° and again dropped by about 50°. This behavior continues for the duration of the test, though the oscillations have a lower amplitude during the final 2.5 minutes of the test. The temperature was rising for most of the first half of the test and declined somewhat in the second half. The test ended with a temperature of 225°, 50° higher than the initial temperature of 175°. The profile had a steep postive slope in the final seconds indicating that the oscillating tendency was continuing. The best commentary possible for this particular test was that it ultimately was higher in temperature than the others. Futhermore, it was lower than the 5% cob moisture level average at 400 rpm and greater than the 5% cob moisture level average at 500 rpm by a couple of degrees. This profile never achieved a steady state condition.

The profile of the medium cob moisture test at 600 rpm contained some oscillation in the first 3 minutes of test, but settled down to a gradual temperature decrease thereafter. Initial temperatures were at the 250$^{o}$ level and finished in the 200$^{o}$ area at the profiles end. The final four minutes showed reasonably constant temperatures in the 200-220$^{o}$ range. This was very similar to the final temperatures for the medium cob moisture profile at 500 rpm, but somewhat higher than the result at 400 rpm.

The behavior of the high cob moisture level profile was close to that of the medium cob moisture profile. Temperatures were initially high and gradually declined to the 175-210$^{o}$ range. the profile of this moisture level was between 5 and 10 degrees lower than that of the medium moisture level. The slopes of the two curves were also quite similar. The final temperature of this test was near 200 degrees. This was practically the same as for the high moisture profile at 500 rpm and about 10 degrees less than the high moisture average at 400 rpm.

Making comparisons with the grate temperature profiles (figures 6.3 and 6.6 ), it was apparent that the 13 and 18 percent cob moisture profiles were consistent for the two sensors. In both cases the the profiles started at high levels and decreased stedily until the final minutes of the test. The 13 percent cob moisture averaged were higher in temperature on profiles of both sensors (grate and cooler inlet).

Even the 5 percent moisture profile follows a similar overall trend for both sensors. However the wide oscillations at the cooler inlet sensor were not evident in the grate temperature profile.

## 6.4 Gas Cooler Exit Temperature Results

A thermistor was used to detect the temperature of the gas at the cooler exit. The purpose of this sensor was to verify that the temperature of the gas leaving the gasification system was as cool as was economically possible. The advantages of cool gas were: 1) water vapor and tar are condensed and removed from the gas stream, and 2) the gas is denser and contains more energy per unit volume as it enters the engine. Water at ambient air temperature was used as the cooling medium, thus the gas temperatures were expected to be in the vicinity of the ambient air temperature. Indeed, the results in figures 6.7, 6.8, and 6.9 show that this was the case.

Ambient air temperatures during the experiment ranged from 17 degrees to 23 degrees. The gas temperatures

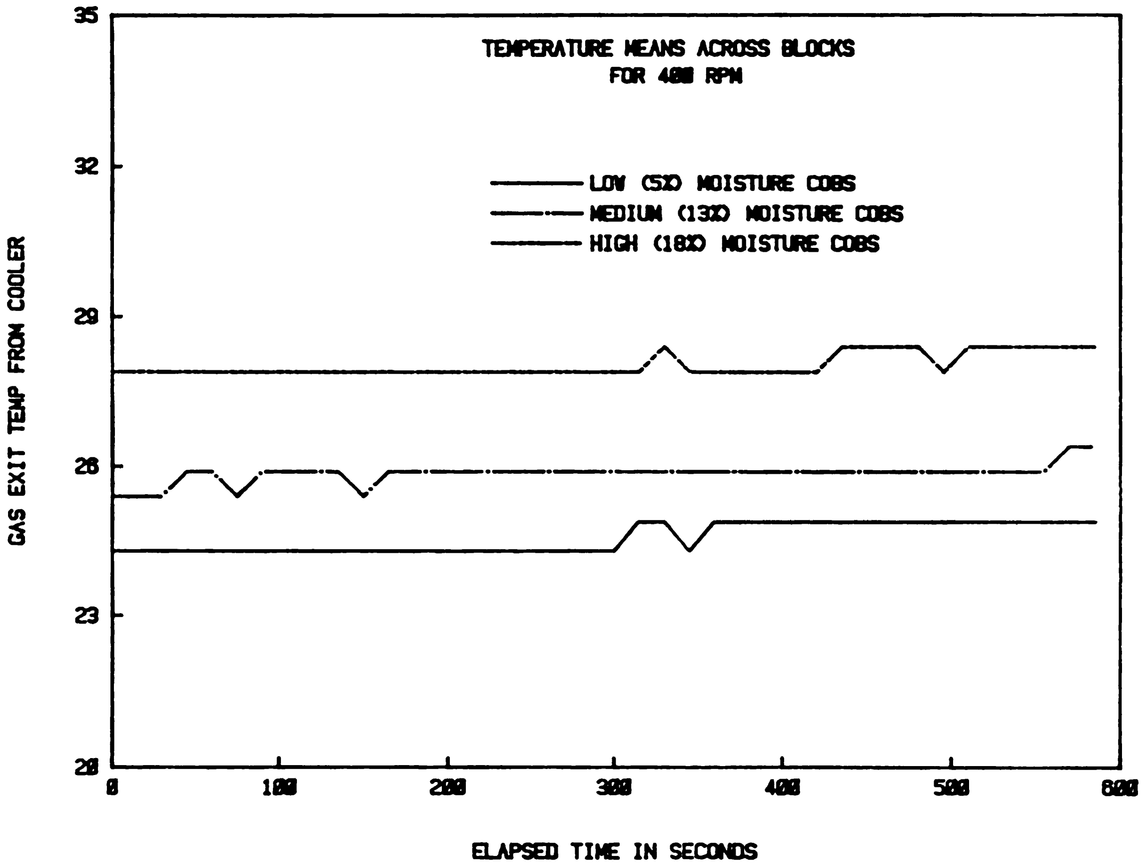



Figure 6.7 Gas temperature profiles at the cooler exit for 400 rpm. Averaged across 3 blocks for the 10 minute length of the test.

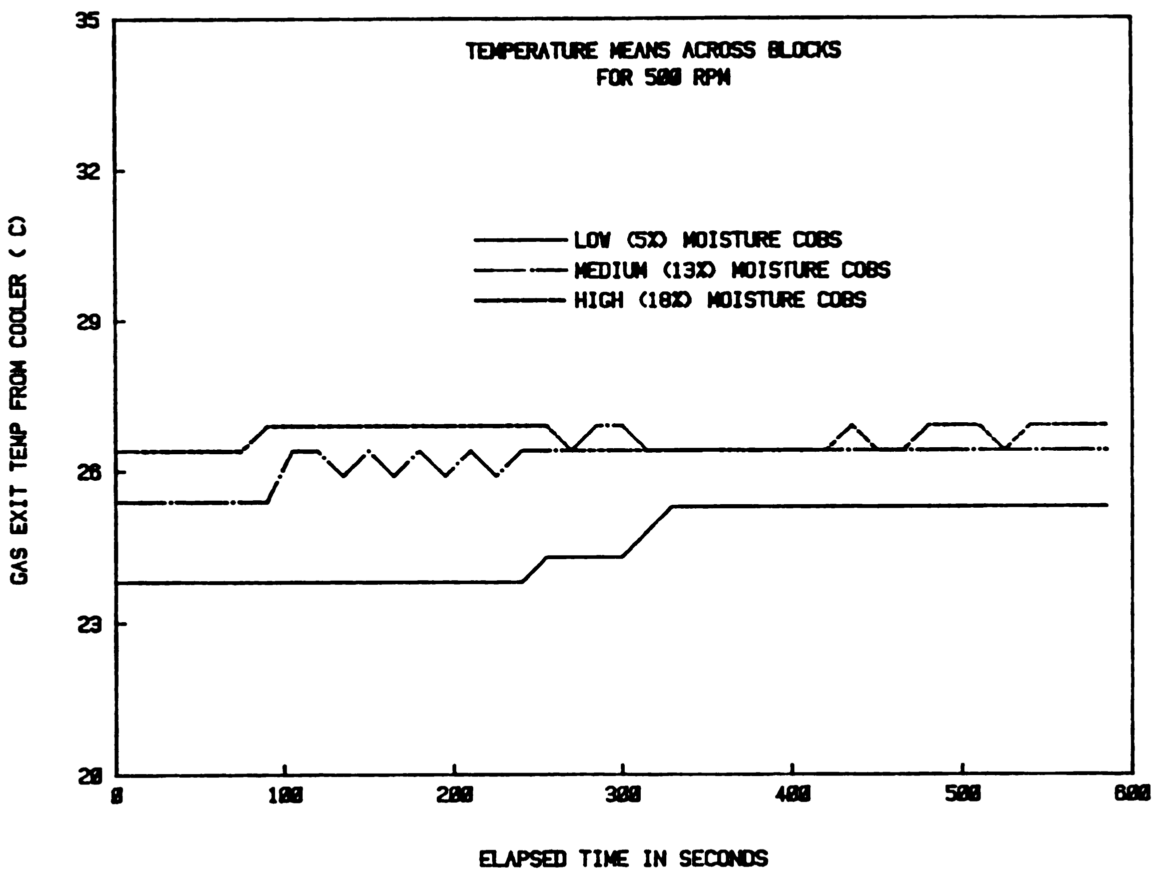



Figure 6.8 Gas temperature profiles at the cooler exit for 500 rpm. Averaged across 3 blocks for the 10 minute length of the test.

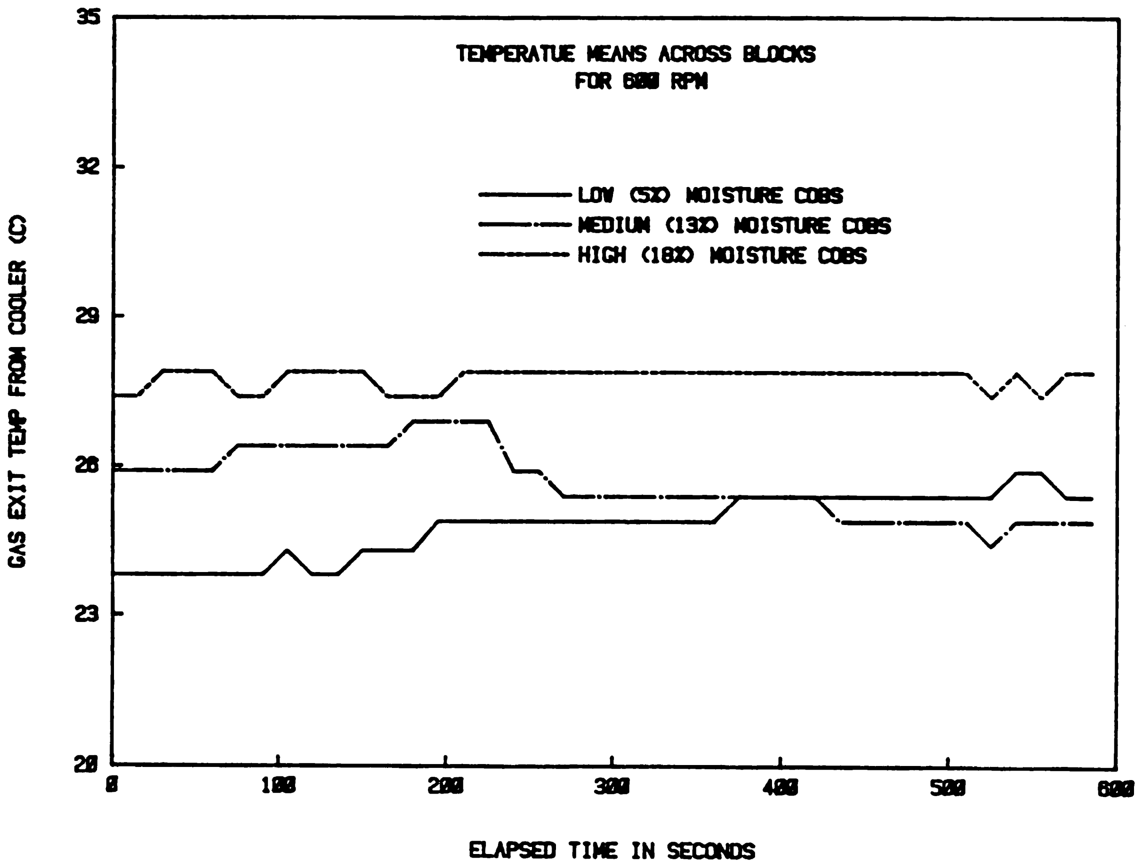



Figure 6.9 Gas temperature profiles at the cooler exit for 600 rpm. Averaged across 3 blocks for the 10 minute length of the test.

detected by the thermistor (channel 3) range from 23 degrees to 28 degrees. At the maximum, only 4 degrees separated the warmest and coolest treatment averaged at any given engine speed. Suprisingly, the high cob moisture averages were the warmest of all moisture levels and the low cob moisture averages were the coolest. This was the case at all engine speeds. This outcome was possibly due to three principal conditions: 1) the higher cob moisture profiles started at higher temperatures at the gasifier grate than the low cob moisture profiles. This heat was transferred to the water in the cooler, raising the water temperature. The heat stored in the water was not rapidly dissipated, and thus the temperature was maintained at a higher level than would be the case with a low moisture fuel that did not raise the gasifier grate temperature as high, 2) the water was not stirred, agitated, or pumped to a heat exchanger to remove heat from the water or distribute the heat through the mass of water, 3) the cooling hose was positioned at the top of the gas cooler unit such that it was two thirds submerged. Since heat rises, the warmest water would have remained in the vicinity of the hose, and maintained the temperature at equilibrium.

