Operation and Performance of Biogas-Fueled Cogeneration Systems

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ABSTRACT

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This paper presents some of the technical and logistical problems associated with two cogeneration systems tested in an energy-integrated farm system. Two spark ignition industrial engines coupled to induction generators were used to produce electricity. Heat was also recovered from the engine coolant and from the engine exhaust. The heat recovered was used for heating an anaerobic digestion system and for domestic space and water heating. Annual electricity production for 1983 and 1984 was 61 129 and 110 480 kWh, respectively. There where two major engine problems encountered with the first cogeneration system. The first problem was the failure of wrist pins caused by oil acidity. The second problem was the build-up of carbon residue around the pistons and valves. The first problem was corrected with the use of a high TBN oil and better oil management. The build-up of carbon residue continued to be a problem with the first engine despite several engine modification. However, this was not a problem with the second engine tested. From an economic assessment it was determined that the economics of farm scale cogeneration was marginal. Depending on the system reliability, payback period for the systems studied was from 9.7 to 21.6 years.

INTRODUCTION

Interest in cogeneration within the agricultural sector has been stimulated by the promising research and development efforts on farm-scale anaerobic digestion systems. Studied by Kah (1978), Jewell et al. (1978, 1985) and Walker et al. (1984) concluded that biogas produced by farm-scale anaerobic digestion systems should be converted to electricity to obtain the highest thermodynamic and economic value. The use of the biogas for electricity production is even more attractive if the rejected heat is recovered from the engine coolant and the exhaust gases, and is used to heat the anaerobic digestion system, provide for domestic space heating, and provide hot water for the farmstead.

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TABLE 1

Farm domestic and total annual electricity usage (kWh) for 1981, 82, 83 and 84

	1981	1982	1983	1984
Farm usage	—	75 710	82 325	89 620
Domestic usage	—	29 830	32 410	22 532
Total usage	91 320	105 540	114 909	112 152
Farm usage on a per cow basis	—	549	457	498

For the last 5 years, the authors have been involved in assessing the performance of on-farm biogas fueled cogeneration systems. This paper presents results from Cornell University's Energy Integrated Dairy System Project (Walker et al., 1984). It explores some of the technical and logistical problems encountered with the two cogeneration systems tested during the project, and presents performance data obtained.

SITE AND SYSTEM DESCRIPTION

The project was conducted on a private dairy farm (approximately 27 km west of the University[1]). At the beginning of the project, fall 1980, the farm had 200 head of cattle which included 120 milking cows. In the fall of 1982, the farm was expanded to approximately 300 head of cattle with 180 lactating cows. The cows were housed in a free-stall barn with cow mats and limited sawdust bedding. The milking cows were grouped into high, medium, and low-production groups. The young stock and dry cows were housed in a separate barn. The animals were fed a total mixed ration.

Annual farm, domestic and total electricity usage for 1981–1984 is presented in Table 1. The farm's electrical rate is based on peak and off-peak use. The peak rate time is from 7:00 to 23:30 (16.5 h/day) and the off-peak is from 23:30 to 7:00 (7.5 h/day). Distribution of electricity used on the farm for 1983 and 84 is presented in Table 2. A more comprehensive site description can be found in Walker et al. (1984).

Anaerobic digester

The anaerobic digester system constructed for this project was based on the plug flow concept. The digester dimensions were 22.6 m×6.1 m×1.8 m (74 ft×20 ft×8 ft). The working volume, based on a manure depth of 1.8 m, was

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[1] The project was conducted on the Millbrook farm, a privately own dairy farm. The owner of the farm are Ronald Space Sr. and Ronald Space Jr. This project was funding by U.S. Department of Energy, New York State Energy Authority, New York State Electric and Gas, and AGWAY.

TABLE 2

Breakdown of electricity usage for 1983 and 1984

Task	1983		1984	
	(kWh/year)	(% of Total)	(kWh/year)	(% of Total)
Milking center				
Refrigeration	13 223	11.5	15 047	13.4
Vacuum pump	13 036	11.3	13 791	12.3
Water heating	12 316	10.7	10 800	9.6
Space hating	4 499	3.9	5 085	4.5
Feeding center				
Harvestor silo	123	0.1	174	0.2
Silos	5 347	4.7	6 084	0.54
Farmstead				
Water pumps	15 474	13.5	9 107	8.1
Pressure pump	1 785	1.6	2 807	2.5
Heifer barn	8 155	7.1	7 668	6.8
Miscellaneous	8 543	7.4	19 057	17.0
Farm	82 325	71.8	89 620	80.0
Domestic				
Space heating	640	0.6	730	0.7
Water heating	5 157	4.5	2 918	2.6
Appliances and lighting	26 612	23.1	18 884	16.8

254.1 m^3. The system was designed for gravity feed and discharge. Biogas production ranging from 140 to 470 m^3/day was observed. A complete discussion of the design and performance of the digester can be found in Walker et al. (1985).

