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Cogeneration of Electricity and Heat from Biogas

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ABSTRACT

A 25 kW cogeneration unit was designed and operated for 2500 h on biogas produced from two anaerobic digesters using dairy manure as their feed. Performance studies detailed specifications for the spark system, thermodynamic performance of the unit, and other important operation parameters. Extended operation also provided insights on the effects of hydrogen sulfide within the biogas on the engine and potential procedures for controlling such problems as well as other long term operating considerations.

INTRODUCTION

Biogas production from animal manures via anaerobic digestion is becoming increasingly well defined. The ultimate value of the technology depends on the extent to which existing farm fuels can be replaced by biogas. The goal of this study was to document the characteristics of a full scale cogeneration facility for the production of electricity and heat.

The specific objectives of the studies related to cogeneration were as follows:

1. Document the critical operating parameters and performance of a cogeneration unit designed to produce electricity and hot water,
2. monitor the ability of an induction generator to transfer acceptable quality electricity to the utility, and
3. identify potential reliability problems of a cogeneration system resulting from extended operation on biogas.

BIOGAS UTILIZATION—LITERATURE REVIEW

Engine manufacturers have developed rather detailed specifications for use of methane based fuels such as sewage treatment plant gases, landfill gases, and natural gas in engines (Riback 1982; Onan, 1977; Caterpillar, 1972; Caterpillar, no date). Commercially produced biogas cogeneration systems have also been produced by Fiat Motor Company (Totem, 1978). The high octane rating of methane (120) is a good indication that it is a suitable fuel for high compression, spark ignition engines (Obert, 1973; Neyeloff and Gunkel, 1975; Stahl et al., 1982b). Biogas has also been considered for use in dual fueled compression ignition engines but problems have been reported (Pesson and Bartlett, 1980; Kofoed, 1981).

The production of electricity in parallel with the utility with common sychronous generators has the potential for high costs and several problems (Caterpillar, 1978; Patton and Iqbal, 1981). Induction generators offer the ability for a small power producer to operate reliably and safely on the utility grid (Chancellor, 1979; Barkle and Ferguson, 1954; Nailen, 1980). In addition to electrical production, an engine generator set can be used for producing hot water from the engine's waste heat (Caterpillar, 1972; Stahl et al., 1982a).

Efforts to predict engine life for operation on methane-based fuels have been reported (Fox et al., 1980 and Picken and Hassan, 1983). However, the interaction between hydrogen sulfide in biogas and engine wear appear to be a critical factor generally not considered by these studies. Waukesha (1981) recommends that "engines . . . with gaseous fuel containing over 0.1% hydrogen sulfide should use oil compounded to a total base number (TBN)* of 8 or higher, so that the oil can adequately counter the acids formed in the combustion of such fuels." Recommendations by Cummins Engine (1980) and Detroit Diesel (1983) suggested a minimum TBN rating of 2.0 and 1.0 respectively for used oil, while Waukesha suggested a minimum TBN level of 4 for used oil.

DESCRIPTION OF COGENERATOR

A 25 kW cogeneration unit was selected for this project. The engine is a 3.70 L, 10:1 compression ratio unit carries a continuous duty power rating for natural gas of 36 kW (48 hp) at 1800 rpm. The generator is a single phase, 240 V induction generator rated at 25 kW with a synchronous speed of 1800 rpm. The engine's heat recovery system consisted of a water-to-water heat exchanger and a heat recovery silencer for removal of thermal energy from the engine cooling and exhaust system respectively. Cummins Mohawk Diesel, Inc., assembler of the cogeneration unit, and White Engine, Inc., the engine manufacturer, provided key assistance throughout this research project.

A system of controls was included with the cogenerator to allow unattended operation of the unit. Controls have been provided to protect the engine against (a) engine overspeed; (b) low engine coolant level; (c) high engine coolant temperature; (d) low oil pressure and level; (e) low gas supply pressure; and (f) inadequate fuel supply. Controls were also designed to protect the generator against (a) reverse flow of current and (b) excessive current flow (greater than 150 A).

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*Total Base Number of an oil is an indicator of the degree of alkalinity, or amount of acid the oil can neutralize. Larger numbers indicate a greater ability of the oil to neutralize acid.