### 6.4.1 Gas Cooler Exit temperature Results at 400 RPM

The low percent cob moisture average was steady from the beginning of the run, rising about 0.5 degrees to 24.5

degrees celsius at the mid point of the test. This was the lowest temperature at 400 rpm.

The 13 percent cob moisture averages were confined to the 25.5 to 26.0 degree range for practically the entire test, moving up to 26.5 degrees at the very end.

Up at the 18 percent moisture level temperatures were steady at 28 degrees for more than half the duration of the test. An increase of 0.5 degrees occurred during the final 3 minutes.

### 6.4.2 Gas Cooler Exit Temperature Results at 500 RPM

In this series of profiles the low percent moisture averages began at slightly less than 24 degrees and remained at this level until the mid point of the test. From there it increased 1 degree in a step like fashion. The test expired with the temperature steady at 25 degrees. This was half a degree higher than the 5 percent moisture profile at 400 rpm.

Initial temperature levels for the medium cob moisture averages were around 25.5 degrees. There was a jump to 26.5 degrees about 1.5 minutes into the test. After a period of choppy behavior the temperature settled to a level between 26 and 26.5 degrees. This was the same level as the medium moisture profile at 400 rpm, and 1.5 degrees higher than the low percent moisture level at 500 rpm.

For the high cob moisture profile, temperatures were confined to a 0.5 degree range between 26.5 and 27.0

degrees for the entire test. This moisture level yielded the highest temperatures at this engine speed. However this was 1.5 degrees lower than the same moisture profile at 400 rpm.

### 6.4.3 Gas Cooler Temperature Results at 600 RPM

Steadily rising temperatures characterized the low percent cob moisture profile (figure 6.9) for three quarters of the test. Subsequently, temperatures stabilized in the 24.5 to 25 degree range. This was the same area that the 400 rpm and the 500 rpm profiles attained.

The only real decrease in temperature occurred with the medium cob moisture level in this group of tests. Beginning at 26 degrees the temperature rose to nearly 27 degrees after 3.5 minutes. This was followed by a steep decline to just above 25 degrees, where it remained for the rest of the test. This was about 1 degree lower than the outcome of the 400 and 500 rpm profiles, and 0.5 degrees above the 5 percent moisture profile at 600 rpm.

At 25 percent cob moisture temperatures at 600 rpm were the most stable of all tests at this speed (figure 6.9). Varying between 27 and 28 degrees, the profile stayed within these limits for the entire test. Again, this profile contains the highest temperatures recorded at this speed, but this was only three degrees above the lowest profile which was the low (5 percent) cob moisture temperature profile.

## 6.5 Fuel Comsumption Test Results

Given the variations in engine speed and engine power encountered in the experiment, tests of significance were performed on both of these parameters. The factorial design was employed to accomplish this since it was capable of testing significance for the factors involved, and test for significant differences between blocks. The tests of significance for speed and power were considered over the three levels of the moisture factor, and for blocks. It was these two conditions that determined if the differences in the observations were large enough to be attributed to causes other than chance.

The engine speed data of Table 6.2 was used in the factorial analysis of variance program to test for significant differences between moisture levels and between blocks. The ANOVA (Analysis of Variance) Table is table 6.6. To determine significance at the 5% level the calculated F value in the ANOVA table was compared with the tabular F value with 2 degrees of freedom for the numerator and 16 degrees of freedom for the denominator. This F value was 3.63, and was larger than the calculated F values in Table 6.6. Therefore the observed difference between moisture levels and between blocks were not significant at the 5% level. However at the 10% level, speed differences between moisture contents do become significant.

The data obtained on engine power was compiled in Table 6.4. That data comprised observations on all nine treatments of each block. These values were used to obtain the ANOVA results of Table 6.7. Comparing the calculated F value, with the tabular F value, revealed no significant differences between blocks or between moisture levels. This was true at both the 5 and 10 percent confidence levels.

The two analyses mentioned above confirm that the engine speed and power data were not sufficiently different at the 5% level to void the objectives of the experiment, although engine speed was barely significant at the 10% level. With this in mind the ANOVA for diesel fuel consumption follows.

### 6.5.1 Diesel Fuel Mode

The reduced power levels at 400, 500 and 600 RPM were duplicated to measure the amount of diesel fuel consumed at each of these speeds. Diesel fuel consumption was measured using a 250ml graduated cylinder (graduations of 2ml) with a siphon tube attached to the engines' fuel line. The power output of the engine was measured using the load cell-prony brake system described earlier in this document. The digital data acquisition system accumulated readings for the 5 minute long tests at a rate of one point per second for force and engine speed. A digital multimeter was alternately connected to the speed and force sensors to

Table 6.6 Engine Speed ANOVA Table

| Source | df | SS | Mean Square | F |
|---|---|---|---|---|
| Blocks | 2 | 1235.67 | 617.835 | 1.5763 |
| A (Speed) | 2 | 204867.0 | 102434.0 | 261.339** |
| B (Moisture) | 2 | 2155.56 | 1077.78 | 2.74973 |
| AB | 4 | 1010.77 | 252.693 | 0.64469 |
| Error | 16 | 6271.33 | 391.958 | |
| Total | 26 | 215540.33 | | |

Table 6.7 Engine Power ANOVA Table

| Source | df | SS | Mean Square | F |
|---|---|---|---|---|
| Blocks | 2 | 0.005925 | 0.0029625 | 1.08953 |
| A (Speed) | 2 | 2.97252 | 1.48626 | 546.608** |
| B (Moisture) | 2 | 0.008633 | 0.004317 | 1.58756 |
| AB | 4 | 0.006413 | 0.001603 | 0.58967 |
| Error | 16 | 0.043505 | 0.002719 | |
| Total | 26 | 3.03 | | |

monitor the speed and force magnitudes during the test. Minor adjustments to the speed and the prony brake were made necessary.

The power levels employed were 0.63 KW (0.85HP) at 400 RPM 0.87 KW (1.17 HP) at 500 RPM and 1.3 KW (1.80 HP) at 600 RPM. Once the power level was adjusted, fuel consumption tests were run for 5 minutes. The 5 minutes consumption figures were 46.00 ml at 380 RPM, 67.5 ml at 500 RPM, and 81.5 ml at 600 RPM. These values served as the basis for comparison with the dual fueled results.

### 6.5.2 Dual Fueled Mode

The diesel fuel tests performed in this experiment used both fuel and producer gas from corn cobs to power the engine, since diesel fuel was necessary to initiate combustion. In essence the more energy the producer gas contained, the less diesel fuel was consumed. This will occur to the point at which the amount of diesel fuel injected into the cylinder was insufficient for combustion. The engine then slowed until the governor permitted the injection of enough diesel fuel for ignition again.

The tests spanned a period of 3 weeks. Five treatments were re-applied during this period because of incorrect adjustments and/or calibration of instruments and/or equipments. A major difficulty was maintaining the moisture levels of the high moisture cobs employed in the test. During the execution of the block 1 treatments, moisture loss from the 15 and 25% moisture cob was evident. Modification in the conduct of the experiment diminished the moisture loss but did not eliminate it altogether. It was most pronounced in the 25% moisture material, loosing up to 7% points wet basis in one day. To a lesser degree engine speed and power also posed some difficulty in adhering to desired levels. Details of these conditions were provided in previous sections of this chapter.

The diesel fuel consumption data for the experiment are in Table 6.8. This was the absolute diesel consumption for blocks(replicates) 1, 2, and 3. The general trend in that data follows expectations, which were; A) increasing diesel fuel consumption with increasing engine speed and load, and B) increasing diesel fuel consumption with increasing cob moisture content. There were 2 exceptions out of the 29 data points. One at the 5% nominal moisture level at 400 and 500 rpm, the other at 500 rpm between the 15 and 25% moisture levels.

The objectives of the experiment were to 1) determine which of the moisture levels most reduced the consumption of diesel fuel, and 2) determine whether the differences in diesel consumption due to moisture were significant. The data in Table 6.8 contains the observations on diesel fuel consumed and related statistics. The values in the table have been converted from ml per 10 minutes of test to ml per kilowatt hour. The data forms the basis of the analysis of variance shown in Table 6.9.

Table 6.8 Diesel Fuel Comsumption Treatment Data - Dual Fueled Mode

1st Letter : L = Low Speed M = Medium Speed H = High Speed
2nd Letter : L = Low Moisture M = Medium Moisture H = High Moisture

| | LL | LM | LH | ML | MM | MH | HL | HM | HH | Totals |
|---|---|---|---|---|---|---|---|---|---|---|
| Block 1 | 22 | 40 | 41 | 16 | 48 | 50 | 36 | 66 | 85 | 404 |
| Block 2 | 17 | 18 | 23 | 36 | 56 | 57 | 44 | 60 | 83 | 394 |
| Block 3 | 23 | 35 | 42 | 26 | 48 | 46 | 47 | 73.5 | 80.5 | 421 |
| Totals | 62 | 93 | 106 | 78 | 152 | 153 | 127 | 199.5 | 248.5 | 1219 |
| Means | 20.67 | 31 | 35.33 | 26 | 50.67 | 51 | 42.33 | 66.5 | 82.83 | 45.15 |

Table 6.9 Diesel Consumption ANOVA Table

| Source | df | SS | Mean Square | F |
|---|---|---|---|---|
| Blocks | 2 | 41.4 | 20.7 | 0.350402 |
| A (Speed) | 2 | 5568.29 | 2784.15 | 47.1291** |
| B (Moisture) | 2 | 3456.07 | 1728.04 | 29.2516** |
| AB | 4 | 609.04 | 152.26 | 2.5774 |
| Error | 16 | 945.20 | 59.075 | |
| Total | 26 | 10620.0 | | |

The test of significance was performed using the F-test. For both factors the numerator degrees of freedom was 2 and the denominator degrees of freedom was 16. Dividing the factor mean squares by the error mean square resulted in significant outcomes for both factors at the 5% level. Asteriks adjacent to figures in the F column indicate significance. The interaction, line AB in the ANOVA table, was not significant but it was close to being significant at the 10% level. More information on interaction was revealed by constructing response scales for each factor. Interaction was important because it revealed if the response of one factor to the other (or others) was of a dependent or independent nature.

Figure 6.10 shows the response curve for factor B at factor A engine speed. Interaction was likely when the curves displayed change in magnitude (slope) or a change in direction on the interval between any two levels of the factor represented by the X-axis. From these curves it appears that interaction was at hand. The slope of the medium moisture content curve (factor B) was different than for the low and high moisture curves below and above it. However since the curve in question stayed within the bounds established by the other two curves, its response was not radical enough to cause outright significance.

