CATERPILLAR®

Getting More Power from “Opportunity” Fuels

Low-energy fuels are a growing source of sustainable, renewable energy. A site- and engine-specific maintenance program built around trend analysis can help you use them profitably, in ways that maximize uptime, kilowatt-hours, and revenue.

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NOTE: This is the one of two articles about optimizing maintenance for gaseous-fueled industrial engines. This article focuses on engines that use low-energy fuels such as landfill methane, wastewater treatment or agricultural biogas, synfuels, and coal mine methane. The other article concentrates on specific maintenance issues related to engines that use pipeline natural gas fuel.

Introduction

The global shift toward sustainability has raised the profile of fuels we used to call wastes, like methane from landfills and wastewater treatment plant digesters. Increasingly, they’re seen as valuable forms of renewable energy, fueling gas engines that generate electricity for their host facilities or the utility grid.

These fuels are free in the sense that you don’t pay a utility for them, but they’re quite different from clean pipeline natural gas in the way they behave in engine-generators. Constituents in these fuels demand extra vigilance in engine operation and maintenance.

As in operations using natural gas, your gensets’ most valuable commodity is time – specifically uptime producing power and revenue. It follows that the goal of engine maintenance is to enable as much uptime as possible. High uptime boosts revenue and spreads capital and operating costs over more kilowatt-hours – reducing that critical variable of cost per kilowatt-hour.

“By-the-book maintenance” from the engine owner’s manual will rarely give you maximum uptime when using landfill or digester methane, biogas from animal manure or crop residue, coal mine methane, synfuels, or any low-energy fuel. Instead, the key is to apply best practices to arrive at the optimum maintenance program for your project. The winning ticket is trend analysis: understanding how the engine responds to its fuel, load, ambient conditions and other factors over time, and adjusting maintenance accordingly.

Why Low-Energy Fuels?

The conversion of low-energy fuels to electricity embodies the ideal solution to an environmental problem: It turns what is otherwise a harmful greenhouse gas waste into a product with a practical use and economic value.

Today’s low-energy-fuel projects benefit from advanced engine-generator sets that elevate performance, efficiency, and emissions compliance. These units, designed specifically to operate on low-energy fuels, are capable of electrical efficiencies as high as 43.5 percent and out-of-engine NO_x emissions as low as 0.5 g/bhp-hr. They have proven themselves in many applications worldwide.

Still, low-energy-fuel projects challenge operators to generate reliable electricity at competitive cost. To be viable, such projects must produce electric energy both at a profit for the operator and at market-competitive prices. Meanwhile, fuel heating value can change abruptly and frequently, and fuel impurities tend to shorten engine component life, increase maintenance, and drive up lifecycle operating costs.

All this makes a sound maintenance program – and especially trend analysis – even more important than in natural-gas-fueled generation. Unplanned downtime is to be avoided, especially for major failures and lengthy repairs. But planned downtime also must be kept to the minimum appropriate to the application. If equipment is serviced more often than truly necessary, then labor is wasted, production is lost, and consumable supplies and spare parts are discarded before the end of their useful lives.

Enemies in Your Fuel

The biggest variable affecting biogas project costs is fuel quality. Depending on its source, biogas contains a variety of impurities:

- **Hydrogen sulfide (H_2S).** Most biogases contain H_2S, a natural product of the anaerobic digestion process by which bacteria break down organic matter in landfills and digesters. H_2S when mixed with water creates a weak sulfuric acid that will invade engine oil and corrode critical engine components.
- **Halogenated hydrocarbons.** These substances (mainly chlorides and fluorides) differ from H_2S in that they are pollutants found in wastewater and solid waste streams. However, their effects within engines are the same: They combine with water to form corrosive acids.
- **Siloxanes.** These silicon compounds, from household products like cleaners, shampoos and soaps, deodorants and beauty products, form hard, ceramic-like deposits on cylinder components. They are present in landfill and wastewater digester gas in varying amounts. In landfills, siloxanes are deposited in finite amounts, and so their levels in landfill gas decline over time. In wastewater treatment, siloxanes are replenished constantly and so persist in the fuel.
- **Silicon (dust, sand, grit).** Found in most biogases, these hard particles cause premature abrasive wear.
- **Water/leachate.** Engines are typically designed to operate at up to 80 percent relative humidity as measured by the non-condensing water in the fuel. Most biogases exceed that level significantly. Moisture in landfill gas arises from water brought in with the rubbish and from rain or snow on the landfill. This moisture ultimately comprises the landfill leachate containing variable chemicals.