In addition to the cogenerator, a system to interface the cogenerator to two anaerobic digesters and the dairy's hot water and electrical system was also installed. A water circulation system removed heat from the engine coolant and exhaust and distributed the heat to the digesters, dairy water heater, and two mechanisms to reject the excess heat. The interface to the dairy's electrical grid included a lockable manual disconnect switch accessible to utility personnel and an additional 150 A fuse and disconnect at the point of connection. A 15 kVA capacitor bank was also added for correcting power factor. The biogas passed through a particulate filter and condensation trap prior to its delivery to the engine at about 25 cm of water pressure. A Winslow gas conditioner was utilized for the last 1280 h of operation with an advertised purpose to "neutralize the dissolved sulfur compounds (mercaptans) in digester gas streams and reduce corrosion" (Bacher, no date). A more detailed description of the unit and its interface is available from Jewell et al., 1985.

TEST PROCEDURES

The initial set of tests were designed to define the performance of the unit. Those tests were (a) to define critical spark system and fuel-air mixture parameters for providing smooth operation; (b) to describe the characteristics of the induction generator; and (c) to determine the thermodynamic performance of the cogenerator. Much of this information was collected from a series of one-hour tests over which data on fuel and air utilization, heat recovery and electrical production, and other generator performance factors were collected.

The testing program also involved two distinct long term operating periods on raw biogas (1220 h) and biogas passed through the Winslow filter (1280 h). Electrical production, gas consumption, maintenance requirements, and oil condition (including standard wear metals, TBN, oil viscosity, and miscellaneous contaminants) were monitored through these periods. At the end of each test period, the engine was disassembled and the internal components checked with the assistance of representatives from White Engine and Cummins Mohawk. During these periods, the engine was run 8 to 16 hours per day, seven days per week with engine coolants temperatures maintained between 80°C (175°F) and 90°C(195°F).

RESULTS AND DISCUSSION OF COGENERATION PERFORMANCE STUDIES

The following discussion is a summary of the experiences gained from working with a cogenerator over a 2,500 h operating period. Over this period the cogenerator produced in excess of 40,000 kWh of electricity and about 290 million kJ (275 million Btu) of heat energy as hot water, of which about 67 million kJ (64 million Btu) were delivered to the dairy to replace water heating needs.

Spark System Studies

One initial testing was designed to check spark plug gap, plug heat range, and spark timing for their effect upon engine operation. Timing of the spark proved to be a critical parameter for maintaining smooth engine operation while the other factors had minimal influence over the range checked. At rated load and lean operation, a spark timing of less than 20 degrees before top dead center (BTDC) resulted in very rough operation and regular misfiring. Advancing the timing to 33 deg BTDC provided reasonably smooth operation and was the minimum level at which peak power was achieved. The smoothest operation was observed for a spark setting from 40 to 50 deg BTDC. However, power output began to slowly diminish for a spark timing of 45 deg BTDC or greater.

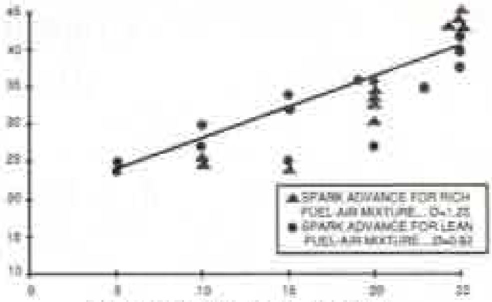

Fig. 1—Influence of load and fuel-air mixture on minimum spark advance at which maximum power is achieved for various throttle settings. (Fuel: Biogas . . . Speed: 1800 rpm).

Minimum spark timing advance for maximum power varied from about 25 deg BTDC at 5 kW to about 40 deg BTDC at rated load for both the rich and lean fuel-air mixtures (Fig. 1). An additional advance of the spark by about 5 deg provided the smoothest operation without a loss in power for all conditions checked. These settings for spark timing are far more advanced than generally expected for other gaseous fuels such as LP-gas and natural gas. Apparently the dilution effect of the carbon dioxide in the biogas slows the flame speed in the cylinder and additional time is needed for combustion of the fuel.

Induction Generator Studies

Our next series of tests was designed to define some of the characteristics of the induction generator. The induction generator's power output varied from no load occurring at the synchronous speed of 1800 rpm to rated load of 25 kW at 1837 rpm. The generator's power factor without capacitance correction peaked at 66% lagging (Fig. 2). With the addition of a 15 kVA capacitance bank, power factor was raised to 84% at rated load.

