# Biogas in Small-scale Rural Electricity Generation

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## Abstract

Small-scale anaerobic fermentation of organic wastes, particularly cattle manure, to yield both methane-rich fuel gas (biogas) and fertiliser is discussed and found to be potentially beneficial in rural African situations. An experimental study on the fuelling of a portable engine-alternator set with simulated biogases (mixtures of methane, $CH_4$, and carbon dioxide, $CO_2$) is then presented. The only modification required for gas-fuelling of the engine (a normally petrol-fuelled, side-valve machine rated at 5,2 kW mechanical output) is the fitting of a simple commercially available gas feed adaptor. The engine runs reasonably smoothly on gases containing up to 31% $CO_2$; at higher $CO_2$ concentrations simultaneous fuelling with a pilot quantity of petrol is necessary. Replacement of petrol with pure $CH_4$ is found to result in a 17% loss in maximum power output. Increasing $CO_2$ content of the gas leads to further losses of maximum power, with a 35% loss at 31% $CO_2$. Specific fuel consumption data are presented and the overall efficiency of the unit (electrical output divided by calorific input) is found to be higher with gas-fuelling than with petrol. The loss in power on fuelling with biogas, instead of petrol, can be partially offset by increasing the compression ratio of the engine.

## Introduction

The general aim of this study was to assess biogas as a fuel in the very small-scale generation of electricity in rural African situations. 'Very small-scale' here implies output powers of less than 5 kW, typically deriving from portable engine-alternator sets. Such units are usually driven by governed, spark-ignition (SI), side-valve engines. 'Rural African situations' are to be understood as precluding complex or expensive machinery, modifications and operating techniques.

Since the latter constraints, as well as common practice, argue against the use of compression-ignition (CI) engines, such machines were excluded from this study.

### *Generation of Biogas*

The term 'biogas' describes the methane-rich mixture of gases that is produced by the anaerobic (oxygen-free) bacterial digestion of organic material. A swamp in which submerged vegetable matter decomposes and liberates 'marsh gas' is thus a natural biogas generator or digester.

The simplest man-made digester is a double-drum unit of the type shown in Figure 1. The outer drum, with its top cut out, is filled with a mixture of, say, animal manure, water and seeding mixture (fluid from an operative digester). The smaller, similarly open drum is inverted and, with the gas valve open, is pushed down into the slurry until all free air is displaced (Figure 1a). After a few days (sometimes weeks) the digester becomes active, biogas is generated and the inner drum, acting as a floating gas storage dome, rises (Figure 1b). The first drum of gas is vented since it usually contains some air which with methane forms a potentially explosive mixture. Subsequent drums contain usable gas, at least 50% (by volume) of which is methane, and the remainder largely carbon dioxide. Total gas yields of drum digesters appear not to be reported; other simple rural units, however, have gas yields of at least 0,2 $m^3/kg$ dry cattle manure [1,2], that is, approximately 0,04 $m^3/kg$ wet manure. (Other manures and most vegetable feed materials have higher yields.) Thus one drum charge consisting of half fresh manure and half water could yield some 20 drums of gas. The spent slurry is a fertilizer of value equal to that of the original manure, but having greatly reduced pathogen concentrations and odour problems. Double-drum digesters are, however, messy to operate and too small; they are valuable mainly as demonstration units and for the production of seeding mixture. Detailed instructions for the building and operating of a digester consisting of two standard oil drums are given by Fry and Merril [3].