In figure 6.11, the response curves for factor A at factor B, cob moisture content, were diagrammed. The evidence for interaction in this case was diminished

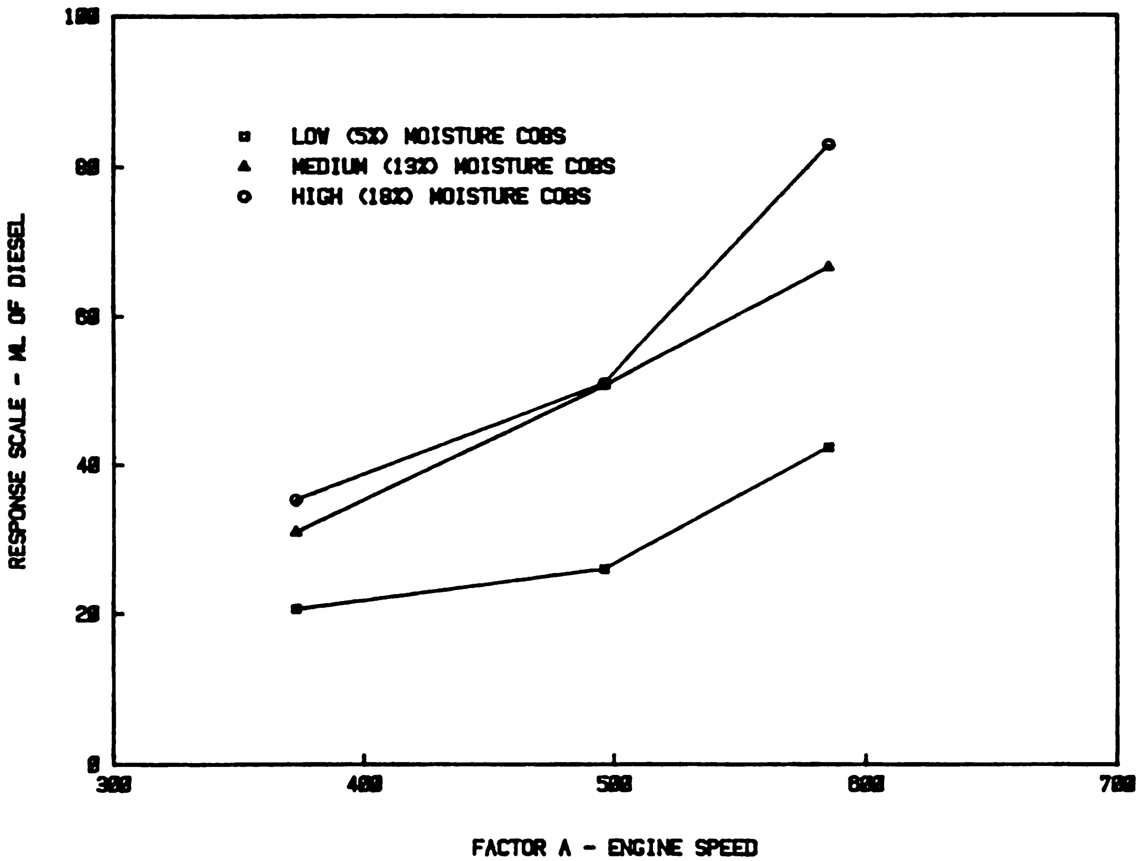



Figure 6.10 Diesel fuel consumption at low, medium and high cob moisture levels. Engine speed points are 373 rpm, 496 rpm, and 585 rpm.

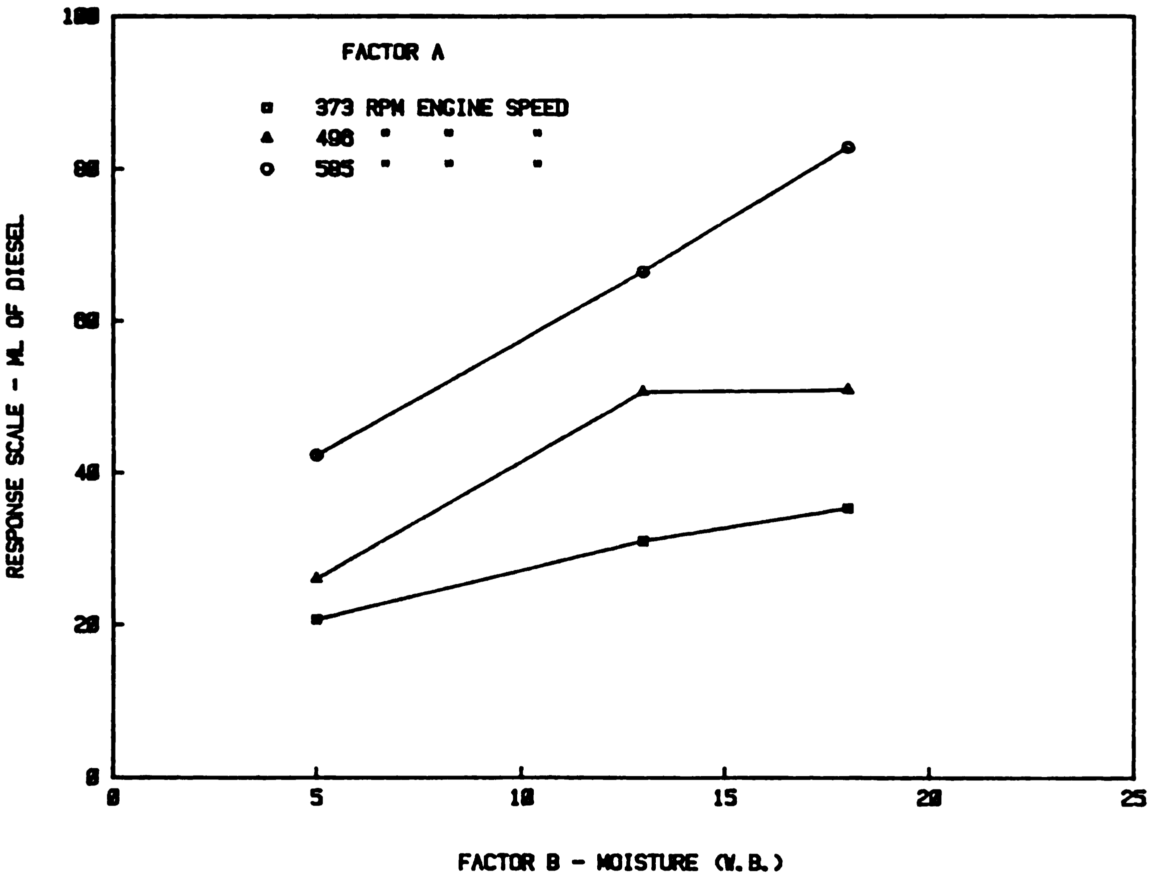



Figure 6.11 Diesel fuel consumption at low, medium and high engine speed levels. Moisture points (wet basis) are 5%, 13%, and 18%.

considerably compared to the previous one, though there were some hints of interaction. Again it was the middle curve, 496 rpm that showed magnitude changes different from the other two. As was the case in the previous response curve, the apparent interaction was not radical enough to affect the test of significance. In fact, there was a strong possibility that these manifestations were not interaction at all, but variance attributable to chance, or bias in the experimental conduct i.e. variation in moisture level of the cobs. It was impossible to tell what the source of these conditions were without further experimentation focusing on these effects.

### 6.5.3 Regression Curve Fit to Fuel, Power and Speed Means

These means of table 6.8 were converted to fuel consumption in ml/KWH (milliliters per kilowatt hour). The results were included in Table 6.10. The data in Table 6.10, were combined with engine speed data of Table 6.3, to perform four linear regressions, one for the diesel fuel consumption in diesel only mode and one for each of the 3 moisture levels. The composite plots of these fitted regression curves are in figure 6.12. This figure shows the relationship of fuel consumption at the various moisture levels, to each other, and to fuel consumption on diesel fuel alone. It was evident in this representation that low moisture fuel produced the highest diesel fuel substitution effect.

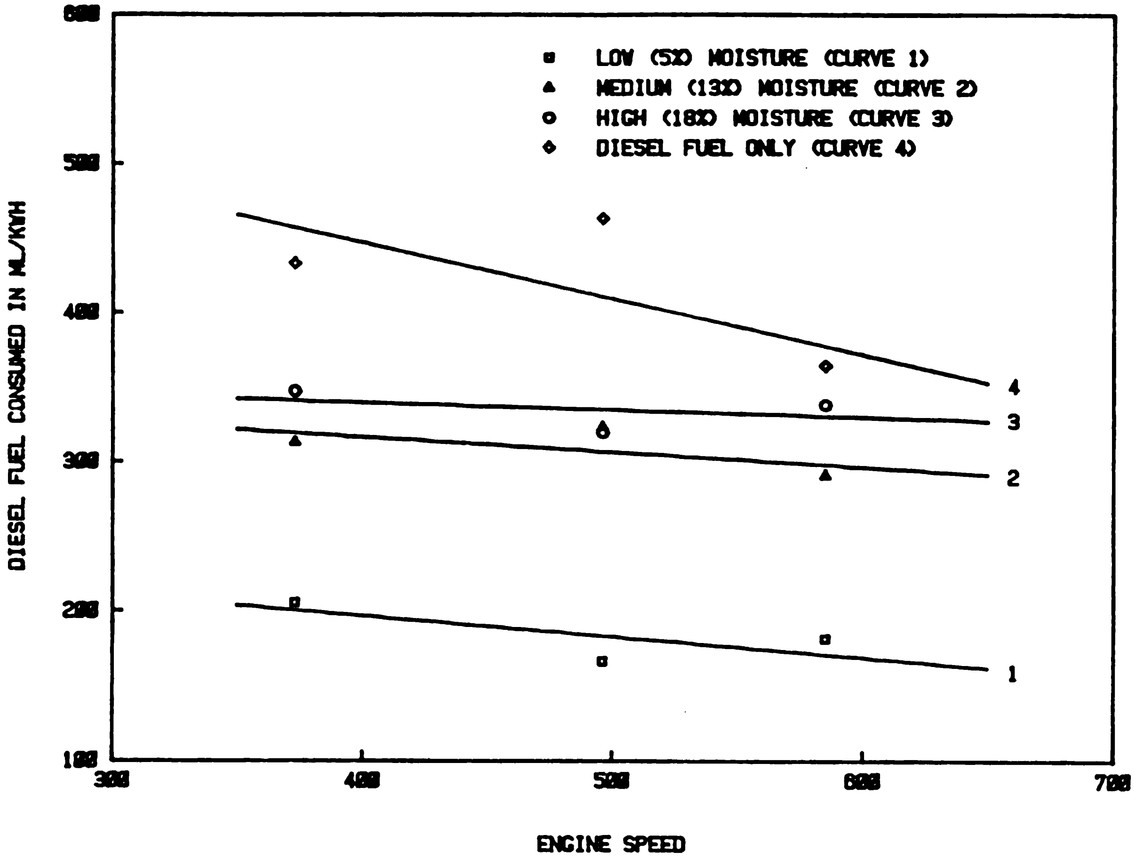



Figure 6.12 Linear regression plots of diesel fuel consumption in ML/KWH. Curves 1,2, and 3 are the low medium and high moisture levels wet basis. Curve 4 is pure diesel fuel.

The consumption of corn cobs was recorded though not as precisely as the diesel fuel consumption. Only 2 replicates of data were acquired, one for block one and one for block 2. The measurement method was a simple pan type container with a volume of 1,375ml. The number of containers used during a treatment was noted, and this value was multiplied by the volume of the container to get the volume of cobs consumed. The results are included in Table 6.11. Though the process was crude the trends in the data show that as moisture content increased the volume of cobs comsumed decreased. This was consistent with the diesel fuel consumption results explained elsewhere. Naturally, the drier and easier burning cobs were consumed more rapidly than wet ones which don't burn as easy. Thus the proportion of energy supplied by each fuel varied with the moisture content of the corn cobs. The drier the cobs the more cobs and less diesel fuel consumed and vice versa.