Cogeneration systems

The first cogeneration system installed at the site was powered by a six-cylinder, 5.4-L spark-ignition industrial engine with a compression rate of 8:1 operated at a speed of 1200 RPM. The engine was equipped with two carburetors — one for biogas (55% methane and 44% carbon dioxide) and one for propane. A gas pressure booster was used to increase the pressure of the biogas leaving the digester from 5 cm of water pressure to 40.4 cm of water pressure (see Fig. 1). In addition to boosting the biogas pressure, the gas was passed through a commercially available chemical filter to neutralize the dissolved sulfur compounds (see Fig. 1).

The power level of the cogeneration system was controlled by a patended device called a 'tracker-trol'. This control mechanism is basically a diaphragm that responds to changes in the blower pressure. This diaphragm was con-

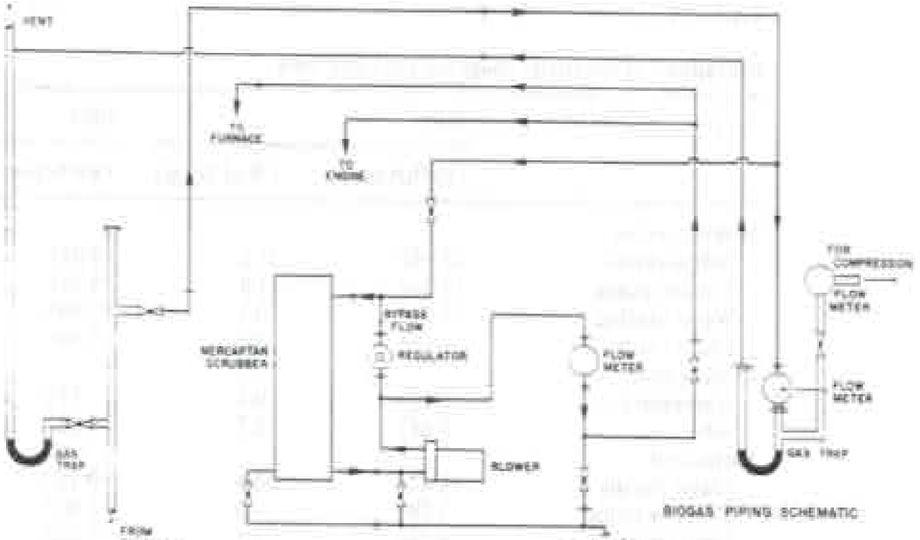

Fig. 1. Schematic of the gas handling system.

nected to the engine throttle linkage. An increase or decrease in the blower pressure, caused by changes in the digester pressure, resulted in an increase or decrease in the throttle setting. This control mechanism allowed electric power production to track biogas production. In addition, the cogeneration system could be operated manually at a preset power level.

The engine was coupled to a 30-kW induction generator. The synchronous speed of the generator was 1220 RPM. An induction generator was selected over a synchronous generator because the later type requires very expensive and sophisticated controls for parallel operation with the utility grid. Parallel operation was needed in order to prevent problems associated with either the digester or cogeneration system from interrupting farm operations. Because an induction generator receives its excitation signal from the power grid, it generates clean reliable power without the sophisticated controls needed for a synchronous generator (Segaser, 1978). Tabulated in Table 3 are the specifications for the generator.

The engine was equipped with heat exchangers to recover heat from the engine cooling system and the exhaust. The heat recovery system was designed to extract 50% of the fuel energy supplied in the form of heat. Presented in Fig. 2 is a schematic of the heat recovery and allocation system. Engine coolant flowed through the engine. From the engine the coolant flowed through the exhaust heat exchanger in a concurrent direction with the exhaust gases. The temperature of the coolant after leaving the exhaust heat exchanger varied from 88 to 96°C. After leaving the exhaust heat exchanger, the coolant was circulated through another heat exchanger, which was operated countercur-

TABLE 3

Induction generator specifications

Phase	1
Synchronous speed	1220 RPM
Voltage	240 V
Frequency	60 Hz
Nomal power factor	91%
Excitation power	
no load	8 kVa
full load	14 kVa

rent to the fluid for the digester heating loop. After leaving this heat exchanger, the engine coolant flows either to the farm residence or the radiator for additional cooling. This allocation of heat was regulated with a series of thermostatitically controlled directional valve.