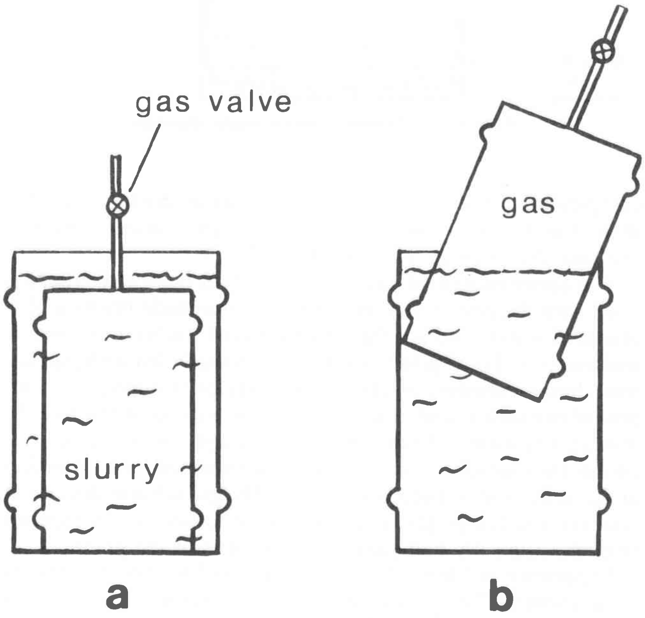

Figure 1 – Two-drum digester

At the opposite end of the scale, both in size and sophistication, is the operation felicitously named CRAP (Caloric Recovery Anaerobic Process Inc.) of Guymon, Oklahoma. The plant is fed by the manure of 100 000 cattle from adjacent feedlots and produces some 45 000 $m^3$ of methane per day which is sold to a gas company supplying Chicago. Spent slurry is separated, the solids being processed into feed supplement for the cattle and the liquid sold as fertilizer (see [1]).

Between these two extremes lies a diversity of digester designs (see reviews [1,4]). Of these only simple family-size, or possibly small community-size units, are of interest in the present study. Such intermediate-technology digesters have found wide acceptance in India and, spectacularly so, in China where 7,2 million plants were built between 1970 and 1980 [1,2]. Rivett-Carnac [1], in assessing biogas in the South African context, suggests that appropriate adaptations of the Chinese family-scale plant designs might suit rural 'kraal' situations.

Chinese digesters are described in detail in an official people's manual, now available in translation [2]. All designs avoid the

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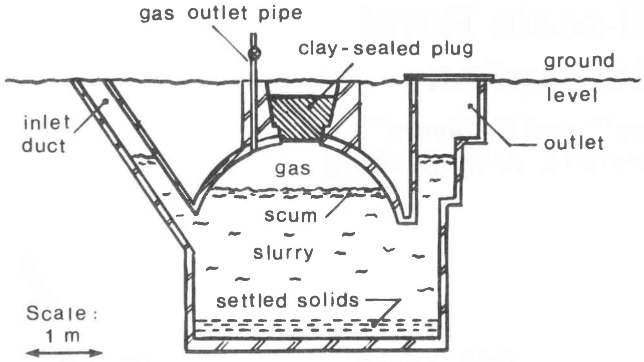

**Figure 2 – Chinese family-scale digester**

complexities of a floating gas dome (characteristic of Indian plants) and consist essentially of slightly pressurized, impervious pits. An example is shown in Figure 2.

The entire excavated cavity (unless hewn from solid rock) is lined with dressed stones, pebbles or home-made bricks and is rendered water- and gas-tight by means of traditional cements and mortars. The digester is semi-continuously fed with pig manure, human sewage, vegetable material (for example, pre-composted rice stalks) and dilution water. Occasional stirring of the mixture (by means of poles inserted through inlet or outlet) improves the digestion process. Spent slurry is removed by bucket at the outlet and is spread onto fields. The gas is burnt directly in cookers and lamps [2]. The removal of settled solids requires periodic (typically half-yearly) shut-downs of the plants.

Experience in China [2] shows the gas yields of such digesters to be about 0,17 m³ of gas per m³ of pit volume in summer and some 25% less in winter. (The digesters are relatively insensitive to ambient temperature because of the insulating effect of the surrounding soil.) If it is assumed that the same yield is obtainable under local 'kraal' conditions (the admixture of human sewage and vegetable feedstock to the cattle manure would be beneficial to this end) then the 15 m³ digester shown in Figure 2 would produce at least 2 m³ of gas per day. This would require a feed rate of some 50 kg of wet cattle manure per day, that is, the total manure output of 2,5 cows, or on the assumption that only half the manure is collected, the output of 5 cows.