The single greatest strength of this package was the induction generator. The simplicity of connecting it to

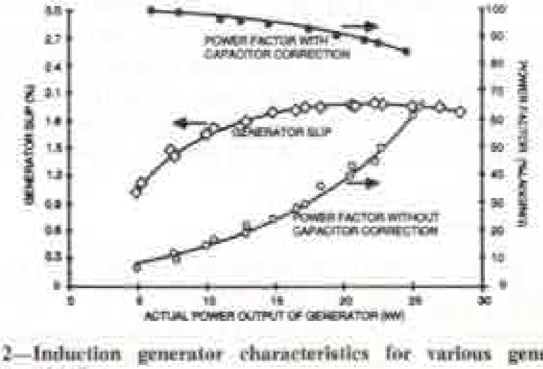

Fig. 2—Induction generator characteristics for various generator electrical loads.

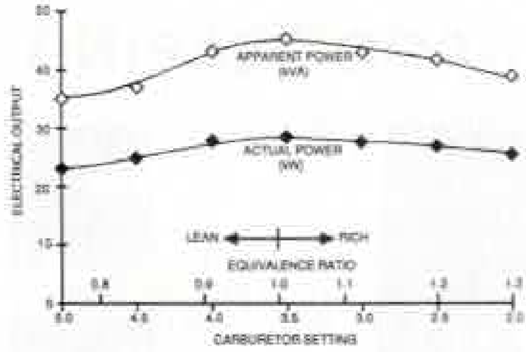

Fig. 3—Maximum electric output of cogenerator at various fuel to air mixtures.

the utility electrical service plus the lack of problems of operating in parallel with the utility made this feature a very trouble free part of the system. Protection of our unit from reverse current flow proved valuable on several occasions.

Thermodynamic Studies

The thermodynamic performance was first checked at full load and at varying fuel-air mixture levels. For the test conditions monitored, maximum power output of 28.5 kW for the cogenerator was observed at a slightly rich fuel-air mixture (Fig. 3). Electrical efficiency (electrical energy output/lower heating value of biogas) peaked at 26% between an equivalence ratio (ϕ)† of 0.8 and 0.9 for the range tested (Fig. 4). The thermal efficiency of the heat recovery system peaked between 42 and 45% for fuel-air mixtures leaner than $\phi = 1.9$. Lean operation shows definite advantages in terms of the efficiency of energy recovery but at some sacrifice of power.

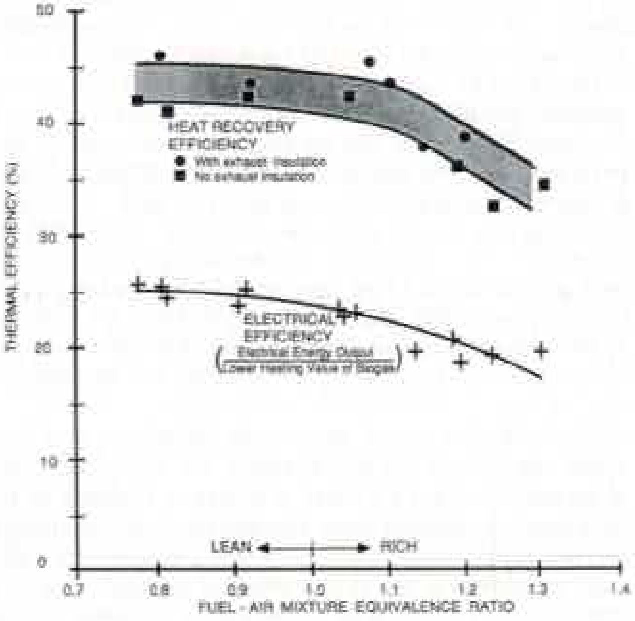

Fig. 4—Thermal efficiency of cogenerator at rated power vs. fuel-air mixture.

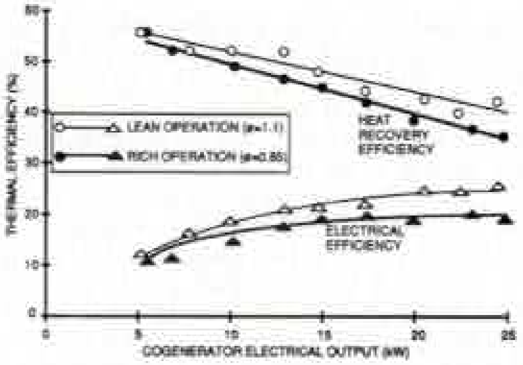

Fig. 5—Cogenerator efficiency at various electrical loads.