Table 6.10 Diesel Fuel Consumption in ML/KWH

| | Low Speed | Medium Speed | High Speed |
|---|---|---|---|
| Low H2O | 205.32 | 166.5 | 181.49 |
| Med H2O | 312.96 | 323.57 | 290.8 |
| Hi H2O | 347.66 | 319.75 | 338.3 |

Table 6.11 Corn Cob Comsumption Data and Statistics

| | | Block 1 | Block 2 | Total | Mean |
|---|---|---|---|---|---|
| Low | L | 1.71 | 2.275 | 3.985 | 1.99 |
| Speed | M | 1.422 | 2.275 | 3.697 | 1.848 |
| | H | 1.479 | 1.71 | 3.189 | 1.59 |
| Med | L | 2.559 | 2.275 | 4.834 | 2.417 |
| Speed | M | 1.71 | 0.85 | 2.56 | 1.28 |
| | H | 1.71 | 0.85 | 2.56 | 1.28 |
| Hi | L | 2.275 | 2.559 | 4.834 | 2.417 |
| Speed | M | 1.71 | 2.275 | 3.985 | 1.99 |
| | H | 1.422 | 1.422 | 2.844 | 1.422 |

L = low moisture, M = medium moisture cobs, H = high moisture cobs.

## 6.6 Hypothetical Irrigated Farm Model Using Gasification

The experimental results indicated an average diesel fuel savings of 55 percent at 600 rpm, and 56 percent at 400 rpm when low moisture corn cobs (5% wet basis) were used. The value of such savings in a typical production situation is the theme of this section.

The fuel consumption results were applied to a hypothetical farm in the Sahel region of Africa. The power of the engine was scaled up to 4.47 kw instead of 1.39 kw. This was done to take advantage of the most of the optimum power for use in the farm model. The engine chosen for the model was the 4.47 kw - 650 rpm Eicher Goodearth model ESW-1. This unit had a maximum speed near that studied in the research experiment, and a low power output. The engine was a product of India and the same firm also manufactured pumps for their engines. The 125 mm X 125 mm, 1500 rpm pump was selected for this application, since data available from Jenkins (1984) show the static head to be less than 10 meters in northern Mali. The technical specifications for the engine and pump were available in the Eicher Goodearth Limited brochure provided in the appendix.

### 6.6.1 Engine Power Derating and Pump Discharge Capcity

Since producer gas has much less energy per unit volume than diesel fuel, the power produced by an engine will be lower than its normal rating at a given engine speed (Cruz, 1980; Johansson, 1980). Derating the power output of the engine by 30 percent provided the probable power when operating on producer gas. This was 3.13 kw for the engine used in the farm model. This power was employed in the financial cost - benefit analysis and used to determine the capacity of the surface irrigation system and the level of fuel consumption for both diesel and biomass fuels. Table 6.12 shows the pump discharge rates at 6, 8, and 10 meter heads. Since engine power was reduced by 30 percent so were the discharge rates for the pump.

Table 6.12 Model Farm Pump Discharge Rates

| Head in Meters | Flow in $m^3/hr$ | Flow Reduced by 30 % |
|---|---|---|
| 6 | 126 | 88.2 |
| 8 | 111.6 | 78.1 |
| 10 | 90 | 63 |

### 6.6.2 Water Requirement for Corn

The water requirement for corn in arid areas was 0.774 cm per day peak consumptive use for a yield of 5.65 tons/ha (90 bu/acre) in the Texas plains (Turner and Anderson, 1971). This was equivalent to 77.4 $m^3$ per hectare per day. This value was increased by 30 percent to 100.6 $m^3$ per day to account for losses due to surface irrigation. Carruthers and Clark (1983) cites surface irrgation application efficiency as being around 70 percent. It was further assumed that the pumping plant and equipment operate a maximum of 10 hours per day. This was typically the daily pumping period observed in the Timbuctu region of Mali. Given these operational parameters the land area irrigable at each of the specified heads mentioned in table 6.13 were 8.77 hectares at 6 meters, 7.77 hectares at 8 meters and 6.26 hectares at 10 meters.

### 6.6.3 Quantity of Corn Cobs Available for Gasification

Mantuffel and Tyner (1980) cited yields of 3.0 tons (3,000 kg) per hectare for corn in the Senegal River Valley. This value was assumed for the corn yield in the farm model. A higher yield of 5.65 tons per hectare was employed in a sensitivity analysis included in subsequent sections of this chapter. Payne (1979) reported that corn cobs equal approximately 18.6 percent of the grain yield. Corn cobs at harvest were usually high in moisture. For this model the moisture content at harvest was assumed to be 30 percent wet basis. Relative humidity levels in the Sahel zone of Africa were low during the irrigation season from October to March. Figure 6.13 shows the mean humidity levels for Africa in October. The Sahel region averaged 30-50 percent relative humidity for October. In conjunction with the data provided by White (1984) on equilibrium moisture content of corn cobs (figure 3.4 and 3.5) it was evident that equilibrium corn cob moisture levels will fall to the 5 percent wet basis range. Thus the weight of the cobs was reduced by 25 points to the 5 percent moisture level, for the farm model. These weights are listed in table 6.13 for the three surface areas irrigable by the system.

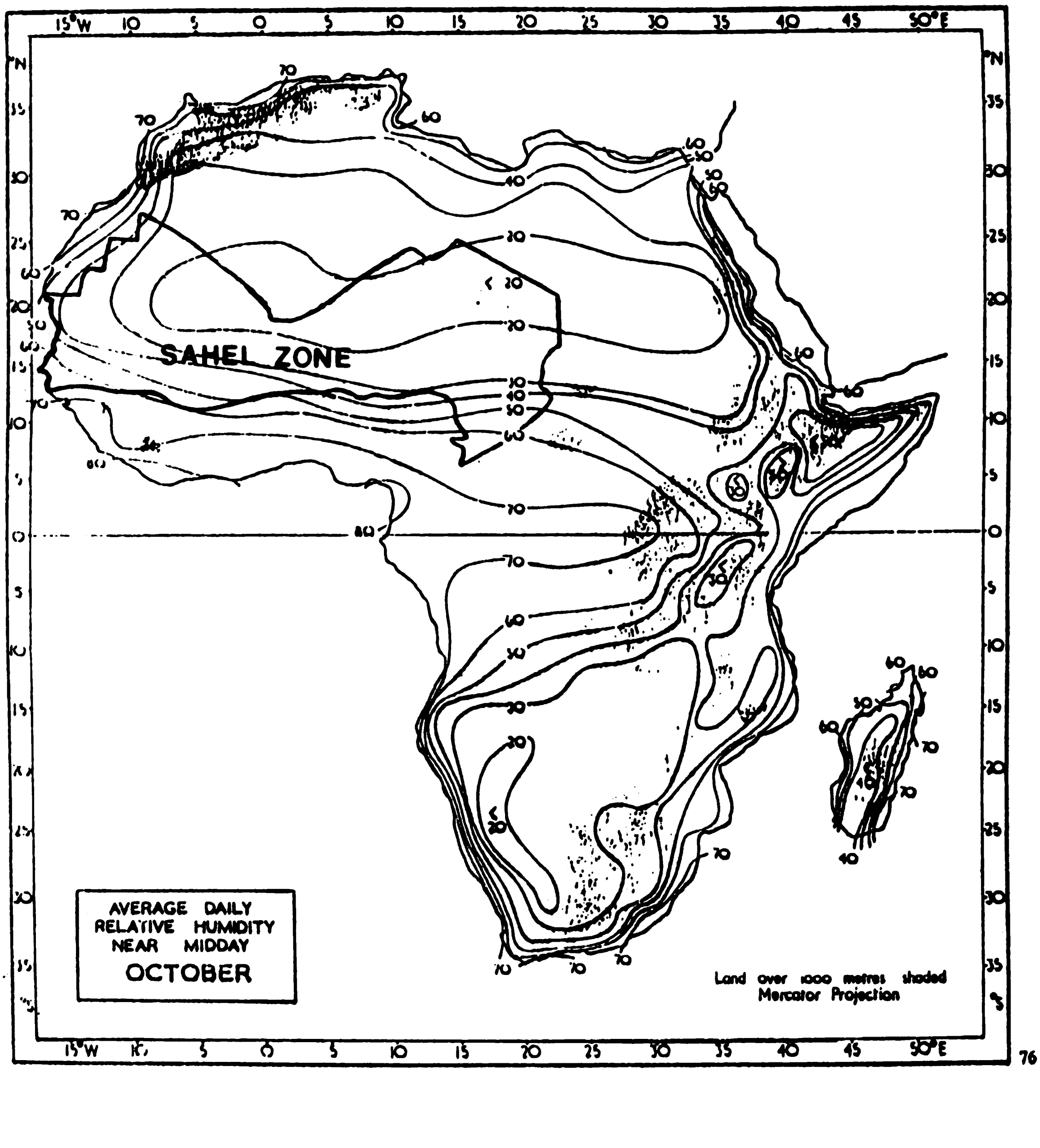



Figure 6.13 Mean Relative Humidity for Africa for the month of October. Source: FAO, 1980

Table 6.13 Corn Cob Produced on the Model Farm

| Area (ha) | Weight at 30% moisture content | Weight at 5% moisture content |
|---|---|---|
| 8.77 | 4,893.7 kg | 3,610.0 kg |
| 7.77 | 4,335.7 " | 3,195.0 " |
| 6.26 | 3,493.1 " | 2,574.0 " |

The experimental data for corn cob consumption were expressed in terms of volume in liters per 10 minutes of test. The experimental values indicated that there were 165.5 grams per liter of cobs. Therefore 3,610 kgs of cobs were equivalent to 21.8 $m^3$ of cobs. Corresponding values for the remaining two field sizes were 19.3 $m^3$ and 15.55 $m^3$ for the 7.77 ha and 6.26 ha fields respectively.

### 6.6.4 Corn Cob Consumption

The experimental data showed that 2.42 liters fo cobs were consumed during a 10 minute test period at 600 rpm and 1.4 kw of power. This translates to 14.52 liters/hour. This value was inflated arbitrarily by 30% to be conservative in deriving the financial benefit as a result of employing the gasification system. The inflated corn cob consumption figure was 18.88 liters/hour. At 1.4 kw the specific fuel consumption became 13.48 liters/kw-hr.

### 6.6.5 Theoretical Corn Cob Consumption on the Model Farm

The engine power on the hypothetical farm was 3.13 kw. Given the experimental cob consumption of 13.48 liters per kw-hr,the 3.13 kw engine consumed 42.19 liters of corn cobs per hour. If the pump was operated for 10 hours a day, the daily cob consumption would have been 421.9 liters or 0.4219 $m^3$. Table 6.14 shows the number of days and the percent of the season covered by gasifier operation.

Table 6.14 Effective Seasonal Working Days Using Producer Gas in the Farm Model

| Area (ha) | Number of days operation w/gas | % of 105 day season covered |
|---|---|---|
| 8.77 | 51.7 | 49.24 |
| 7.77 | 45.75 | 43.57 |
| 6.26 | 36.86 | 35.1 |

### 6.6.6 Diesel Fuel Consumption

Fuel consumption figures in grams per kw-hr ranged from a high af .326 kg/kw-hr to a low of .265 kg/kw-hr (Eicher Goodearth Ltd.,1984; Overseas Ltd., 1984), according to specifications recieved from manufacturers. The higher figure was used in the analysis, so the predicted benefit would be conservative.

An engine producing 3.13 kw at 650 rpm required 1.02

kg of diesel fuel per hour of operation. Taking 1 gram of diesel to be approximately equal to 1 ml in volume, diesel fuel consumed became 1,020 ml per hour or 1.02 liters per hour.

The seasonal diesel fuel consumption was obtained by multiplying the hourly consumption by the number of hours operated per day (10), and multiplying the result by the number of days of irrigation per season. The outcome was 1,071 liters per 105 day season.