Rivett-Carnac [1] estimates that by employing rurally available materials and building techniques, the costs of such plants (excluding labour) could be approximately R80 in South Africa (1982 values).

Since many parts of rural Africa suffer from fuel shortage (or rapid deforestation), soil impoverishment and water pollution, biogas projects are clearly desirable. Their successful implementation, however, is subject to at least the following factors: The availability of water, a resource already severely strained in many regions; the willingness and ability of the population to bear the necessary costs, and the social acceptance of – and indeed commitment to – such schemes. Thus, inherent objections might exist to the management of what are, in essence, excrement pits, and the extraordinary diligence and discipline displayed by the Chinese in the building and running of their digesters might not be equalled by other populations.

### *Nature and Uses of Biogas*

A large variety of organic material is amenable to anaerobic digestion. Depending on this feed material and on the method of digestion, the composition of the resulting gas lies within the following ranges: 50 to 70% methane ($CH_4$), 25 to 45% carbon dioxide ($CO_2$), 1 to 5% hydrogen ($H_2$), 0,5 to 3% nitrogen ($N_2$) and traces of hydrogen sulphide ($H_2S$), carbon monoxide (CO) and oxygen ($O_2$); (all percentages by volume throughout this report).

The gas may be used in 'raw' or 'scrubbed' form, the latter involving reduction or elimination of the $CO_2$ content by chemical means, for example, by bubbling through aqueous solutions of calcium hydroxide. Because of the cost of chemicals and the attention required in operating scrubbing systems, applications requiring such gas processing are considerd liabilities in intermediate technology situations.

The chief usage of biogas is thus appropriately the fuelling of cookers and lamps for which scrubbing is unnecessary [2].

The gas also has potential as a fuel for internal combustion engines, of both SI and CI types. In developing technology situations the engines might serve to power water pumps, stationary agricultural machines or – the subject of the present study – small alternators. (For reasons already discussed, consideration is given here to SI engine-alternator sets only.) The operating and performance characteristics of SI engines fuelled on pure $CH_4$ (fully scrubbed biogas) and on natural gas (typically 92% $CH_4$/8% higher alkanes) are well documented [5,6,7]. In essence, 'methane is a superb fuel' [8], but when used as a replacement for petrol in an otherwise unmodified engine, leads to a reduction in peak power output of some 15%. The effect of the presence of $CO_2$ in the gas, however, and the interaction of $CO_2$ concentration with the performance of governed engine-alternator units appears to be less widely known [4,9].

### *Specific Aims*

In view of the foregoing, the specific aims of this study were to provide answers to the following practical questions:

(1) What are the minimum modifications that permit gas-fuelling of the engine, while leaving the liquid fuel system unaltered?

(2) What concentrations of $CO_2$ in the biogas are acceptable, (a) for starting; and (b) for running of the engine? (Is scrubbing necessary?)

(3) What is the electrical power output that can be expected of the engine-alternator set when fuelled with biogases of various $CO_2$ contents, rather than petrol?

(4) What will be the specific biogas consumption (m³/kWh electrical)? (What will be the size of the required digester?)

(5) How may the performance of gas-fuelled sets be improved by simple means?

## Test facility and procedure

### *Engine and Alternator*

The engine selected for testing was a Briggs and Stratton model 195 400. This is a governed, single-cylinder, four-stroke, side-valve unit, having a rated (sea level) power output of 5,2 kW at 3 000 rev/min. The compression ratio is 6,2 and the ignition system is of the magneto type with a fixed timing of 12° before top dead centre.

The directly-coupled alternator was a Pincor revolving field unit rated at 13,65 A at 220 V output, with a frequency of 50 Hz at 3 000 rev/min.