Thermodynamic performance was next checked over a range of loads from 5 to 25 kW for three carburetor settings (ϕ equal to 0.85 and 1.1 is illustrated in Fig. 5). Electrical efficiency is consistently higher at the leaner fuel-air setting and during operation near rated load. Heat recovery efficiency peaks at lean fuel-air mixtures (similar to electrical efficiency) and at low load levels (dissimilar to electrical efficiency). The total thermal efficiency of the cogenerator remains fairly constant with load and favors the leaner fuel-air-mixtures.

An evaluation of the thermodynamic performance of the cogenerator revealed few surprises. Electrical efficiency and peak power curves are characteristic of most other gaseous fueled engines (Obert, 1973). However, the consequences of selecting operating conditions based upon thermodynamic efficiency may be the more dramatic consideration. These observations reveal that lean carburetor settings and loads approaching the cogenerator's maximum will be desirable operating conditions, if electricity has a higher value than hot water. Operation at $\phi = 1.1$ rather than $\phi = 0.85$ would result in 24% less electricity per unit of biogas being produced (Fig. 6). In a similar light, operation at loads less than about 60% of maximum power may cause some relatively large reductions in electrical production. Our unit will produce 28% less electricity per unit of gas during operation at 10 kW as opposed to 25 kW ($\phi = 0.85$).

Several important steps should be taken to promote efficient conversion of biogas to electricity. First, the unit must be sized to allow operation at 60% of maximum power or more. Anticipated hourly biogas production (liters of biogas/hour) divided by a factor of 700 (L of biogas/kW-h or 25 cubic ft/kW-h(should provide a

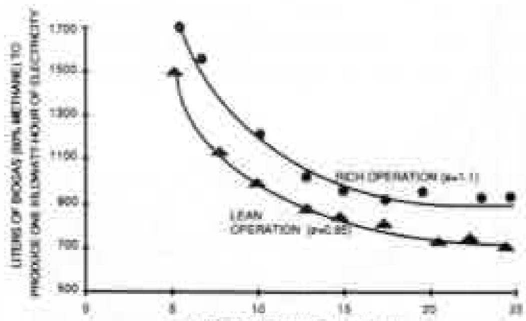

Fig. 6—Comparison of gas consumption per unit of electricity produced at various loads and fuel-air mixtures for a 25 kW cogenerator.

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†Equivalence Ratio (ϕ)-Actual fuel to air ratio divided by stoichiometric fuel to air ratio; $\phi<1.0$ represents lean mixtures and $\phi>1.0$ represents rich mixtures.

starting point for sizing a co-generator (kW). Next, during installation it would be desirable for the installer to check the fuel-air mixture provided by the carburetor. One possible method would involve first locating the carburetor setting at which maximum power is attained. Then a leaning of the fuel-air mixture that results in a 10% reduction in maximum power should provide an efficient setting for the carburetor. Finally, it will be critical for the farmer to keep daily records of the volume of gas consumed by the engine per kilowatt-hour of electricity produced. Gas consumption of the cogenerator greater than 850 L per kWh (30 cu ft^3 per kWh) may be an indication of the need for maintenance, low average loads, or other developing problems.

Wear Related Observations

From the outset of this project, an attempt was made to gain some understanding of potential wear and maintenance problems that might be associated with combustion of biogas in an internal combustion engine. Although not entirely expected at the beginning of this project, the hydrogen sulfide in the fuel proved quite troublesome. Much of our attention eventually focused on the effects of these contaminants on the lubrication oil and wear within the engine. During the 2500 h of operation of the cogenerator, the time was split between operation on raw biogas and biogas scrubbed by a Winslow biomass filter.

During the initial tests with raw biogas, oils with a Total Base Number (TBN) of 6, 8.79, and 10 were tried for periods of 128, 282 and 808 h of engine operation respectively. Oil change intervals of 150 h or less were used at all times except during one 250 h test period. Our biogas maintained a hydrogen sulfide content averaging between 3000 and 4000 ppm.