### 6.6.7 Diesel Fuel Saved by Using Gasification

Gasification operated the engine - pumpset for 49.24 % of the season for the largest field (8.77 ha). Diesel fuel consumption was reduced by 55 % while producer gas was used. Thus the amount of diesel fuel saved in a typical season is:

| | | | | |
|---|---|---|---|---|
| Low Moisture | 1,071 l/sn X 0.4924 X 0.55 = | 290.05 | liters/sn | |
| Med " | 1,071 l/sn X 0.4924 X 0.20 = | 105.47 | " | " |
| High " | 1,071 l/sn X 0.4924 X 0.113= | 59.59 | " | " |

therefore 290.05 liters of diesel fuel were saved each season using gasification to operate a diesel powered pump, pumping at 6 meters of head to irrigate 8.77 ha of corn field. This was equivalent to reducing seasonal diesel fuel consumption by 27.08%. At medium cob moisture content seasonal diesel fuel consumption is reduced by 9.85%, and

at high cob moisture diesel fuel consumption is reduced by only 5.56%.

## 6.7 Financial Cost - Benefit Analysis

The financial analysis procedure used was the financial internal rate of return, based on that described by Gittinger (1982) in his work on project analsis. With this method the incremental net benefit stream or incremental cash flow is used to derive the internal rate of return. The incremental net benefit stream is obtained by subtracting the "with" gasification systems costs from the "without" gasification system costs. The "with" gasification costs include the cost of the gasification equipment, the added cost of maintenance, and the costs of fuel both diesel and corn cobs. The financial internal rate of return is a measure of investment worth. It is a measure of the rate of return on capital outstanding per period, during the time that capital is invested. The financial internal rate of return is the discount rate that yields a net present worth of the incremental net benefit stream equal to zero.

Initially three scenarios were considered, all of which concern corn cob moisture content. The effect on financial attractiveness of the gasification system was evaluated, as the corn cob moisture content increased.

In these scenarios it was assumed that the cost of corn cobs was zero, the cost of diesel fuel was $0.65 per liter, and that the total cost of the gasification system was $626.00. The cost of the pump set including the engine was $1,000.00, 2.99 times the f.o.b. price ($355.00) at the shipping point from the country of origin (pump price taken from Eicher Good Earth Ltd. 1984 price list). Maintenance cost for a normal diesel was 20% of the purchase price per year. Maintenance for a diesel gasification system was calculated as that of a regular diesel unit plus 14% (Groenveld, et al). The cost of a gasifier system operator was excluded because the irrigation pumps in the Sahel typically had an attendant on hand to refuel the engine, check the motor oil, start and stop the engine, and deter theives that would otherwise steal fuel and parts from the pump set. It was assumed that this person would handle loading of corn cobs into the gasifier and related duties. The life of the system was assumed to be 5 years. The varying factor in these scenarios is cob moisture content, which imply higher diesel fuel consumption as moisture increases. Otherwise, the above assumptions are equal for each of these scenarios.

Tables 6.15 to 6.17 contain the partial budgets for the three scenarios with and without gasification. The incremental net benefit and financial rates of return that correspond to the partial budgets are shown in tables 6.18 to 6.20.

Table 6.15 Partial Budget for Irrigation Costs, With and Without Gasification Fuel,for a Model Farm of 8.77ha Low Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.65 per liter - Grain Yield of 3 tons per hectare

| Item | w/o gas | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|---|
| Gasifier Cost | 0 | 626 | - | - | - | - |
| Maintenance | 200 | 228 | 228 | 228 | 228 | 228 |
| Diesel Fuel | 696 | 508 | 508 | 508 | 508 | 508 |
| Biomass Fuel | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 896 | 1362 | 736 | 736 | 736 | 736 |

Table 6.16 Partial Budget for Irrigation Costs, With and Without Gasification Fuel,for a Model Farm of 8.77ha Medium Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.65 per liter - Grain Yield of 3 tons per hectare

| Item | w/o gas | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|---|
| Gasifier Cost | 0 | 626 | - | - | - | - |
| Maintenance | 200 | 228 | 228 | 228 | 228 | 228 |
| Diesel Fuel | 696 | 635 | 635 | 635 | 635 | 635 |
| Biomass Fuel | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 896 | 1489 | 863 | 863 | 863 | 863 |

Table 6.17 Partial Budget for Irrigation Costs, With and Without Gasification Fuel,for a Model Farm of 8.77ha High Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.65 per liter - Grain Yield of 3 tons per hectare

| Item | w/o gas | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|---|
| Gasifier Cost | 0 | 626 | - | - | - | - |
| Maintenance | 200 | 228 | 228 | 228 | 228 | 228 |
| Diesel Fuel | 696 | 669 | 669 | 669 | 669 | 669 |
| Biomass Fuel | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 896 | 1523 | 897 | 897 | 897 | 897 |

Table 6.18 Incremental Net Benefit and Financial Internal Rate of Return for an 8.77 ha Model Farm, Low Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.65 per liter Grain Yield of 3 tons per hectare

| Year | Cost W/O Gas | Cost W/Gas | Increm Net Benefit | NPW 14% |
|---|---|---|---|---|
| 1 | 896 | 1362 | -466 | -409 |
| 2 | 896 | 736 | 160 | 123 |
| 3 | 896 | 736 | 160 | 108 |
| 4 | 896 | 736 | 160 | 95 |
| 5 | 896 | 736 | 160 | 83 |
| | | | | 0 |

Financial Internal Rate of Return = 14%

Table 6.19 Incremental Net Benefit and Financial Internal Rate of Return for an 8.77 ha Model Farm, Medium Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.65 per liter Grain Yield of 3 tons per hectare

| Year | Cost W/O Gas | Cost W/Gas | Increm Net Benefit | NPW 0% |
|---|---|---|---|---|
| 1 | 896 | 1489 | -593 | -593 |
| 2 | 896 | 863 | 33 | 33 |
| 3 | 896 | 863 | 33 | 33 |
| 4 | 896 | 863 | 33 | 33 |
| 5 | 896 | 863 | 33 | 33 |
| | | | | ---- |
| | | | | -461 |

The Financial Internal Rate of Return is negative since the total Net Present Worth at 0% discount rate is negative.

Table 6.20 Incremental Net Benefit and Financial Internal Rate of Return for an 8.77 ha Model Farm, High Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.65 per liter Grain Yield of 3 tons per hectare

| Year | Cost W/O Gas | Cost W/Gas | Increm Net Benefit |
|---|---|---|---|
| 1 | 896 | 1523 | -627 |
| 2 | 896 | 897 | -1 |
| 3 | 896 | 897 | -1 |
| 4 | 896 | 897 | -1 |
| 5 | 896 | 897 | -1 |

The Financial Internal Rate of Return is negative since the entire net benefit stream is negative.

Of the above three scenarios only that of the low cob moisture has a positive internal rate of return. Thus under the given assumptions, low moisture cobs are necessary for the gasification system to operate more profitably than a pure diesel system.

### 6.7.1 Inclusion of Cob Costs

Corn cob costs were considered in 3 additional scenarios. These involved costs of \$1.00 per $m^3$, \$3.00 per $m^3$, and \$5.00 per $m^3$. These cob costs were only analysed with the low moisture cobs since that was the only out come with a positive financial internal rate of return.

In previous sections of this chapter it was shown that a grain yield of 3 tons per hectare will provide 22 $m^3$ of corn cobs from an 8.77 ha farm. This quantity was used as the seasonal consumption of cobs, and thus was the basis for determining the cost of cobs in the partial budgets. Tables 6.21 to 6.23 contain the partial budgets for these scenarios. Following these are the corresponding incremental net benefit streams and the financial internal rates of return, in tables 6.24 to 6.26.

Table 6.21 Partial Budget for Irrigation Costs, With and Without Gasification Fuel, for a Model Farm of 8.77ha Low Moisture Cobs at cost of $\$1.00/m^3$ - Diesel Fuel Cost of $0.65 per liter - Grain Yield of 3 tons per hectare

| Item | w/o gas | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|---|
| Gasifier Cost | 0 | 626 | - | - | - | - |
| Maintenance | 200 | 228 | 228 | 228 | 228 | 228 |
| Diesel Fuel | 696 | 508 | 508 | 508 | 508 | 508 |
| Biomass Fuel | 0 | 22 | 22 | 22 | 22 | 22 |
| Total | 896 | 1384 | 758 | 758 | 758 | 758 |

Table 6.22 Partial Budget for Irrigation Costs, With and Without Gasification Fuel, for a Model Farm of 8.77ha Low Moisture Cobs at cost of $\$3/m^3$ - Diesel Fuel Cost of $0.65 per liter - Grain Yield of 3 tons per hectare

| Item | w/o gas | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|---|
| Gasifier Cost | 0 | 626 | - | - | - | - |
| Maintenance | 200 | 228 | 228 | 228 | 228 | 228 |
| Diesel Fuel | 696 | 508 | 508 | 508 | 508 | 508 |
| Biomass Fuel | 0 | 66 | 66 | 66 | 66 | 66 |
| Total | 896 | 1428 | 802 | 802 | 802 | 802 |

Table 6.23 Partial Budget for Irrigation Costs, With and Without Gasification Fuel, for a Model Farm of 8.77ha Low Moisture Cobs at cost of $\$5/m^3$ - Diesel Fuel Cost of $0.65 per liter - Grain Yield of 3 tons per hectare

| Item | w/o gas | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|---|
| Gasifier Cost | 0 | 626 | - | - | - | - |
| Maintenance | 200 | 228 | 228 | 228 | 228 | 228 |
| Diesel Fuel | 696 | 508 | 508 | 508 | 508 | 508 |
| Biomass Fuel | 0 | 110 | 110 | 110 | 110 | 110 |
| Total | 896 | 1472 | 846 | 846 | 846 | 846 |

Table 6.24 Incremental Net Benefit and Financial Internal Rate of Return for an 8.77 ha Model Farm, Low Moisture Cobs at cost of $\$1/m^3$ - Diesel Fuel Cost of $0.65 per liter - Grain Yield of 3 tons per hectare

| Year | Cost W/O Gas | Cost W/Gas | Increm Net Benefit | NPW 5% | NPW 6% |
|---|---|---|---|---|---|
| 1 | 896 | 1384 | -488 | -465 | -460 |
| 2 | 896 | 758 | 138 | 125 | 123 |
| 3 | 896 | 758 | 138 | 119 | 116 |
| 4 | 896 | 758 | 138 | 114 | 109 |
| 5 | 896 | 758 | 138 | 108 | 103 |
| | | | | 1 | -9 |

The Financial Internal Rate of Return is for this scenario is 5.10%

Table 6.25 Incremental Net Benefit and Financial Internal Rate of Return for an 8.77 ha Model Farm, Low Moisture Cobs at cost of $\$3/m^3$- Diesel Fuel Cost of $0.65/liter Grain Yield of 3 tons per hectare

| Year | Cost W/O Gas | Cost W/Gas | Increm Net Benefit | NPW 0% |
|---|---|---|---|---|
| 1 | 896 | 1428 | -532 | -532 |
| 2 | 896 | 802 | 94 | 94 |
| 3 | 896 | 802 | 94 | 94 |
| 4 | 896 | 802 | 94 | 94 |
| 5 | 896 | 802 | 94 | 94 |
| | | | | -156 |

The Financial Internal Rate of Return is negative since the total Net Present Worth at 0% discount rate is negative.

Table 6.26 Incremental Net Benefit and Financial Internal Rate of Return for an 8.77 ha Model Farm, Low Moisture Cobs costing $\$5/m^3$ - Diesel Fuel Cost of $0.65 per liter Grain Yield of 3 tons per hectare

| Year | Cost W/O Gas | Cost W/Gas | Increm Net Benefit | NPW 0% |
|---|---|---|---|---|
| 1 | 896 | 1472 | -576 | -576 |
| 2 | 896 | 846 | 50 | 50 |
| 3 | 896 | 846 | 50 | 50 |
| 4 | 896 | 846 | 50 | 50 |
| 5 | 896 | 846 | 50 | 50 |
| | | | | -376 |

The Financial Internal Rate of Return is negative since the total Net Present Worth at 0% discount rate is negative.