To allocate heat to the house, a pipeline consisting of 305 m (1000 ft) of black iron pipe was run from the utility building to the house and back. Part of the pipeline was buried underground and insulated with 5 cm of polyurethane insulation which was sealed against water. The above ground portion of the pipeline was insulated with 6.4 cm of polyurethane insulation with an all-service jacked to hold and seal the insulation in place. At the house the pipeline

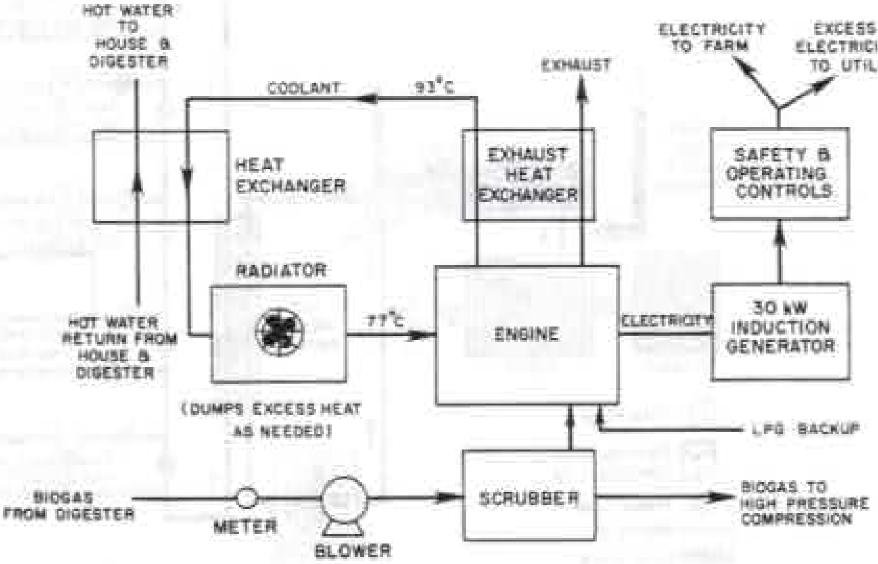

Fig. 2. Heat recovery system for first cogeneration system.

TABLE 4

35-kW induction generator specifications

Phase	1
Synchronous speed	1800 RPM
Voltage	240 V
Frequency	60 Hz
Nominal power factor	92%
Excitation power	
no load	2 kVa
full load	14 kVa

was connected to two heat exchangers — one for the hot water heater and another one for the house space heating boiler.

Because of some major problems encountered with the first engine, which will be addressed later in this paper, a new engine was incorporated into the cogeneration system during the last six months of the project. This unit was a six-cylinder, 4.9-L spark-ignition engine, with a compression ratio of 8:1 and was operated at a speed of 1800 RPM. Like the first engine, this one was equipped with two carburetors. The gas handling system was the same as used with the first engine. In addition to replacing the engine, the induction generator was

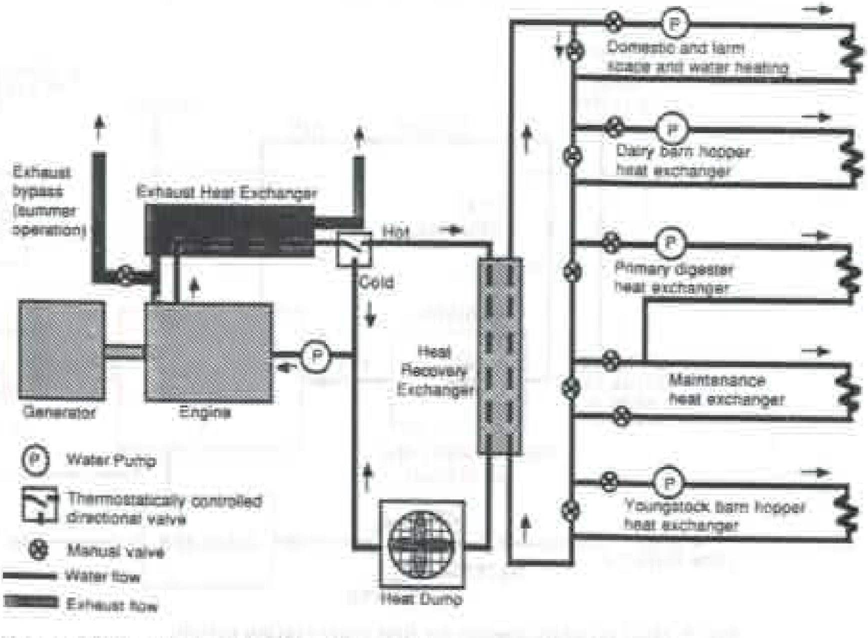

Fig. 3. Schematic of modified heating and transport system for modified cogeneration system.