The higher TBN oil provided only minor relief on the rapid deterioration of oil TBN level. A high TBN oil when used in the engine for a 250-h interval dropped from its initial rating of 10 to the minimum acceptable level of 2 within 55 h of operation (Fig. 7). Additional operating time on the oil resulted in undesirably low oil TBN levels. High TBN oils alone were not capable of countering the buildup of acid in our engine crankcase.

After 1,220 h of operation the engine was partially disassembled for inspection. The most important observations were noted on the rod bearing surfaces (Fig. 8). Bearing inserts on 1, 2 and 4 were fairly evenly pitted and bearing 3 showed excessive damage to the surface in the form of flaking away of the surface material. The rapid acidity buildup in the lubrication oil during operation on unscrubbed biogas appears to be the most likely cause of the pitting of rod bearing surfaces (Cummins, 1979).

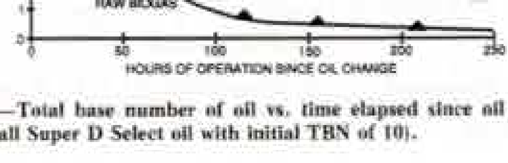

Fig. 7—Total base number of oil vs. time elapsed since oil change (Kendall Super D Select oil with initial TBN of 10).

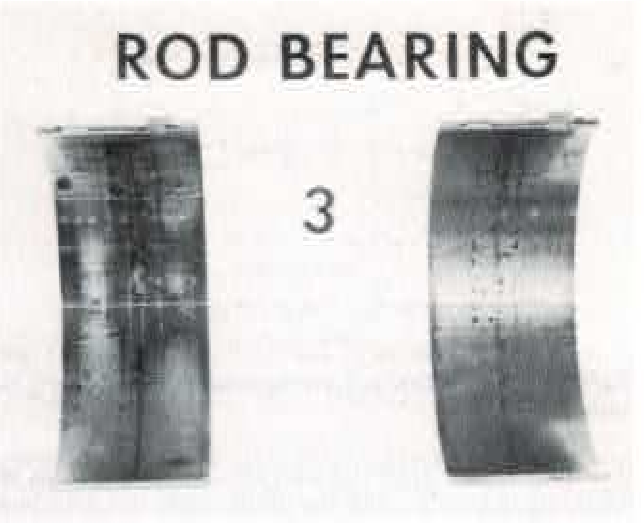

Fig. 8—The hydrogen sulfide in the biogas can accelerate degradation of some engine components such as these rod bearing inserts.

Prior to additional engine operation, a Winslow gas conditioner was installed and all engine components displaying excessive wear were replaced. Oil analysis for the period following this modification indicated that the oil TBN level remained higher for much longer periods of time (Fig. 7) supporting the value of the Winslow filter. An oil change interval of 250 hours was used for operation on gas treated with the Winslow filter which corresponded to a final TBN level of approximately 2.

At the 2504 h mark (1280 h of operation on scrubbed biogas) a major failure occurred in the form of a rod failure. The primary failure occured at the No. 2 wrist pin bushing. This resulted in a failure of a connecting rod bolt and a connecting rod. The remaining wrist pin bushings exhibited a loss of copper liner material and extreme clearances between the pin and bushing as a result of the wear. This problem was attributed to the affects of corrosive action of acid contaminants accumulating in the oil.

In addition, all rod bearing inserts exhibited a considerable number of pinhead-sized pits on the insert surfaces. Two of the inserts also exhibited areas where patches of bearing surface material of approximately 2 to 5 mm in diameter had flaked off. The main bearings, which appeared in good condition at the 1,220 h teardown, now exhibited numerous signs of surface pitting. The rod bearing inserts and main bearings had been in place 1,280 and 2500 h, respectively. An analysis of the Winslow gas conditioning filter indicated the filter was capable of performing its function throughout the test period.

At the beginning of these tests, an assumption was made that might share the blame for the rapid wear observed. An oil TBN level of 2 was considered to be minimum acceptable limit for determining oil change interval (assuming TBN was the limiting factor). Although this was not closely adhered to during the first test period on raw biogas, it was closely followed during the final 1280 h of operation. A higher cutoff point, such as TBN equal to 4 as suggested by Waukesha, would have required an oil change interval of 75 h or less rather than 250 h during operation on filtered biogas.