### *Gas Fuel Adaptor*

The simplest and cheapest method of adapting the engine for biogas fuelling was found to be the fitting of a commercially available liquid petroleum gas (LPG) fuel adaptor. This 'gas carburettor', a Beam model 1 120 B, was attached to the engine's air intake upstream of the petrol carburettor (Figure 3). The unit is comprised of a venturi, the throat region of which is drilled with feed holes through which fuel gas, supplied at ambient pressure, is drawn at a flow rate approximately proportional to the air intake rate. Mixture strength is set by a needle valve in the gas inlet port. In a real situation, gas reduced to ambient pressure would be supplied directly to the adaptor from the bio-

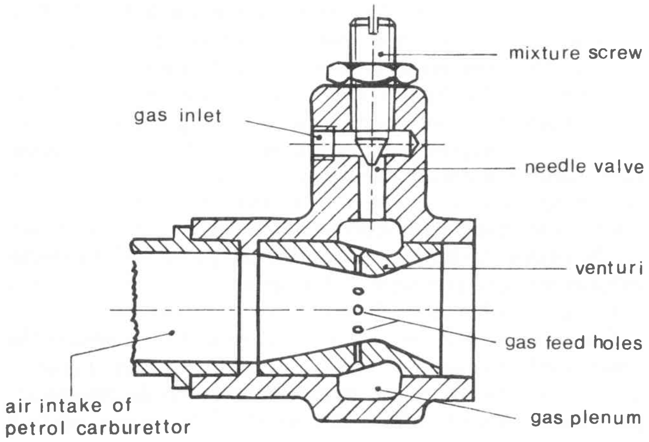

**Figure 3 – Gas feed adapter**

gas generator. In the present study, gas from high-pressure storage cylinders was passed through intermediate regulators and was finally supplied to the adaptor at atmospheric pressure via a Beam model 52 B demand regulator.

The liquid fuel system remained unaltered. In practical usage this would permit rapid change-over to petrol fuelling in the event of a failure of the gas supply.

*Simulated Biogas*

Since real biogas was not readily available, the engine was fuelled with mixtures of pure $CH_4$ and $CO_2$. Various compositions were fed either from cylinders of premixed gas (made up by the gas suppliers), or by dynamic metering and mixing from separate cylinders. The compositions covered the range from pure $CH_4$ to 58% $CH_4$/42% $CO_2$. For the purpose of this study the presence of the other components in natural biogas were ignored. Of these, hydrogen is likely to be the most important.

*Measurements*

The following mass flow rates were determined:
*air, by measuring the pressure drop across an orifice meter, fitted with the usual surge-damper arrangement [10];
*gaseous fuels, by means of rotameters;
*petrol by weighing and timing.
Exhaust gas temperatures were measured by means of a thermocouple probe fitted into the exhaust port.

Ignition timing was determined by a stroboscope and timing marks retrofitted to the flywheel.

The electrical output of the alternator was dissipated in a step-switchable resistance box; power output was determined from measurements of current and voltage; frequency was measured on a digital counter.

*Testing Procedure*

After starting the engine on the desired fuel, the throttle governor was adjusted, in accordance with the manufacturers' instructions, to give an engine speed of 3100 rev/min (51,7 Hz) at no load. The air/fuel ratio (AFR) was set, as would be expected of the rural operator, by adjusting the petrol or gas carburettor's mixture needle valve to a position roughly halfway between the rich and lean limits of smooth running. Frequency and mixture settings were refined during the engine's warm-up period and then left unaltered throughout the test. All readings listed above were taken first at no load and – with progressive loading – after a settling-down period at each load setting.

## Results and discussion

The following fuels were tested: petrol of regular grade (octane number 87), pure $CH_4$ and simulated biogases having $CO_2$ contents of 12,5; 20; 23; 31 and 42%.

*Starting and Smooth Running*

The engine could be hand-started (using the fitted recoil ripcord) on all fuels except the 42% $CO_2$ biogas, where starting on petrol and 'blending-over' to gas was necessary. Running was smooth with $CO_2$ concentrations in the gas of up to 23%, very slightly irregular at 31% and unsatisfactory at 42%.