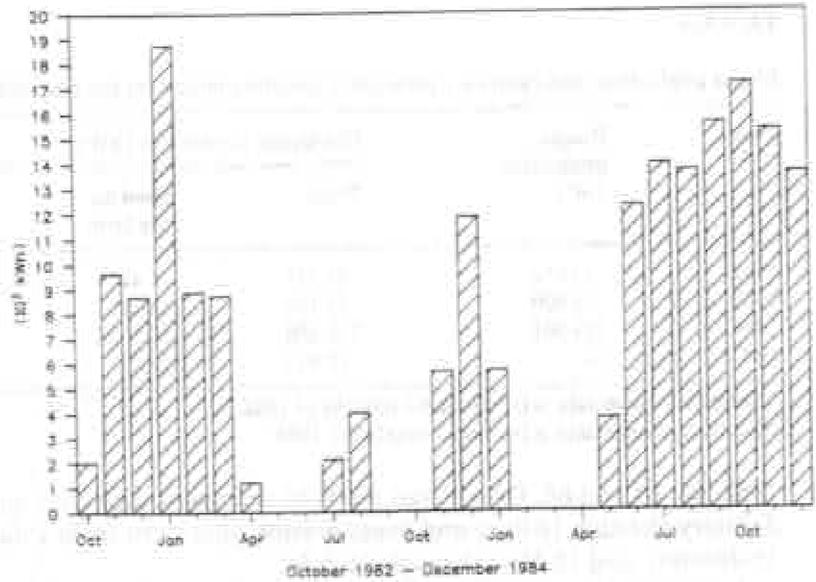

Fig. 4. Electricity production for October 1982 through December 1984.

replaced with one that operated at 1800 RPM. Tabulated in Table 4 are the specifications for the new generator.

In addition to changing the engine and generator, the heat recovery system was altered. The modified heating system involved isolating the engine cooling system from the home heating network, as well as the digester heating network. Presented in Fig. 3 is a schematic of the modified heating system.

SYSTEM PERFORMANCE AND OPERATIONAL EXPERIENCES

Monthly electricity production data for the period October 1982 through 1984 are presented in Fig. 4. The first cogeneration system was operated from 4 October 1982 through 16 January 1985. The second cogeneration unit was started in May 1985 and was still in operation at the time of preparation of this paper. Unfortunately, the new engine was installed during the last six months of the project; therefore, operational experience and performance data for this system was limited.

The first cogeneration system was operated for 50 days on LP gas, from 22 December 1982 to 10 February 1983. During this period of operation on LP gas 28 940 kWh of electricity was produced. Electricity production for the last 3 months of 1982 totaled 20 377 kWh. Annual electricity production for 1983 and 1984 was 61 129 and 110 480 kWh respectively. The total electricity production for the first 7 months of 1985 totaled 38671. Tabulated in Table 5 are annual biogas production data, and electricity production and distribution data for

TABLE 5

Biogas production, and electricity production and distribution for the year 1982, 83, 84 and 85

Year	Biogas production (m^3)	Electricity production (kWh)		
		Total	Used on the farm	Sold to the utility
1982[a]	34 618	20 377	14 427	5 950
1983	54 900	61 129	44 723	16 406
1984	133 961	110 480	65 773	44 717
1985[b]	—	38 671	28 671	9 720

[a] Electricity usage data is for the last 3 months of 1982.

[b] Electricity usage data is for first 7 months of 1985

1982, 83, 84 and 85. Data listed for 1985 represent digestion operation from 1 January through 16 July and cogeneration operation from 1 January through 16 January and 15 May through 31 July.

A review of the data in Table 5 and the plot of the monthly electricity production (Fig. 4) would suggest that the potential exists to dramatically increase the level of electricity production. This conclusion is based on fact that 92% of the 110480 kWh produced during 1984 was generated during the last 7 months of the year. If this level of production could have been maintained year-round, electricity production for 1984 would have been approximately 174200 kWh per year. Another indication of the potential of cogeneration is the electricity production obtained during the 50 days of operation on LP gas. During this period the cogeneration system was operated at close to peak performance. If this level of performance could have been achieved with biogas, annual electricity production of 210000 kWh could have been realized.

There were several problems encountered during the course of the project that limited its success. Given the strong energy coupling between the digester and the cogeneration system, it was not surprising that a problem with one system would impact on the performance of the other. For example, monthly gas production for first four months of 1984 was considerably lower than levels recorded during the last seven months of 1984 (see Fig. 5). Part of the reduction in gas production during this period can be attributed to the fact that the cogeneration system was down for repairs for approximately 3½ months (see Fig. 4), thus a large heat source was lost that could not be replaced by the back-up heating system (Walker et al., 1985). The lower biogas production cannot be solely attributed to the lost of the cogenerated heat. Higher ammonia concentrations and other factors played a role in limiting biogas production. Many of these factors are addressed by Walker et al. (1985). It must be emphasized that the technical and economic performance of biogas fueled cogeneration systems depends on the reliable and efficient operation of both systems.