From our experiences with biogas containing a relatively high level of hydrogen sulfide, three conclusions can be drawn. They are: (a) high TBN oils alone cannot be expected to counter the effects of acid accumulation in the oil; (b) the Winslow filter in combination with high TBN oils and medium length oil change intervals (250 h) cannot counter the effects of acid accumulation in the oil; and (c) the effects of acid accumulation in the oil creates the greatest problems with but is not limited to components containing copper.

Other Observations

This study clearly illustrated the need of the cogenerator to include a well designed protection system to allow unattended operation. The final control package for protecting the engine against a failure proved adequate, with one exception. It would be desirable to have a sensor that would shut the engine down when excessive vibration is noted. The period prior to our engine failure was characterized by a 2.5 h period of moderate engine vibration and a 1.5 h period of excessive vibration. If the engine had been shut down during this period, serious damage would have been avoided.

Our experience would indicate that it is highly desirable to protect the engine from operation under the following potential situations: (a) excessive engine coolant temperature; (b) low coolant level; (c) low oil pressure; (d) low oil level; (e) overspeed; (f) excessive vibration; and (g) low gas pressure. The generator and electrical system must be protected from: (a) over current, (b) reserve current flow. The electrical utility may require additional desirable features for the electrical protection system such as over and under voltage, and frequency limitations, and ground fault protection. The protection package for the cogenerator is not the place for cutting corners or reducing costs.

The heat recovery and utilization system went through a number of modifications before working entirely satisfactorily. Our experiences with this system illustrated the importance of several general requirements. First, it is essential to provide an adequate means of wasting heat from the system at the same rate at which heat is recovered from the engine (coolant and exhaust) to avoid overheating of the engine. Second, the heat recovery and distribution (heating loop) must be capable of maintaining a minimum return water temperature to the engine coolant heat exchanger after the initial start-up of the engine to avoid prolonged operation of the engine at reduced coolant temperature. Third, the digester heating system should be capable of transferring heat to the manure at a rate equal to the maximum potential rate of heat produced by the cogenerator and should be given highest priority for heat utilization. Details of our procedures for meeting these requirements are described fully by Jewell et al., 1985.

One final observation should be made relative to the location of the cogeneration system. Our unit was located in the immediate proximity of two digesters and several manure storage facilities. This environment was responsible for any copper piping, copper electrical contacts, or other copper materials quickly becoming tarnished with a dark residue. It may be wise to consider moving the cogenerator away from the digester and other manure storage facilities and providing good ventilation for any structures housing such equipment. Consideration should also be given to packaging of motors, generators, controls, and electrical contacts in gas tight containers to prevent the potential harmful affects of sulfur based gases.

CONCLUSIONS AND FUTURE RESEARCH NEEDS

As a result of our operating experiences with a biogas fueled cogeneration unit, several important conclusions deserve highlighting.

1. Spark advance selection is a critical parameter for maintaining smooth engine operation. The required level of advance is greater than more conventional fueled engines (25 to 40° BTDC for attaining maximum power).
2. Operation at peak electrical efficiency requires consideration of fuel to air mixture ($\phi = 0.8$ to 0.9 preferred) and generator load (greater than 60% preferred).
3. Simplicity of the interconnection to and parallel operation with the utility electrical grid was observed with an induction generator.
4. Accelerated wear of internal engine components is a potential problem for extended operation on biogas. At hydrogen sulfide levels of 3000 to 4000 ppm, accelerated wear of bearings and wrist pins was severe.
5. Efforts to control this wear by use of high TBN oils and a mercaptan gas scrubber were not adequate.

Before biogas fueled generation systems become a viable energy alternative, two key ares of concern must be addressed. Can cogeneration packages be designed to allow cost efficient operation for extended operation? The design must consider the critical importance of efficient conversion of biogas to electricity. Accelerated wear problems due to sulfur compounds in biogas must be addressed. Finally, reasonably priced control packages that allow unattended cogenerator operation and regular operation checks of control accuracy and ability to operate deserve greater design consideration.

Secondly, operator management practices for maintaining a cogeneration unit must be more thoroughly defined. The operator must be capable of monitoring electrical efficiency of the unit and identifying possible causes of a declining efficiency. Parameters for accurately predicting acid build up in the oil and oil change intervals remain to be identified that fit within the time and skill constraints of farmers. Finally, more experience with additional sites, animal species, and management practices is needed to develop recommendations for regular maintenance and overhaul schedules for biogas fueled engines must be developed.

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