The effects of contaminants can be magnified by low fuel methane content: Lower fuel heating value means more cubic feet of fuel (thus more impurities) passing through the engine to produce the desired kilowatt-hours.

Dealing with Impurities

All these impurities tend to necessitate shorter maintenance intervals and more intensive monitoring of engine condition and trends. The first step is to understand exactly what is in the fuel. Engine manufacturers set limits on the amounts of the different impurities in the fuel – these vary by engine type and model (Figure 1 presents an example).

Daily	1000 Hours	2000 Hours	8000 Hours
❑ Air Tank Moisture and Sediment, Drain ❑ Check Coolant ❑ Check Engine Air Cleaner Indicator ❑ Check Engine Oil Level ❑ Check Fuel Filter Pressure ❑ Check Fumes Disposal Filter Pressure ❑ Check Generator Bearing Temperature ❑ Check Generator Load, Voltage, Frequency ❑ Check Jacket Water Heater ❑ Check Power Factor ❑ Walkaround Inspection	❑ Drain Aftercooler Condensate ❑ Inspect Alternator ❑ Inspect/Adjust Belts ❑ Measure Crankcase Pressure ❑ Inspect Crankcase Vibration Damper ❑ Clean Engine Crankcase Breather ❑ Change Oil & Oil Filter ❑ Clean Engine Timing Sensor ❑ Check Engine Valve Lash & Bridge ❑ Inspect Flex Coupling ❑ Drain Gas Pressure Regulator Condensation ❑ Test Generator Winding Insulation ❑ Inspect/Replace Hoses & Clamps ❑ Check Inlet Air ❑ Clean Radiator ❑ Measure Valve Stem Projection ❑ Inspect Water Pump	❑ Check/Adjust Carburetor Air-Fuel Ratio ❑ Check Compressor Bypass ❑ Inspect Generator ❑ Lubricate Generator Bearing ❑ Inspect Vibration	❑ Replace Fumes Disposal Filter ❑ Check Rotating Rectifier ❑ Inspect Turbo
250 Hours		**3000 Hours**	**10,000 Hours**
❑ Check Battery Level ❑ Coolant Sample (L1) ❑ Cooling System Additives ❑ Engine Oil Sample ❑ Fumes Filter Disposal		❑ Inpsect/Replace Spark Plugs	❑ Inspect Generator Bearing
		4000 Hours	**15,000 Hours**
		❑ Test Crankcase Blowby ❑ Test Cylinder Pressure ❑ Inspect Engine Mounts ❑ Check Engine Relays ❑ Check/Adjust Ignition Timing ❑ Inspect Starting Motor	❑ Replace Engine Oil Temperature Regulator ❑ Top End Overhaul
			30,000 Hours
			❑ In-Frame Overhaul ❑ Change Coolant
			60,000 Hours
			❑ Major Overhaul

Figure 1: Maintenance checklist.

A gas sample will reveal the methane content and contaminant levels in the fuel. Understand, though, that low-energy fuel quality can vary significantly, not just seasonally but daily and even hourly.

Landfill fuel in particular is variable, influenced by weather (wet or dry, hot or cold) and by the areas of the landfill from which most of the fuel is being drawn. For example, old landfill cells may produce fuel with lower heating value (because most organic material has already been degraded and biological activity has declined) but may also contain more impurities (because toxics were dumped there before regulations were tightened).

Fuel needs to be analyzed over time to understand the impurity levels, methane content and heating value, and how much those parameters change over time. Trending of all these is important, especially at landfills. Landfill gas is typically collected from all cells into a single manifold that in turn feeds the engines. However, the gas supply from one or more cells can be interrupted for any of several reasons, such as construction, wellhead degeneration, and filling with water or leachate after a heavy rain. When that happens, fuel quality to the engines may change substantially – getting better or worse – and therefore more frequent fuel sampling may be advisable.

In choosing a strategy for dealing with impurities, there is no single right answer: The best approach for a given site depends on operating conditions, financial objectives and, above all, on biogas quality. Two basic approaches that can be used alone or together.

Treat the fuel

Various technologies can remove significant amounts of fuel impurities. For example:

- A chiller, demister or coalescing filter effectively removes water.
- Siloxanes can be captured by adsorbents such as charcoal and silica gel.
- Air filtration is effective against silicon (dust/dirt) and other particulates.
- Activated carbon adsorbent removes hydrogen sulfide and other acid precursors.