Since raw digester gases frequently have $CO_2$ contents of the order of 40% (and this figure varies with seasons and digester feedstock), the above findings suggest that for SI engine applications some gas scrubbing facility will generally have to be provided. Picken, however, (unpublished, quoted in [9] p. 152) found the onset of irregular combustion to occur at $CO_2$ concentrations of 45 to 50%. This result is more encouraging, since such $CO_2$ levels are rare in natural digester gases. The limiting $CO_2$ concentration is, in any event, expected to vary with combustion chamber characteristics (particularly compression ratio) and may well respond favourably to the presence of $H_2$ in the fuel gas. (It is not clear whether Picken used natural $H_2$-containing biogas, or simple $CH_4/CO_2$ fuel mixtures.)

A practice preferable to gas scrubbing would appear to be dual fuelling of the engine. The technique is well established for CI engines [11,12] and could be adapted for SI engine usage as follows: a pilot quantity of petrol, just sufficient to ensure smooth running, is supplied via the liquid carburettor, while raw biogas – the main fuel – is simultaneously aspirated through a venturi gas adaptor. The technique was, in effect, used during the 'blending-over', referred to above, and presents no undue difficulties.

*Engine Performance and Electrical Output*

Experimental results of speed (frequency) vs electrical power output for the various fuels are shown in Figure 4. The output frequency initially fell approximately linearly with power, as the throttle butterfly-valve opened progressively under the action of the governor. As the full-throttle position was approached, regulation became increasingly worse, until at the wide open position it was totally lost. (The test on the biogas of 42% $CO_2$ was an exception, here the throttle was essentially fully open throughout the run.)