Of the three cob cost scenarios, only one had a positive financial internal rate of return (IRR). The outcome with low moisture cobs at a cost of \$1.00 per $m^3$, and diesel fuel cost of \$0.65 per liter had a financial of 5.1 percent. The other outcomes had negative financial IRR's, indicating that raising cob prices above the \$1.00 per $m^3$ level had a negative financial effect on the gasification system.

## 6.8 Sensitivity Analysis

Certain assumptions in the scenarios of the two preivious sections, such as water use, grain yield, and diesel fuel price, might have been too conservative. In the following sections of this chapter, these assumptions were modified by increasing them and recalculating the outcomes. This process revealed how sensitive the attractiveness of the gasification system is to changes in important assumptions.

### 6.8.1 Increased Corn Yield

The grain yield was increased from 3.0 tons to 5.65 tons per hectare. The higher figure corresponds to the yield cited by Turner and Anderson (1972) for a water use rate of 0.774 cm per day (see section 6.6.2). The higher yield would make more cobs available for operating the gasification system. The more cobs are used the less diesel fuel is used, thus increasing the benefits of gasification.

The higher corn yield provided more corn cobs. A yield of 5.65 tons per hectare provided 41 $m^3$ versus 22 $m^3$ of cobs from a corn yield of 3.0 tons per hectare. From section 6.6.5 it was calculated that the gasification system would consume 0.422 $m^3$ per day. Therefore 41 $m^3$ of low moisture cobs are sufficient for 97.24 days of operation. The irrigation season covered 105 days, thus 41 $m^3$ of cobs permitted the gasification system to operate for 92.61 percent of the season. Diesel fuel consumption without gasification was 1,071 liters (section 6.6.6). The diesel fuel saved by the gasification system at the higher yield of 5.65 tons of grain per hectare is as follows:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Low | Moisture | Cobs | 1,071 | liters | X | 0.9261 | X 0.55 = | 545.5 l |
| Medium | " | " | " | " | X | " | X 0.20 = | 198.37 l |
| High | " | " | " | " | X | " | X 0.113= | 112.081 |

Where 0.9261 is the percent of the irrigation season that gasification was operable, and 0.55, 0.20, and 0.113 are the percents of diesel fuel saved at low, medium, and high cob moisture contents respectively, when gasification was employed. These savings translated to a seasonal reduction in diesel fuel consumption of 50.9%, 18.5%, and 10.5% for low, medium, and high cob moistures respectively.

Taking these savings into account, the seasonal cost of diesel fuel for the 8.77 hectare model farm was:

Low Moisture Cobs (1071 l - 545.5 l)X \$0.65 = \$341.58

Med " " (1071 l - 198.37l)X \$0.65 = \$567.21

High " " (1071 l - 112.08l)X \$0.65 = \$623.30

These are the values contained in the partial budgets of tables 6.27 to 6.29.

The financial internal rate of return, incremental net benefit, and discountet net present worth for the three outcomes cited above, are contained in tables 6.30 to 6.32.

Table 6.27 Partial Budget for Irrigation Costs, With and Without Gasification Fuel, for a Model Farm of 8.77ha Low Moisture Cobs at Zero Cost - Diesel Fuel Cost of \$0.65 per liter - Grain Yield of 5.65 tons per hectare

| Item | w/o gas | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|---|
| Gasifier Cost | 0 | 626 | - | - | - | - |
| Maintenance | 200 | 228 | 228 | 228 | 228 | 228 |
| Diesel Fuel | 696 | 342 | 342 | 342 | 342 | 342 |
| Biomass Fuel | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 896 | 1196 | 570 | 570 | 570 | 570 |

Table 6.28 Partial Budget for Irrigation Costs, With and Without Gasification Fuel, for a Model Farm of 8.77ha Medium Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.65 per liter - Grain Yield of 5.65 tons per hectare

| Item | w/o gas | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|---|
| Gasifier Cost | 0 | 626 | - | - | - | - |
| Maintenance | 200 | 228 | 228 | 228 | 228 | 228 |
| Diesel Fuel | 696 | 567 | 567 | 567 | 567 | 567 |
| Biomass Fuel | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 896 | 1421 | 795 | 795 | 795 | 795 |

Table 6.29 Partial Budget for Irrigation Costs, With and Without Gasification Fuel, for a Model Farm of 8.77ha High Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.65 per liter - Grain Yield of 5.65 tons per hectare

| Item | w/o gas | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|---|
| Gasifier Cost | 0 | 626 | - | - | - | - |
| Maintenance | 200 | 228 | 228 | 228 | 228 | 228 |
| Diesel Fuel | 696 | 623 | 623 | 623 | 623 | 623 |
| Biomass Fuel | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 896 | 1477 | 851 | 851 | 851 | 851 |

Table 6.30 Incremental Net Benefit and Financial Internal Rate of Return for an 8.77 ha Model Farm, Low Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.65 per liter Grain Yield of 5.65 tons per hectare

| Year | Cost W/O Gas | Cost W/Gas | Increm Net Benefit | NPW 90% |
|---|---|---|---|---|
| 1 | 896 | 1196 | -300 | -158 |
| 2 | 896 | 570 | 326 | 90 |
| 3 | 896 | 570 | 326 | 48 |
| 4 | 896 | 570 | 326 | 25 |
| 5 | 896 | 570 | 326 | 13 |
| | | | | 18 |

The Financial Internal Rate of Return is greater than 90%.

Table 6.31 Incremental Net Benefit and Financial Internal Rate of Return for an 8.77 ha Model Farm, Med Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.65 per liter Grain Yield of 5.65 tons per hectare

| Year | Cost W/O Gas | Cost W/Gas | Increm Net Benefit | NPW 0% |
|---|---|---|---|---|
| 1 | 896 | 1421 | -525 | -525 |
| 2 | 896 | 795 | 101 | 101 |
| 3 | 896 | 795 | 101 | 101 |
| 4 | 896 | 795 | 101 | 101 |
| 5 | 896 | 795 | 101 | 101 |
| | | | | -121 |

The Financial Internal Rate of Return is negative since the total NPW is negative at 0% discount rate.

Table 6.32 Incremental Net Benefit and Financial Internal Rate of Return for an 8.77 ha Model Farm, High Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.65 per liter Grain Yield of 5.65 tons per hectare

| Year | Cost W/O Gas | Cost W/Gas | Increm Net Benefit | NPW 0% |
|---|---|---|---|---|
| 1 | 896 | 1477 | -581 | -581 |
| 2 | 896 | 851 | 45 | 45 |
| 3 | 896 | 851 | 45 | 45 |
| 4 | 896 | 851 | 45 | 45 |
| 5 | 896 | 851 | 45 | 45 |
| | | | | -401 |

The Financial Internal Rate of Return is negative since the total NPW is negative at 0% discount rate.

At low cob moisture content, the financial internal rate of return was extremely high (>90%) as can be seen from table 6.30. However, for cobs at high moisture contents, even the better yield does not produce a postive financial IRR (tables 6.31 and 6.32). This resulted from the relatively small amount of diesel fuel saved when medium and high moisture cobs were gasified. At medium moisture only 20% of the diesel fuel was saved and at high moisture only 11.3% of the diesel fuel was saved.

6.8.2 Increased Corn Yield combined with Cob Cost

This analysis was done only for cobs at low moisture content, because positive rates of return were not possible at medium and high moisture contents. The cost of cobs were considered at three levels; $1.00, $3.00, and $5.00 per cubic meter.

At the higher yield of 41 $m^3$ per season, the cost of the corn cobs was $41.00, $123.00 and $205.00. These values are used in the partial budgets of tables 6.33, 6.34 and 6.35.

The outcomes for the financial internal rate of return are given in tables 6.36, 6.37 and 6.38. Of the 3 outcomes, 2 have positive financial IRR's. The cob price of $1.00 per $m^3$ showed a return of 75%. The cob price of $3.00 per $m^3$ showed a return of 32.24%. Only the cob price of $5.00 per $m^3$ gave a negative rate of return.

Table 6.33 Partial Budget for Irrigation Costs, With and Without Gasification Fuel, for a Model Farm of 8.77ha Low Moisture Cobs costing $1/m^3$ - Diesel Fuel Cost of $0.65 per liter - Grain Yield of 5.65 tons per hectare

| Item | w/o gas | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|---|
| Gasifier Cost | 0 | 626 | - | - | - | - |
| Maintenance | 200 | 228 | 228 | 228 | 228 | 228 |
| Diesel Fuel | 696 | 342 | 342 | 342 | 342 | 342 |
| Biomass Fuel | 0 | 41 | 41 | 41 | 41 | 41 |
| Total | 896 | 1237 | 611 | 611 | 611 | 611 |

Table 6.34 Partial Budget for Irrigation Costs, With and Without Gasification Fuel, for a Model Farm of 8.77ha Low Moisture Cobs costing $\$3/m^3$-Diesel Fuel Cost of $0.65 per liter - Grain Yield of 5.65 tons per hectare

| Item | w/o gas | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|---|
| Gasifier Cost | 0 | 626 | - | - | - | - |
| Maintenance | 200 | 228 | 228 | 228 | 228 | 228 |
| Diesel Fuel | 696 | 342 | 342 | 342 | 342 | 342 |
| Biomass Fuel | 0 | 123 | 123 | 123 | 123 | 123 |
| Total | 896 | 1319 | 693 | 693 | 693 | 693 |

Table 6.35 Partial Budget for Irrigation Costs, With and Without Gasification Fuel, for a Model Farm of 8.77ha Low Moisture Cobs costing $\$5/m^3$-Diesel Fuel Cost of $0.65 per liter - Grain Yield of 5.65 tons per hectare

| Item | w/o gas | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|---|
| Gasifier Cost | 0 | 626 | - | - | - | - |
| Maintenance | 200 | 228 | 228 | 228 | 228 | 228 |
| Diesel Fuel | 696 | 342 | 342 | 342 | 342 | 342 |
| Biomass Fuel | 0 | 205 | 205 | 205 | 205 | 205 |
| Total | 896 | 1401 | 775 | 775 | 775 | 775 |

Table 6.36 Incremental Net Benefit and Financial Internal Rate of Return for an 8.77 ha Model Farm, Low Moisture Cobs costing \$1/$m^3$ - Diesel Fuel Cost of \$0.65 per liter Grain Yield of 5.65 tons per hectare

| Year | Cost W/O Gas | Cost W/Gas | Increm Net Benefit | NPW 70% | NPW 80% |
|---|---|---|---|---|---|
| 1 | 896 | 1237 | -341 | -200 | -190 |
| 2 | 896 | 611 | 285 | 99 | 88 |
| 3 | 896 | 611 | 285 | 58 | 49 |
| 4 | 896 | 611 | 285 | 34 | 27 |
| 5 | 896 | 611 | 285 | 20 | 15 |
| | | | | 11 | -11 |

The Financial Internal Rate of Return is 75%

Table 6.37 Incremental Net Benefit and Financial Internal Rate of Return for an 8.77 ha Model Farm, Low Moisture Cobs costing \$3/$m^3$ - Diesel Fuel Cost of \$0.65 per liter Grain Yield of 5.65 tons per hectare

| Year | Cost W/O Gas | Cost W/Gas | Increm Net Benefit | NPW 30% | NPW 35% |
|---|---|---|---|---|---|
| 1 | 896 | 1319 | -423 | -325 | -313 |
| 2 | 896 | 693 | 203 | 120 | 111 |
| 3 | 896 | 693 | 203 | 92 | 82 |
| 4 | 896 | 693 | 203 | 71 | 61 |
| 5 | 896 | 693 | 203 | 55 | 45 |
| | | | | 13 | -14 |

The Financial Internal Rate of Return is 32.24%.

Table 6.38 Incremental Net Benefit and Financial Internal Rate of Return for an 8.77 ha Model Farm, Low Moisture Cobs costing $\$5/m^3$ - Diesel Fuel Cost of $0.65 per liter Grain Yield of 5.65 tons per hectare

| Year | Cost W/O Gas | Cost W/Gas | Increm Net Benefit | NPW 0% |
|---|---|---|---|---|
| 1 | 896 | 1401 | -505 | -505 |
| 2 | 896 | 775 | 121 | 121 |
| 3 | 896 | 775 | 121 | 121 |
| 4 | 896 | 775 | 121 | 121 |
| 5 | 896 | 775 | 121 | 121 |
| | | | | -21 |

The Financial Internal Rate of Return is negative since the total NPW is negative at 0% discount rate.