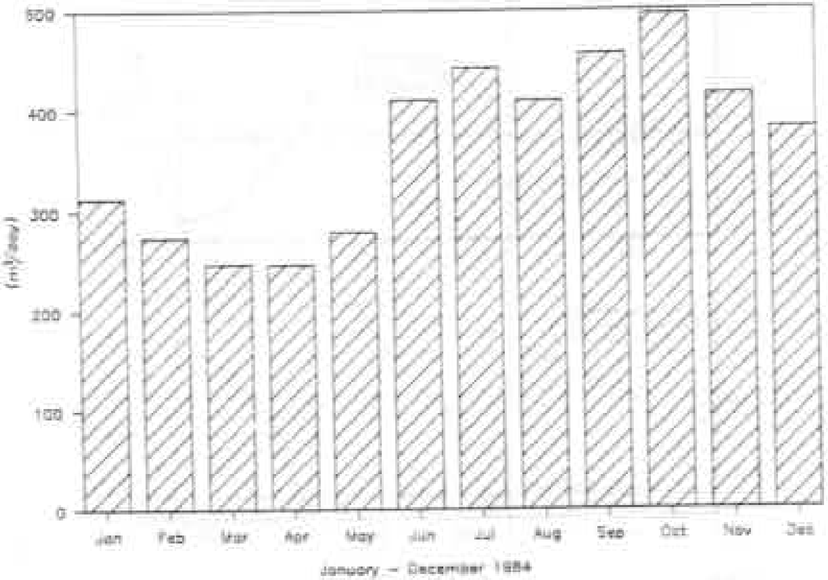

Fig. 5. Monthly biogas production for 1984.

Engine problems

There where two major engine problems encountered with the first cogeneration system. The first problem was the failure of wrist pins and the corrosion of the main and rod bearings. The failure of the wrist pins occurred after 1370 h. This failure was caused by oil acidity which attacked the copper and alloys used in the wrist-pins and bearings. The oil acidity problem was caused by hydrogen-sulfide (which was present in the gas at a level of 1200–2400 ppm) entering the oil and forming sulfuric acid. In addition to the oil acidity problem, a carbon residue was deposited around the pistons and valves.

One indicator of the acidity of the oil was TBN (Total Base Number). TBN is a measure of the buffering capacity of oil. With use, the TBN of the oil decreases. Figure 6 shows how the TBN of the engine oil from one of the earlier series of tests decreased with time. Within 50 h of operation the TBN of the oil had dropped to the minimum acceptable TBN level. Once the TBN dropped to the minimum acceptable level the wear metals concentration of the oil increased as shown in Figs. 6. Wear due to oil acidity showed up as increased levels of copper in the oil. Increased lead wear was due to extreme clearances between the wrist pins and bushings which resulted in damage to the pistons and piston sleeves. The first major overhaul of the engine was due to failure of the wrist pins after 1370 h of operation.

The oil acidity problem was controlled by using a high TBN oil. Figure 7 shows the TBN for a later series of oil tests. When the oil change interval was

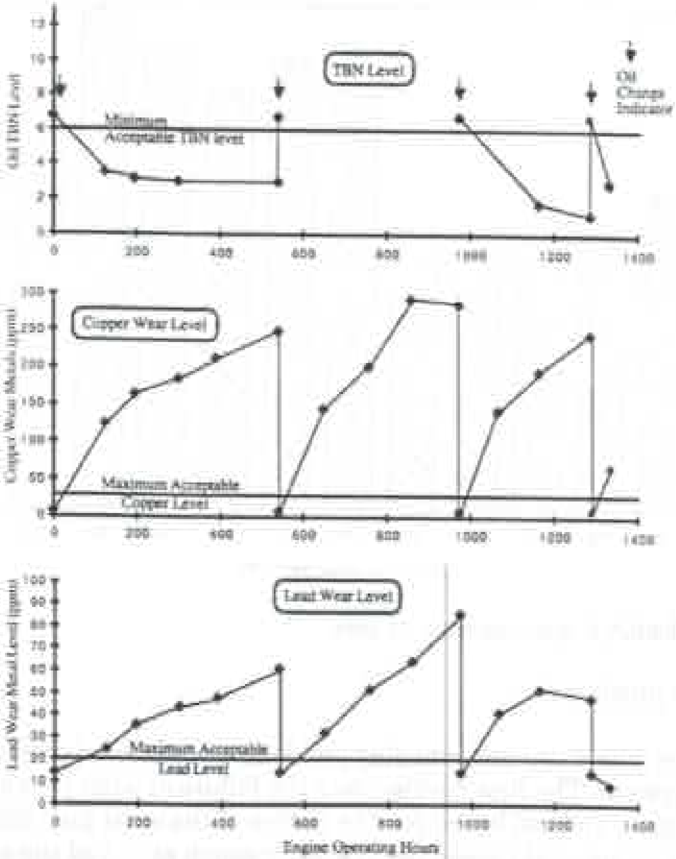

Fig. 6. Oil analysis parameters for monitoring the effect of hydrogen sulfide in the biogas during a third series of tests. Low TBN levels were accompanied by high levels of cooper and lead.