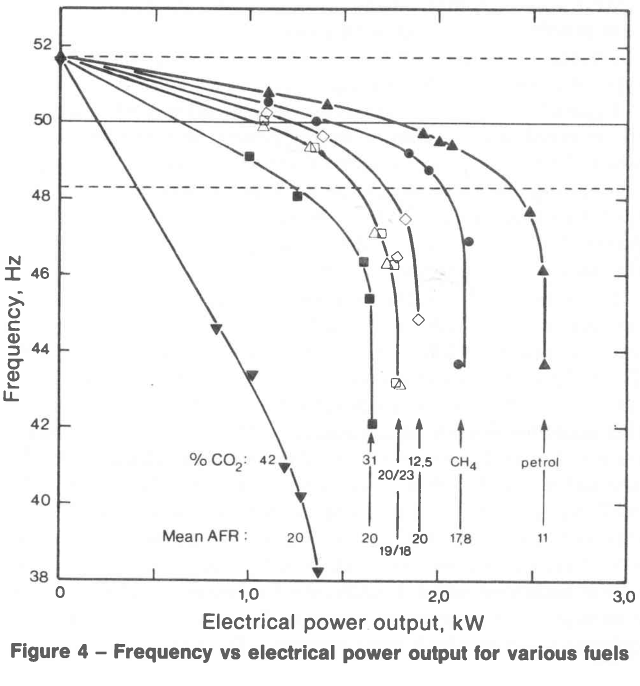

**Figure 4 – Frequency vs electrical power output for various fuels**

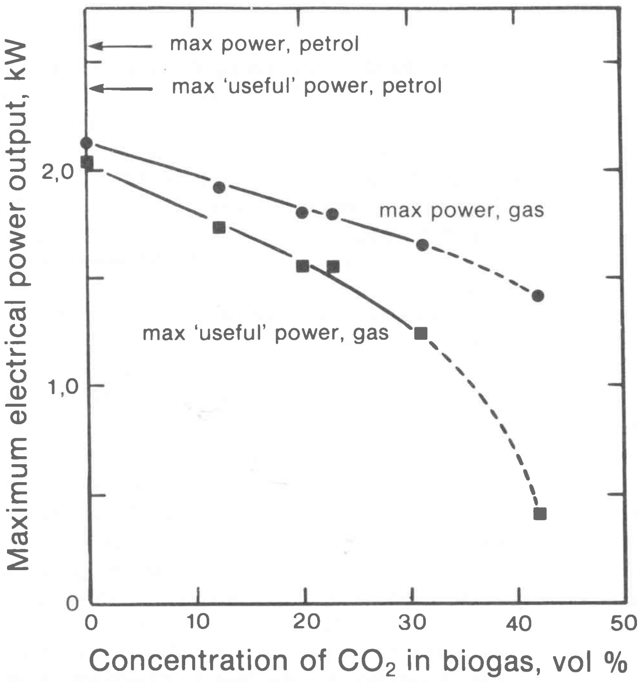

**Figure 5 – Maximum power and maximum 'useful' power vs $CO_2$ content of biogas**

Mean AFR's for these tests are indicated in the figure. For gas-fuelling these are the air/$CH_4$ mass ratios, and for petrol-fuelling the air/liquid feed mass ratios. The corresponding stoichiometric AFR's are 17,2 and approximately 15 respectively. Thus the mixtures tested were stoichiometric to lean with gas-fuelling and very rich with petrol-fuelling. At first sight, this would suggest that the results for petrol and biogas fuels are not comparable. However, the mixture strengths were adjusted (in emulation of the rural operator) to settings at which the engine sounded most satisfactory. The resulting rich mixture on petrol-fuelling appears to be unavoidable and associated with the design of the engine: the rudimentory inlet manifold and the heavy carbon deposits in the engine indicate that a considerable fraction of the petrol was deposited in the liquid phase onto the surfaces of the combustion chamber and incompletely burnt (a feature shared by many motor cycle engines). No such vaporization problems can occur with gaseous fuels. It is thus felt that the mixture strengths achieved in these tests are realistic for this type of engine and the envisaged usage.

Figure 5 shows, first, maximum power and secondly, a quantity referred to as maximum 'useful' power, both vs fuel composition. The latter power is defined arbitrarily as the output corresponding to a frequency of 48,3 Hz (2900 rev/min). The no-load values are 51,7 Hz (3100 rev/min). Maximum 'useful' power is thus a measure of the highest power which is available for the driving of frequency-sensitive equipment.

It will be noted that the maximum power output with petrol-fuelling is of the order of 2,5 kW (maximum 'useful' power is approximately 2,4 kW). The engine itself is rated at some 5 kW. The reduced final output is considered to arise as follows: First, tests were conducted at an elevation of 1 800 m above sea level; this accounts for an approximately 20% reduction in engine output. Secondly, the (mechanical to electrical) efficiency of the alternator may be taken to be of the order of 75%. Thirdly, the AFR varied with load at fixed mixture screw settings (this is inherent in the design of the carburettor), thus increased power would probably have been achieved by fine-tuning of the mixture at each load point. Finally, smaller losses of output may be attributed to the pressure drops in the special air intake and exhaust systems which were necessary for laboratory testing.

Next, Figure 5 shows the maximum power with $CH_4$-fuelling to be some 17% lower than that obtained with petrol. The reasons for this drop are as follows: While the calorific value per unit **mass** is higher for $CH_4$ than for petrol it is some 10% lower on a **volume** basis with both fuels taken as gases at the same temperature and pressure. Further, petrol is fed to the combustion chamber in only partially vaporized form; gaseous fuel, in occupying a larger volume, thus reduces the air-breathing capacity of the engine (irrespective of temperature effects). Finally, the engine ran hotter on $CH_4$ than on petrol fuelling (mean exhaust temperatures were 720 °C as opposed to 640 °C) thus reducing its volumetric efficiency.

Since $CO_2$ is inert, its presence in gaseous fuels displaces the combustible mixture and results in reduced power. Figure 5 shows this to be the case, with maximum power decreasing approximately linearly with $CO_2$ content of the biogas, up to a concentration of 31% $CO_2$, where the loss in maximum power is 35% (referred to petrol). (The data point for gas of 42% $CO_2$ is to be treated with caution.) Maximum useful power follows a similar pattern, but decreases more rapidly with $CO_2$ content.