The outcome for the $1.00 per $m^3$ cob price had a financial IRR of 75 percent. The $3.00 per $m^3$ cob price gave a return of 32.24 percent. In this case increased cob yield permitted higher cob prices to be accomodated by the gasification system. the $5.00 per $m^3$ cob price gave a negative rate of return even at the higher yield.

6.8.3 Increased Diesel Fuel Price

The price of diesel fuel was increased by 20 percent to evaluate the financial effects on the gasification systems viability. The initial diesel price was $0.65 per liter. Adding 20 percent to this resulted in a price level of $0.78 per liter. The seasonal diesel fuel consumption remained at 1,071 liters. The grain yield used was 3 tons per hectare, as was the case in the initial assumptions. The partial budgets and outcomes for low and medium moisture cobs are presented in tables 6.39 to 6.42. The high moisture outcome was excluded because the medium moisture results were negative.

Table 6.39 Partial Budget for Irrigation Costs, With and Without Gasification Fuel, for a Model Farm of 8.77ha Low Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.78 per liter - Grain Yield of 3.0 tons per hectare

| Item | w/o gas | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|---|
| Gasifier Cost | 0 | 626 | - | - | - | - |
| Maintenance | 200 | 228 | 228 | 228 | 228 | 228 |
| Diesel Fuel | 835 | 609 | 609 | 609 | 609 | 609 |
| Biomass Fuel | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 1035 | 1463 | 837 | 837 | 837 | 837 |

Table 6.40 Partial Budget for Irrigation Costs, With and Without Gasification Fuel,for a Model Farm of 8.77ha Medium Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.78 per liter - Grain Yield of 3.0 tons per hectare

| Item | w/o gas | Y1 | Y2 | Y3 | Y4 | Y5 |
|---|---|---|---|---|---|---|
| Gasifier Cost | 0 | 626 | - | - | - | - |
| Maintenance | 200 | 228 | 228 | 228 | 228 | 228 |
| Diesel Fuel | 835 | 753 | 753 | 753 | 753 | 753 |
| Biomass Fuel | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 1035 | 1607 | 981 | 981 | 981 | 981 |

Table 6.41 Incremental Net Benefit and Financial Internal Rate of Return for an 8.77 ha Model Farm, Low Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.78 per liter Grain Yield of 3.0 tons per hectare

| Year | Cost W/O Gas | Cost W/Gas | Increm Net Benefit | NPW 30% |
|---|---|---|---|---|
| 1 | 1035 | 1463 | -428 | -329 |
| 2 | 1035 | 837 | 198 | 117 |
| 3 | 1035 | 837 | 198 | 90 |
| 4 | 1035 | 837 | 198 | 69 |
| 5 | 1035 | 837 | 198 | 53 |
| | | | | 0 |

The Financial Internal Rate of Return is for this scenario is 30%.

Table 6.42 Incremental Net Benefit and Financial Internal Rate of Return for an 8.77 ha Model Farm, Med Moisture Cobs at Zero Cost - Diesel Fuel Cost of $0.78 per liter Grain Yield of 3.0 tons per hectare

| Year | Cost W/O Gas | Cost W/Gas | Increm Net Benefit | NPW 0% |
|---|---|---|---|---|
| 1 | 1035 | 1607 | -572 | -572 |
| 2 | 1035 | 981 | 54 | 54 |
| 3 | 1035 | 981 | 54 | 54 |
| 4 | 1035 | 981 | 54 | 54 |
| 5 | 1035 | 981 | 54 | 54 |
| | | | | -356 |

The Financial Internal Rate of Return is negative since the total NPW is negative at 0% discount rate.

Higher diesel fuel prices had a positive effect on the low moisture scenario. The financial IRR rose 16 points to 30.0 percent compared to the lower price (see table 6.18). In effect the diesel fuel price increase of 20% more than doubled the financial IRR. At higher moisture levels however the return remains negative though better than at the lower diesel fuel price.

A summary of the results of the financial sensitivity analysis is presented in table 6.43. As can be seen from the table positive rates of return were possible only for the low cob moisture content.

Table 6.43 Summary of the Assumed Values of Important Parameters and Financial Internal Rates of Return for Corn cob Gasification, on an 8.77 ha Model Farm Under Surface Irrigation Using a 3.13 kw Slow Speed Diesel Pumpset

| Cob Moisture | Cob Cost $\$/m^3$ | Diesel Fuel Cost $/l | Grain Yield tons/ha | Financial IRR % |
|---|---|---|---|---|
| Low | 0 | 0.65 | 3 | 14.0 |
| Med | 0 | 0.65 | 3.0 | <0 |
| High | 0 | 0.65 | 3.0 | <0 |
| Low | 1 | 0.65 | 3.0 | 5.1 |
| Low | 3 | 0.65 | 3.0 | <0 |
| Low | 5 | 0.65 | 3.0 | <0 |
| Low | 0 | 0.65 | 5.65 | >90.0 |
| Med | 0 | 0.65 | 5.65 | <0 |
| High | 0 | 0.65 | 5.65 | <0 |
| Low | 1 | 0.65 | 5.65 | 75.0 |
| Low | 3 | 0.65 | 5.65 | 32.2 |
| Low | 5 | 0.65 | 5.65 | <0 |
| Low | 0 | 0.78 | 3.0 | 30.0 |
| Med | 0 | 0.78 | 3.0 | <0 |

CHAPTER 7

# CONCLUSION

## 7.1 Experimental Aspects

The ability of a producer gas - diesel engine combination to reduce diesel fuel consumption was evaluated at the laboratory level. Corn cobs of three differing moisture contents was the biomass feedstock. Given the findings of this study the following statements can be made:

1. Dry corn cobs yield the greatest reduction in diesel fuel consumption, in a range of engine speeds between 400 and 600 rpm. At the same power output level, the driest cobs (5% w.b.) saved from 55% to 56% of the fuel normally consumed in full diesel operation (measured in ml/kwh).

2. Higher moisture corn cobs when gasified, also reduce diesel fuel consumption but to a lesser degree than low moisture cobs. As cob moisture increases so does diesel fuel consumption. Medium (13% w.b.,15% d.b.) moisture cobs only saved between 20 and 29% of the diesel fuel consumed on full diesel operation. High moisture cobs (18% w.b.) only reduce diesel fuel consumption by 11.3 - 24.0 percent.

3. Temperatures in the gasification system do not vary appreciably with engine speed or power output, in the range

of engine speeds examined, when the corn cob (biomass) moisture content is relatively steady.

4. The moisture in the corn cobs cools the reaction inside the gas producer. Increasing moisture content increases the temperature drop at the grate. High cob moisture levels cause lower furnace operating temperatures in all cases. The effect is more prevalent at 500 and 600 rpm than at 400 rpm.

At 500 rpm the high cob moisture level steady state temperature mean (552.23$^{o}$C) was 90.44 degrees less than the medium cob moisture mean. The medium cob moisture mean is 57 degrees less than the low cob moisture temperature mean (699.7$^{o}$C).

The situation is practically identical at 600 rpm the means for the low, medium, and high cob moisture levels are 685.3, 626.0, and 536.3 degrees respectively. The high moisture level is 89.7 degrees less than the medium moisture mean. The medium moisture mean is 59.3 degrees less than the low moisture one.

The means at 400 rpm for low, medium, and high moisture cobs are 681.5, 642.7, and 632.1 respectively. Only 10.6 degrees separates the medium and high moisture means.

## 7.2 Financial Aspects

It was clear from the financial analyses that the highest returns came from employing low moisture cobs. Only the low moisture scenarios had positive financial rates of return in all cases analysed. This occurred because low moisture cobs saved the greatest amount of diesel fuel; 55% as compared to 20% for medium and 11.3% for high moisture cobs. Medium moisture cobs never had a positive rate of return in any scenario and neither did high moisture cobs.

At low moisture, the greatest benefit was obtained by increasing the grain yeild. A yield of 5.65 tons per hectare produced a return of over 90%. This was due to the fact that at the higher yield there were enough cobs to operate the gasifier more than 90% of the irrigation season.

When the diesel fuel price was raised 20% to $0.78 per liter, from $0.65 per liter, the financial IRR more than doubled, going from 14% to 30%. Thus higher diesel fuel prices had a favorable financial effect on the gasification system.

Corn cob costs in general could be tolerated in the low cob moisture scenarios at a cost of $1.00 per $m^3$. This price level gave positive rates of return in the two cases studied. Rates of return at medium and high cob moisture were negative without exception when cob costs were introduced. At high yield the $3.00 per $m^3$ price had a return of 32.24% with low moisture cobs. In all other scenarios with cob prices higher than \$1.00 per $m^3$ rates of return were negative.

Given these outcomes, gasification is feasible if the climate in the area allows the equilibrium wet basis moisture content to remain in the 5% range, during the period in which the gasifier operates. In addition, costs of corn cobs could not exceed \$1.00 per $m^3$ if yields are low. If this was possible, the system could pay returns when yields were low and even if there was a cost, albeit low, for the cobs.

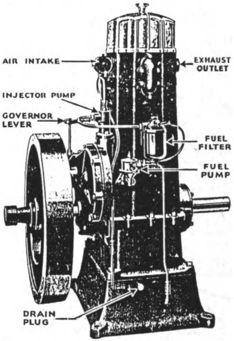
Beyond this the benefit of gasification was derived from the provision of security in the event that a fuel shortage occurred. These circumstances occur frequently in the more isolated areas of the Senegal River Valley and along parts of the Niger river as was indicated elsewhere in this study. Furthermore, given the likelihood of fuel price increases in the future, the benefit of a gasifier would increase accordingly.

# APPENDIX

# APPENDIX

## Slow Speed Diesel Manufacturers

**«STOVER DIESEL ENGINES»**




**Descriptive Illustration of 5 and 10 H. P. Stover Diesel Engines Indicating Location of Operating Parts Not Shown in Illustration on Page 6**

**No. 1205 and 1210 Series**

### Specifications for 5 H.P. Stover Diesel Engine—No. 1205

**Bore**—3⅞ in.

**Stroke**—5¼ in.

**Speed**—900 to 1250 R.P.M.

**Rating** ½ H.P. per 100 R.P.M.

**Maximum Horsepower** .65 H.P. per 100 R.P.M.

**Maximum Torque**—36 lb. ft.

**Fuel Recommended**—Clean free-flowing fuel oil—Baume Gravity 28 to 36°.

**Fuel Consumption**—.48 to .54 lb. per H.P. hour, on Loads Ranging from 60 to 90% of Maximum.

**Lubrication**—Pressure Plunger Oil Pump in Sump.

**Cooling System** Cylindrical Water Tank—125 gals. or Radiator. Thermo-Siphon System.

**Water Evaporation** Depends upon load, temperature and altitude approximately ⅝ gallons per hour on 5 H.P. load at sea level with a 70° room temperature after water reaches 120° to 140°.