below 350 h, the TBN of the engine oil was kept above the minimum level. In general the copper and lead wear stayed below or slightly higher than the maximum acceptable levels during the course of these tests. Results presented in Figs. 6 and 7 clearly show that through oil selection the oil change interval was increased from 100 h of engine operation to 300 h. In addition to using a high TBN oil, a chemical treated oil by-pass filter was installed. The installation of this filter resulted in a doubling of the oil change interval to 600 h of engine operation. However, the oil capacity of the by-pass filter is equal to the oil capacity of the engine oil system. Thus, one must conclude that the bypass filter did not actually increase the useful life of the oil. The strategy of using a high TBN oil and the increased oil capacity obtained with the by-pass filter was successful in controlling the oil acidity problem. The carbon deposits found on the valves and top of the piston heads continued to be a problem with the first cogeneration system. From the detailed oil analyses obtained during this proj-

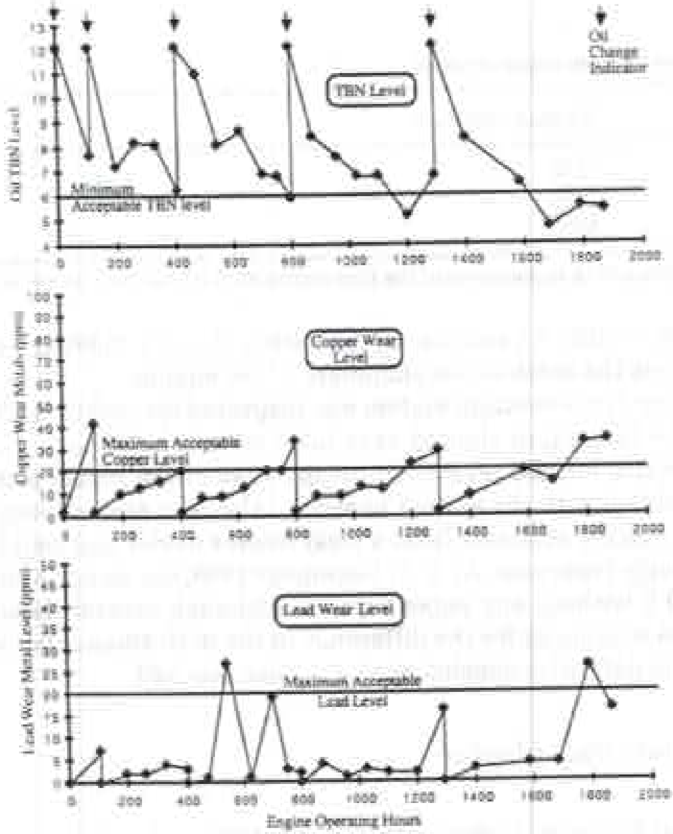

Fig. 7. Oil analysis parameters for monitoring the effect of hydrogen sulfide in the biogas during a fourth series of tests. Extended oil change intervals proved acceptable with the aid of an oil conditioner and maintenance of high TBN oil levels.

ect it was possible to determine when the carbon deposits were damaging the piston and cylinder walls. Significant carbon buildup resulted in high aluminum and iron concentration in the oil analyses.

Several modifications were made to the system in an attempt to reduce carbon deposits. The operating temperature of the engine was lowered from 96°C to 88°C and the water circulation was increased to improve the cooling efficiency of the system. However, these modifications and others failed to eliminate the carbon deposits. Each overhaul required replacement of the pistons and piston sleeves, new valves and a gasket kit. The average cost of an overhaul was $2500.

Tabulated in Table 6 are the hours between engine overhaul for the first cogeneration system. With the exception of the first overhaul, all of the overhauls were due to excessive carbon deposit on the pistons heads and the top of

TABLE 6

Engine hours between major overhaul

Overhaul	Hours of operation
1st	1370
2nd	2213
3rd	5500*

*Actually represents a replacement of the first engine with the second and not an engine overhaul.

the cylinder walls. An analysis of the carbon deposit indicated that engine oil was entering the combustion chambers of the engine.