Tests with systematic variation of AFR on $CH_4$-fuelling showed that maximum power occurs with slightly rich mixtures, rather than the stoichiometric to lean mixtures used in this study. Further the AFR's (at fixed mixture screw setting) varied somewhat with load (this is in the nature of the gas carburettor); thus it was difficult to pre-tune the engine to give a particular AFR at maximum load. For these reasons the two plots of maximum power vs $CO_2$ content in Figure 5 should be seen, not as unique relationships, but rather as guides giving the mean of expected bands of performance.

Figure 6 shows the alternator output voltage vs electrical power; the trends are similar to those of frequency vs power.

Figures 4, 5 and 6 together provide the overall information on the electrical output as a function of fuel type and composition.

### *Gas Consumption and Overall Efficiency*

Figure 7 shows the volumetric consumption of biogas vs electrical power output for various gas compositions (with the somewhat dubious result for gas of 42% $CO_2$ omitted). Since the tests refer to near-constant engine speed the approximately linear increase of fuel consumption with power is to be expected [13]. The scatter in the experimental points may be attributed to the variation in AFR during a run (discussed above) and to the slight variations in gas composition during those tests in which the constituent gases were dynamically fed and mixed.

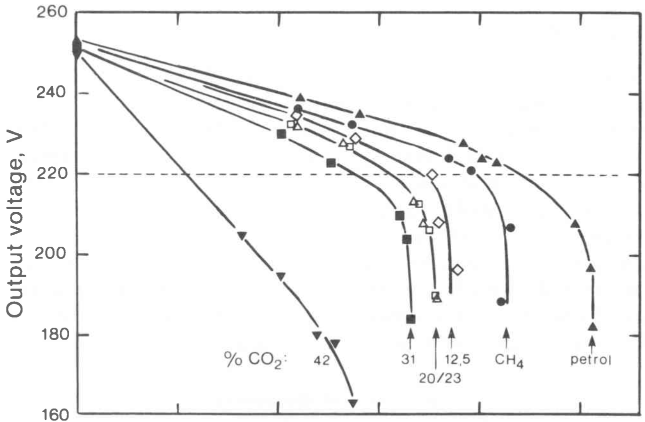

**Figure 6 – Voltage vs electrical power output for various fuels**

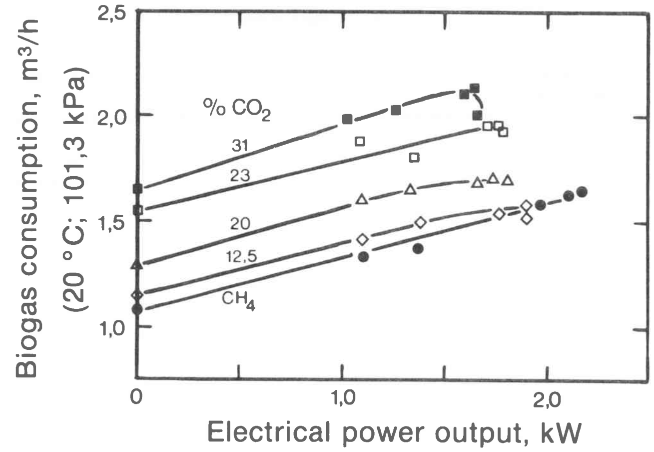

**Figure 7 – Biogas consumption vs electrical power output for various gas compositions**

The data in Figure 7 allow the operator to estimate the size of his biogas digester according to his needs, or alternatively, to estimate the electrical output obtainable from an existing digester. Thus, for example, the family-size digester shown in Figure 2 would permit the engine-alternator set of this study to be run at peak power (roughly 1,6 kW for gas of 30% $CO_2$) for one hour per day. While this might seem a very modest output it must be remembered that digester schemes cannot be viewed meaningfully in terms of energy only. Anaerobic digestion holds great benefits in terms of orderly waste management, public hygiene, soil fertility **and** energy production.