**Rotation** Counter-clockwise or to the left when facing Power Take-off Shaft.

**Cylinder**—Has removable Sleeve—Ground to Size.

**Cylinder Head**—Cast Iron Removable.

**Piston** Cast Iron. Heat Treated and Ground to Size.

**Piston Displacement**—62 cu. inches.

**Compression Ratio**—16 to 1.

**Piston Rings** (5) 4 Plain—1 Oil.

**Piston Pin Diameter** 1⅜ in.

**Piston Pin Bearing**—Bronze—Dia. 1⅜ in., length 1⅞ in.

**Connecting Rod** Drop Forged. H-section.

**Crank Pin Bearing**—Steel Back Babbitted. Dia. 2½ in.—Length 2½ in.

**Flywheel**—Dia. 22 in.—Face 3⅜ in.—weight 230 lbs.

**Crank Shaft** Drop Forged 2½ in. in Bearings, 2⅛ in. at Pulley.

**Keyway**—⅝ in. wide x ¼ in. deep.

**Camshaft** Drop Forged—Cams Forged Integral.

**Camshaft Bearings** 2.

**Timing Gears**—Cast Iron—Automatically Hobbed.

**Crank Shaft Main Bearings** Bronze Back Babbitted. Dia. 2½ in.; length 3 in.

**Governor**—Fly Ball Type Completely Enclosed—Automatically Lubricated.

**Oil Pump**—Vertical—Plunger Type.

**Valves**—Special Heat Resisting Alloy Steel located in Head. Dia. Valve Head 1⅜ in.

**Rocker Arms**—Cast Iron.

**Air Cleaner and Silencers** Supplied as Catalog Equipment without Charges.

**Crank Shaft Extension Beyond Frame**—7¾ in.

**Oil Required in Sump**—7 pts.

**Fuel Tank**—Galvanized Sheet Steel located in Base—capacity—3 gals. Remote tank can be also used.

**Bosch Acro-Combustion Chamber.**

**Bosch Fuel Filter Injection Pump and Nozzle.**

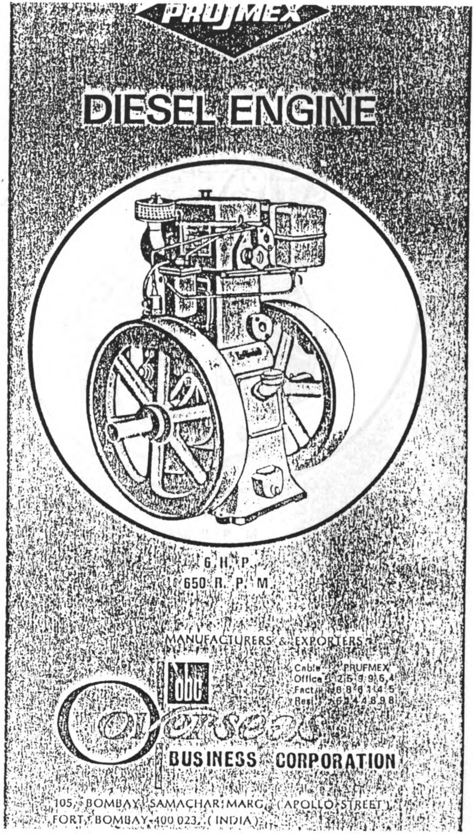
**A. C. Fuel Pump.**

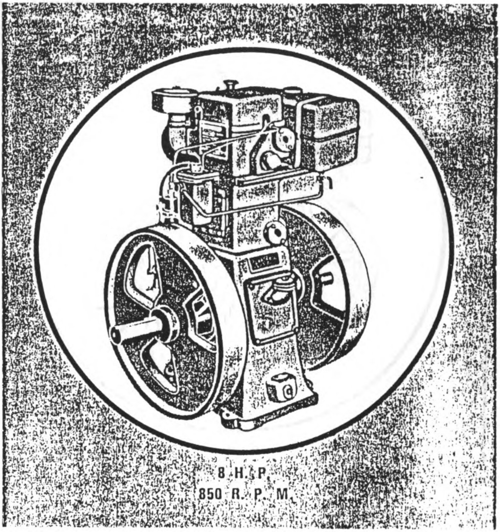
**Starting**—Hand Cranked—Starting Crank Furnished.

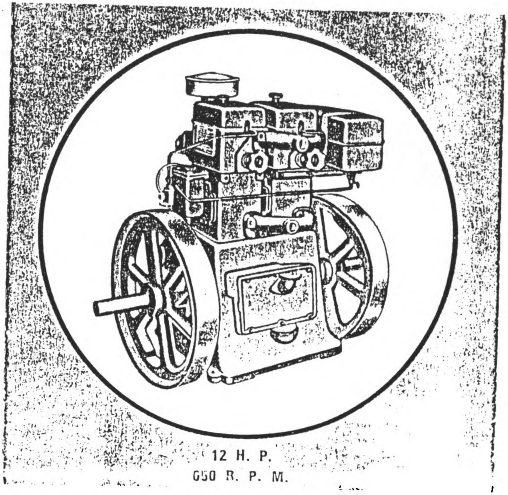
**Clutch—Twin Disc**—Furnished at extra cost with or without either V or flat face pulley. Price depends upon size and type.

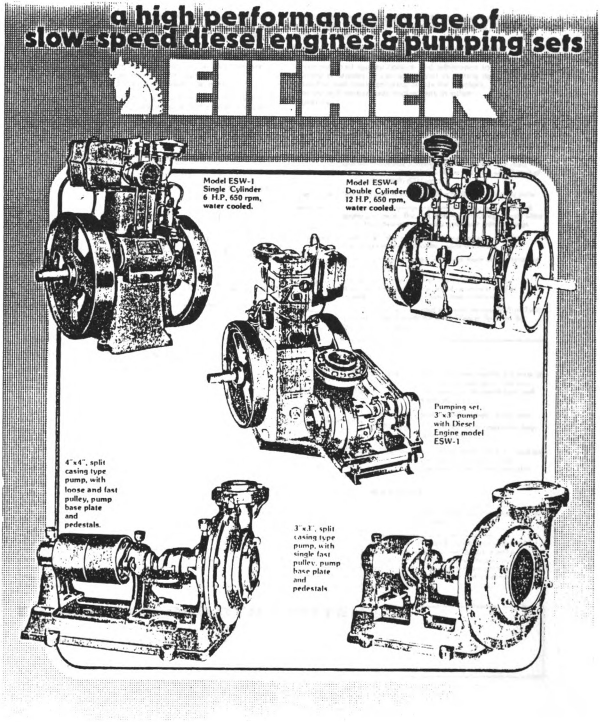
**Pulley**—Catalog equipment does not include pulleys of any description. Additional cost governed by size and type.

**Silencer Exhaust**—Furnished at additional price depending upon type.


DIESEL ENGINE
6 H. P.
650 R. P. M.
MANUFACTURERS & EXPORTERS
Cable PRUFMEX
BUSINESS CORPORATION
105, BOMBAY SAMACHAR MARG, (APOLLO STREET),
FORT, BOMBAY-400 023, (INDIA)


8 H. P
850 R. P. M


12 H. P.
650 R. P. M.


a high performance range of
slow-speed diesel engines & pumping sets
EICHER
Model ESW-1
Single Cylinder
6 H.P, 650 rpm,
water cooled.
Model ESW-4
Double Cylinder
12 H.P, 650 rpm,
water cooled.
Pumping set,
3"x3" pump
with Diesel
Engine model
ESW-1
4"x4", split
casing type
pump, with
loose and fast
pulley, pump
base plate
and
pedestals.
3"x3", split
casing type
pump, with
single fast
pulley, pump
base plate
and
pedestals

Eicher Goodearth Limited pioneered the manufacture of tractors in India, in collaboration with Gebr Eicher, Gmbh, West Germany. Currently Eicher produces over 15,000 tractors per annum.

Today, Eicher is more than just a tractor company. Its manufacturing activity extends, besides tractors to diesel engines, generating sets, agricultural implements and special purpose machines.

Eicher has successfully exported its tractors, diesel engines, agricultural implements and a host of other engineering items like sewing machines, bicycle parts, pumps sets, and hand tools to several countries all over the world.

Eicher is geared to meet export requirements of all types of engineering items with a solid infrastructure to ensure strict quality control and adherence to delivery schedules. It can also assist in setting up assembly and manufacturing plants for tractors, engines and agricultural implements in other countries.

## ENGINE SPECIFICATIONS

| MODEL | ESW-1 | ESW-2 | ESW-3 | ESW-4 | ESW-5 | ESW-6 |
|---|---|---|---|---|---|---|
| H P (B.H.P) | 6 | 8 | 10 | 12 | 16 | 20 |
| R P M | 650 | 850 | 1000 | 650 | 850 | 1000 |
| No of Cylinder | 1 | 1 | 1 | 2 | 2 | 2 |
| Bore (mm.) | 114.3 | 114.3 | 120 | 114.3 | 114.3 | 120 |
| Stroke (mm.) | 139.7 | 139.7 | 139.7 | 139.7 | 139.7 | 139.7 |
| S.F.C (gms/BHP/hr) | 198 | 198 | 210 | 210 | 210 | 220 |
| Cooling System | Water | Water | Water | Water | Water | Water |
| Nett Wt. (Kg.) | 350 | 350 | 350 | 520 | 520 | 520 |
| Gross Wt. (Kg.) | 470 | 470 | 470 | 640 | 640 | 640 |
| Packed Volume | .88 | .88 | .88 | 1.36 | 1.36 | 1.36 |

**Type** Totally enclosed, slow speed, water cooled, single cylinder, four stroke, compression ignition type, vertical diesel engine.

**Power** Engine is rated on effective H.P at crankshaft as a maximum load for continuous running. It can be used to give rated HP for any elevation upto 210 m above sea level, with fuel oil of not less than 18000 BTU per lb.

**Lubrication** Splash system of lubrication is provided for all critical parts.

**Bearings** The small end bearings and cam shaft bearings are of high quality gun metal. The C R bearings are of high quality white metal. Main bearings are heavy type taper roller bearings.

**Governor** With the aid of a spring loaded governor speed can be adjusted easily even while the engine is running.

**Valves** Both the exhaust and inlet valves are made of heat resisting high quality silicon steel.

**Flywheel** The engine is fitted with two well balanced cast iron flywheels which ensure that speed variation is kept at a minimum even under fluctuating load conditions.

**Standard Equipment** Following items are provided free with the engine: Fuel Tank, Starting handle, Foundation Bolts, Silencer, Spanner Set, Oil Can, Screw driver.

## PUMP SPECIFICATIONS

| Size of Pump | | Pump R P M | Impeller Dia. | TOTAL HEAD IN METERS | | | | | | | | ENGINE | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | | |
| mm | Inches | | | DISCHARGE (LITRES/SEC) | | | | | | | | H P. | R P M |
| 80 x 80 | 3 x 3 | 1500 | 230 | - | - | 19.5 | 17.5 | 15.5 | 12.5 | - | - | 6 HP | 650 |
| 100 x 100 | 4 x 4 | 1500 | 215 | - | 24.5 | 22.7 | 19.7 | 17 | - | - | - | 6 HP | 650 |
| 125 x 125 | 5 x 5 | 1500 | 180 | 35 | 31 | 25 | - | - | - | - | - | 6 HP | 650 |
| 80 x 80 | 3 x 3 | 1500 | 230 | - | - | 26.5 | 25.5 | 24 | 23 | 18.7 | - | 8 HP | 850 |
| 100 x 100 | 4 x 4 | 1200 | 230 | - | - | 38 | 32 | 22.5 | - | - | - | 8 HP | 850 |
| 125 x 125 | 5 x 5 | 1200 | 210 | 42 | 39 | 36 | 32 | - | - | - | - | 8 HP | 850 |
| 80 x 80 | 3 x 3 | 1500 | 230 | - | - | 30 | 27 | 26 | 25 | 19.5 | 17.5 | 10 HP | 1000 |
| 100 x 100 | 4 x 4 | 1500 | 250 | - | - | - | 35 | 34 | 31 | 25 | 20 | 10 HP | 1000 |
| 125 x 125 | 5 x 5 | 1500 | 210 | - | 42 | 39 | 36 | 32 | 27 | - | - | 10 HP | 1000 |

**Casing & Impeller** Both casing and impeller are made of high quality close grain cast iron. The impeller is shrouded type, well balanced.

**Shaft** Shaft is made of high carbon steel.

**Ball Bearing** The ball bearing is single row, deep grooved type.

**Stuffing Box** Is of ample depth with C.I. Gland and ensures effective water seal. Gun metal sleeve is also provided.

### WARRANTY

These products carry warranty against any manufacturing defects arising out of normal usage for a period of full six months.

As per company's policy of continuous improvements the specifications given in the leaflet are subject to change or withdrawal at any time without notice and the company accepts no responsibility for any discrepancies which may occur between actual specifications and the description in this publication.

## EICHER GOODEARTH LIMITED

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