The second cogeneration system was inspected for carbon buildup after 2000 hours. The inspection showed very little carbon build up on the piston and cylinder walls, but did reveal significant wear of the rocker arms. This was a minor problem with the system however. Also, the replacement parts for this unit were readily available from a local tractor dealer and could be purchased at a relatively lower cost. As of 31 December 1985, the second engine had logged over 5000 h without any major repairs. Although several theories have been postulated to account for the difference in the performance between these two engines, no definitive conclusions have been reached.

Heat recovery and utilization

From 10 November 1983 to 16 january 1984, a detailed energy blance was performed on the first cogeneration system. During this period 21 131 m^3 of biogas was used to generate 23 144 kWh of electricity. At this level of electricity production approximately 197.3 GJ of heat was recovered. The recovered heat represents 46% of the total energy input to the cogeneration system. Forty-seven percent of the recovered heat was used to heat the digester during this period. The remaining heat was used to preheat manure before it entered the digester.

Maintaining engine efficiency

Maintaining engine efficiency is a major challenge for farm scale cogeneration. The major difficulty is identifying and maintaining the appropriate carburetor setting to produce a fuel-air mixture that would lead to efficient operation of the engine. In a paper by Koelsch et al. (1985) it was noted that one-eight of a turn on the valve controlling the fuel–air mixture can result in 25% greater electricity production. Maintaining an efficient carburetor setting was complicated by the fact that gas quality varied with time requiring frequent adjustments by the farmer.

ECONOMICS OF COGENERATION

The first cogeneration system, rated at 27 kW, was purchased for $23,800 or $800 per kW of capacity. Piping for carrying cogenerated heat to the house, heat exchangers, fittings, circulators, excavation for the pipeline and insulation resulted in an installation cost of $16,000. Thus, the total capital investment for this system was $40,000 or $1480 per kW of capacity. The modification of the first cogeneration system to accomodate a new engine and generator cost $15,000. Purchased new, the 35-kW system, would have cost $35,000. The total investment in the digester reached $80,000 by the conclusion of the project. However, given the valuable insights gained from this project, the investigators believe that the digester cost can be reduced by 25%. If the digester and cogeneration system were implemented in 1985 on the same farm the total installed cost would be approximately $110,000.

For this project the major operating costs incurred have been for general engine maintenance and major overhauls (bearing, pistons, cylinder sleeves and water pumps). For both cogeneration systems the oil change interval was 600 h. Tabulated in Table 7 are the components of an oil change and the associated cost. The data in Table 7 was used to calculate the cost per oil change for a system without an oil by-pass filter (given in Table 8). Oil cost represented 47% of the cost of an oil change.

Tabulated in Table 9 are the parts, supplies and costs per oil change for a system with a by-pass filter. The cost of an oil change for this system is three times the cost of a change for a system without a by-pass filter. Unfortunately, doubling the oil change intervals does not offset the difference in cost between these two system (as indicated by Table 10) because of the cost of the by-pass filter. The difference in annual operation cost between the two systems is only $242.59.

TABLE 7

Parts and supplies for an oil change and their cost

Part	Units	Unit cost ($/unit)
High TBN oil	liters	0.89
Engine oil filter	each	4.50
By-pass oil filter	each	24.00
Labor	manhour	6.00

TABLE 8

Parts, supplies and costs per oil change for a system without a by-pass oil filter

Part of supply	Units	Number of units	Total cost ($)
High TBN oil	liters	7.57	6.73
Engine oil filter	each	1	4.50
Labor	manhour	0.50	3.00
Total	–	–	14.23

Units costs from Table 7 were used to calculate the total cost.

In addition to the oil changes, spark plugs had to be replaced periodically, the biogas blower repaired on averge once a year, the antifreeze in the engine coolant system replenished and the engine overhauled. The major overhaul

TABLE 9

Parts, supplies and costs per oil change for a system with a by-pass oil filter

Part or supply	Units	Number of units	Total cost ($)
High TBN oil	liters	15.14	13.46
Engine oil filter	each	1	4.50
By-pass oil filter	each	1	24.00
Labor	manhour	1.00	6.00
Total	–	–	47.97

Unit costs from Table 7 were used to calculate the total cost

TABLE 10

Annual operating and maintenance expenditure based on experience with first engine and assuming annual engine hours of 7440 (operational 85% of the time)

Operating or maintenance item	Cost ($/year)	
	Without by-pass filter	With by-pass filter
Oil changes	352.23	594.82
Spark plugs	36.00	36.00
Major overhaul*	2500.00	2500.00
Repair of biogas blower	200.00	200.00
Antifreeze	100.00	100.00
Total	3188.23	3430.82

*Replacement of pistons, piston sleeves, and valves.

costs listed in Table 10 represent our best estimate based on experimences with both systems.