While effective at reducing contaminants in the fuel, fuel treatments do add to capital costs. A fuel treatment skid may cost up to $500,000 for the first engine, not counting the cost of maintenance labor and materials and lost production from parasitic loads on the engine. As the site continues to expand in size and the number of engines increases, capital costs have been known to exceed $1 million.

Choose a ‘hardened’ engine

Some manufacturers offer engines with design features that “harden” components and systems against biogas fuel impurities. These units can operate for near-normal maintenance intervals with less intensive fuel treatment. Such modifications include:

Material changes. Bright metals (aluminum and unprotected steel) that are vulnerable to acid corrosion are replaced in certain components. For example, aftercooler cores made from aluminum in standard engines are made of stainless steel in biogas versions; connecting rod bearings use brass backing instead of steel.

Crankcase ventilation. A low-pressure pump ejects blowby gases from the crankcase and draws in warm, fresh, filtered air, so that acids are less likely to form in the oil.

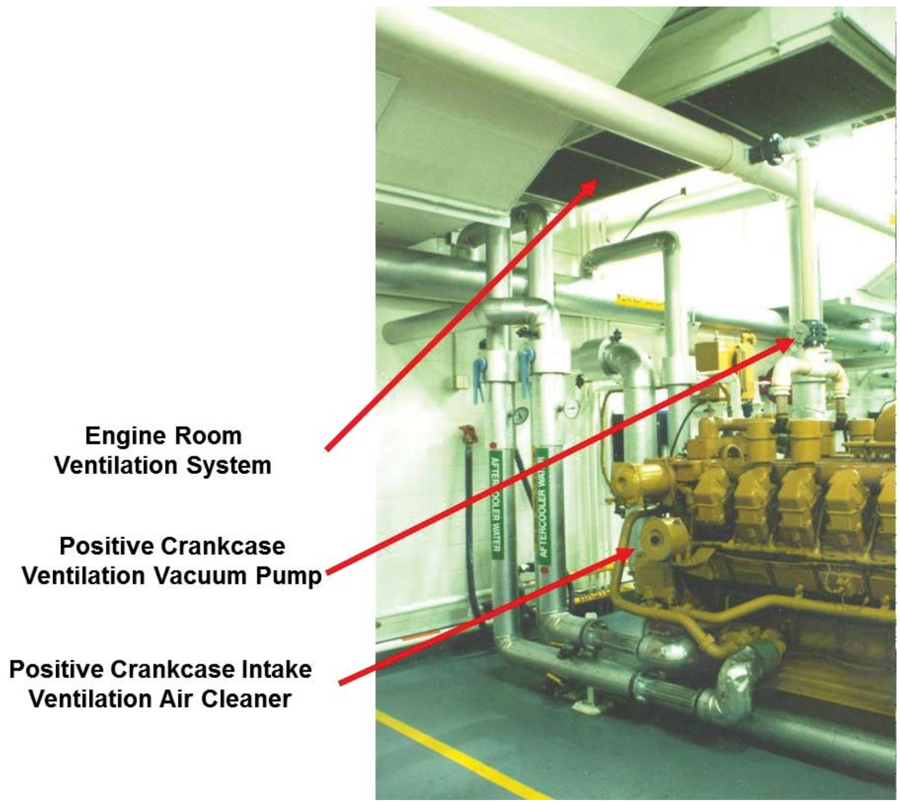

Figure 2: Crankcase ventilation air is warmed to prevent condensation and corrosion from blow-by gasses with fuel borne contaminants

Cooling system changes. Elevated jacket water temperature – 230°F (110°C) versus traditional 210°F (99°C) – helps prevent condensation of water, which collects the sulfur, chlorine and fluorine entrained in the fuel to form weak yet damaging acids. Specifically, the higher temperature keeps water in the fuel entering the engine from condensing on the cylinder liners, and keeps crankcase ventilation gases from condensing on the engine block and other components.