Figure 8 shows overall efficiency (electrical output divided by calorific input) vs electrical power. The considerably higher efficiencies with gas-fuelling are related to the stoichiometric to lean running with gas-fuelling as opposed to the wastefully rich mixture with petrol-fuelling.

*Improving the Performance of Gas-Fuelled Engines*

Here it should be noted that methane has an octane rating of approximately 120 and can be used at compression ratios (CR's) of up to 15. Thus for low CR engines it is to be expected that the loss in peak power resulting from fuelling with biogas, rather than petrol, may be offset – at least partially – by increasing the compression ratio. In the rural context this would be achieved by skimming of the cylinder head, an operation that is particularly simple and non-critical on a side-valve engine such as the one used in these tests.

These expectations were confirmed. Thus, in one series of tests using pure $CH_4$ fuel, an increase in CR from 6,2 to 7,8 resulted in an approximately 10% increase in maximum power. A further increase in CR to 10,1 required more extensive modifications to the cylinder head and, while apparently beneficial with gas-fuelling, led to severe knock even with premium grade petrol, thus destroying the gas/liquid fuel flexibility of the engine.

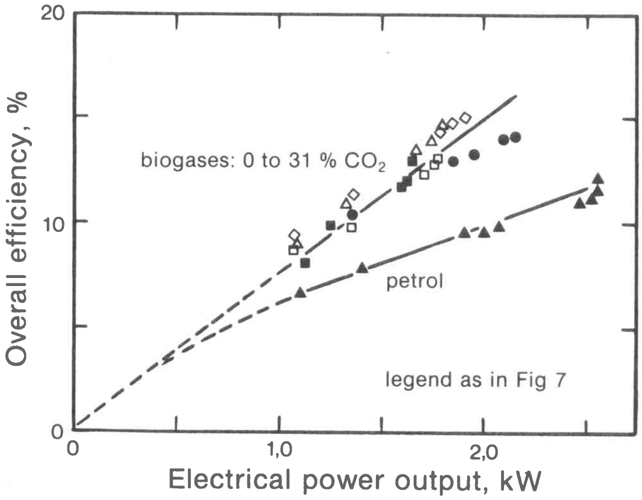

**Figure 8 – Overall efficiency (electrical output/calorific input) vs electrical power output for various fuels**

## Conclusions

These largely take the form of answers to the questions posed in the introductory section. They refer to the engine-alternator set investigated in this study and to units based on side-valve engines of similar size and design.

(1) The minimum modification that permits gas-fuelling of the engine, while leaving liquid fuel system unaltered, is the fitting of a venturi type gas feed adaptor (Figure 3). Such units are widely available, cheap and very simple to install.

(2) Starting and acceptable running of the engine are possible with biogases containing up to 30% $CO_2$. Since raw biogases frequently have higher $CO_2$ contents than this, some scrubbing facility will generally have to be provided. Alternatively, and preferably, the engine might be fuelled simultaneously with a pilot quantity of petrol (just sufficient to prevent rough running) and raw biogas as the main fuel.

(3) The peak electrical power output is some 17% lower with $CH_4$-fuelling than with petrol. Increasing the $CO_2$ content of the biogas leads to further power losses, with a 35% loss (compared with petrol) at 31% $CO_2$ (see Figure 5).

(4) Biogas consumption is approximately that shown in Figure 7. For example, for an electrical power output of 1,5 kW the consumption of gas of 30% $CO_2$ content is some 2,1 $m^3/h$; for pure methane the corresponding figure is approximately 1,5 $m^3/h$.

(5) The engine runs hotter on biogas than on petrol, but with reduced carbon deposits in the combustion chamber and with increased efficiency.

(6) The power output on biogas-fuelling may be increased by raising the compression ratio of the engine. Increasing the CR from 6,2 to 7,8 leads to some 10% increase in maximum power with methane fuelling. Further increases in CR may lead to knock with petrol fuelling.

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