Using the average monetary cost of electricity for farmers in the Ithaca area, the value of the electricity produced in 1984 was $8020. In addition to the electricity revenues, an estimated 1670 L of fuel oil valued at $485 was saved. Thus, the gross income from the cogeneration system was $8505. Subtracting the operating and maintenance cost (for the system without oil by-pass) from the gross income yields net revenues of $5316.77. Assuming a total capital investment of $110,000 the payback using 1984 data is 21.6 years.

This economic assessment projects a bleak picture for farm scale energy production. However, as indicated earlier, considerably more electricity can be produced with a more reliable engine. It was estimated that annual electricity production levels of 180000 to 190000 kWh could be realistically achieved. Annual electricity production of 190000 kWh represents 62% of the theoretical capacity of the second cogeneration system. The monetary value of this electricity production is $13,794. In addition, an estimated 150 l (900 gal) of fuel oil could be saved annually due to the increased availability of heat. Adding the monetary value of the electricity to the savings in fuel oil yields a gross income of $14,784 per year. Using the operating cost for the system with-out by-pass (see Table 10) and a capital investment of $110,000 the payback period for this system could be reduced to 9.7 years. Although more positive, the economcis of the system operating at this level of production would still be marginal. However, the investigators believe that with additional research and development the performance and economics of the digester and cogeneration systems can be improved further.

SUMMARY AND CONCLUSION

The economic assessment demonstrates the importance of reliablility in the economic feasibility of on-farm cogeneration. In order for on-farm cogeneration systems to be economically viable, they must be operated as close to maximum capacity as possible with minimum downtime. The performance of the first cogeneration system was marginal at best. However, the performance of the second system leaves the investigators somewhat more optimistic about the future of biogas fueled cogeneration.

Maintaining appropriate fuel–air mixture is a must. Given the high capital cost and operating expenses it is imperative that as much electricity be sqeezed out of the system as possible. This will necessitate periodic adjustment of the carburetor to compensate for variation in gas quality.

The problems with carbon deposits encountered with the first engine appears to be related to that particular unit and was not encountered with the second unit. As of 31 December 1985 the second engine had logged over 5000 h without any major repairs required.

For the engines tested during the course of this project, oil acidity ws controlled through the use of a high TBN oil and oil testing. oil change interval of 250–300 h was achieved through the use of a high TBN oil and oil testing. The oil change interval was extended by using a chemically treated oil bypass filter. However, the increase in the oil change interval does not off-set the cost of the oil by-pass filter.

Electricity production levels need to be increased. To achieve this, more consitent gas production must be achieved and breakdowns of the engine kept to a minimum. Electricity production levels of 180000–200000 kWh/year (960–1065 kWh/year per cow) can potentially be achieved with improvements in digester and cogeneration system design. In addition, the heat produced by cogeneration is an energy source that can be used more effectively on the farm. However, efficient utilizationis also coupled to the performance of the digester and the cogeneration system.

REFERENCES

Jewell, W.J., Capener, H.R., Dell'orto, S., Fanfoni, K.J., Hayes, T.D., Leuschner, A.P., Miller, T.L., Sherman, D.F., Van Soest, P.M., Wolin, M.J. and Wujcik, W.J., 1978. Anaeroboc fermentation of agricultural residues potential for improvement and implementation. Final Report EY-76-S-02-2981-7, U.S. Department of Energy, Washington, DC, 599 pp.

Jewell, W.J., Koelsch, R.K. and Cummings, R.J., 1985. Cogeneration of electricity and heat from biogas. Final Report prepared for the Science and Education Administration, U.S. Department of Agriculture and the U.S. Department of Energy, Solar Energy Research Institute. A statutory college of the State University at Cornell University, New York State College of Agriculture and Life Sciences, 195 pp.

Kah, G.J., 1978. Energy management strategies for dairy farms. M.S. Diss., Cornell University, Ithaca, NY, 78 pp.

Koelsch, R.K., Walker, L.P. and Pellerin, R.A., 1985. Design consideration for cogeneration system utilizing biogas. ASAE Pap. 85-3566, American Society of Agricultural Engineers, St. Joseph, MI, 27 pp.

Segaser, C.L., 1978. Conventional alternating-current generators and engine generators set. AN-LICESITE 78-1, Oak Ridge National Laboratory, Oak Ridge, TN, 55 pp.

Walker, L.P., Ludington, D.C., Muck, R.E., Friday, R.E. and Heisler, M.G., 1984. The design and analysis of an energy integrated dairy system. Trans. ASAE, 27: 229–240.

Walker, L.P., Pellerin, R.A., Heisler, M.G., Farmer, G.S. and Hills, L.A., 1985. Anaerobic digestion on a dairy farm: overview. Energy Agric., 4: 347–363.