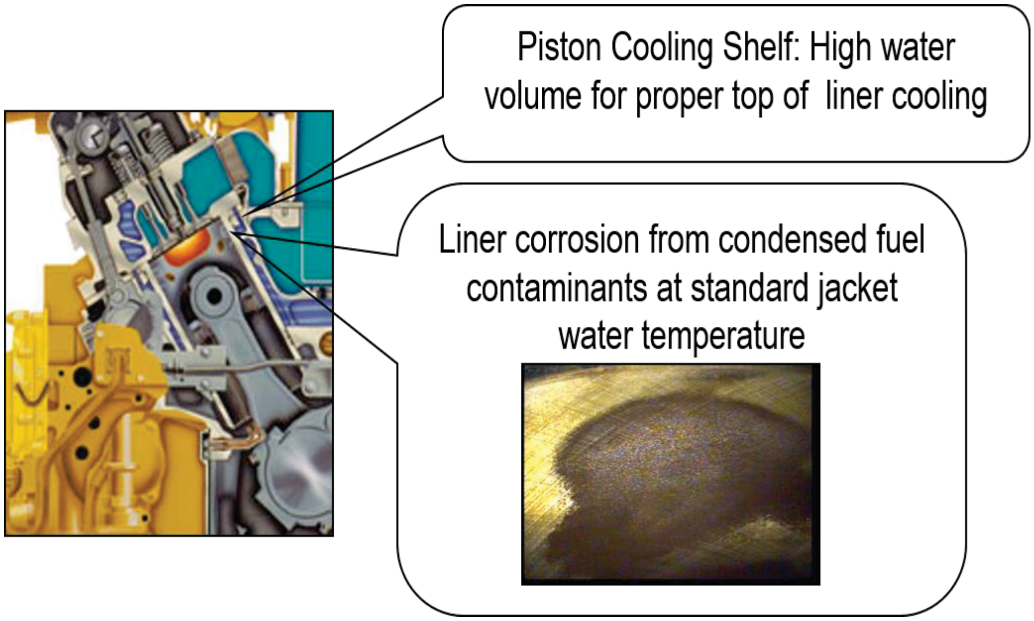

Figure 3: Cylinder liner corrosion and pitting caused by fuel borne hydrogen sulfide mixing with water in the combustion process to form sulfuric acid that condenses on the liner surface. Elevated jacket water temperatures protect internal engine components from corrosion by preventing condensation of water, not allowing sulfuric and other acids to form.

Component geometry changes. Special modifications help limit the effects of fuel siloxanes. For example, valve and valve seat angles are increased to detour formation of hard deposits that, when chipped in normal operation, could prevent proper value closure, allowing combustion gases to escape, cause burned exhaust valves, and erode engine performance.

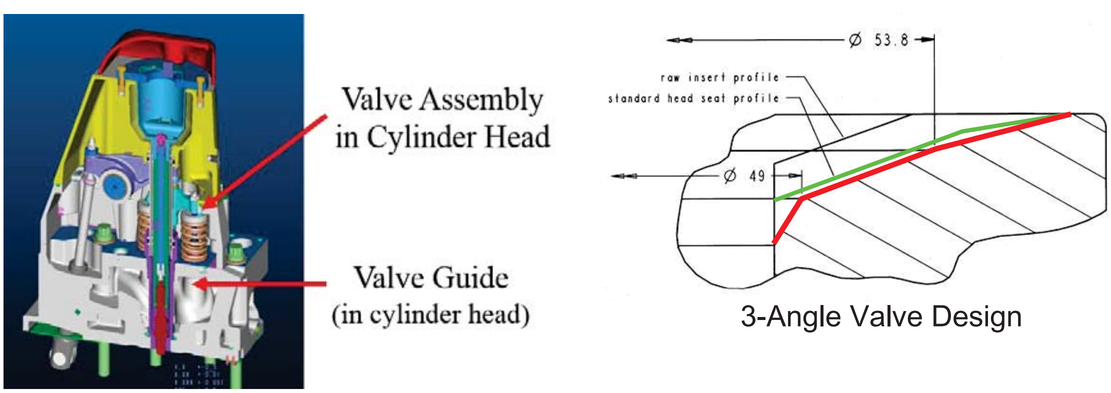

Figure 4: Valve angles modified to reduce siloxane deposits in critical areas

Choosing the right engine option

Dealing with fuel impurities means weighing the pros and cons of different engine technologies and fuel treatment systems and their initial and long-term costs. For example, if the fuel quality falls within the limits prescribed for hardened low-energy-fuel engines, then that technology can be used with minimal or no fuel treatment equipment, likely saving hundreds of thousands of dollars in capital and operating costs.

On the other hand, if the fuel impurities are such that extensive pretreatment is required regardless of the engine technology, then high-compression/high efficiency engines may be a prudent choice, as operating savings from the efficiency gains will help offset the costs of installing and operating the treatment system. Every project is different, and approaches to fuel impurities must be weighed on a fuel- and site-specific basis.

No matter which approach you choose, monitor fuel quality to the engines with an inline sampler downstream of the gas treatment system (if so equipped). Real-time analysis tools can measure fuel methane number and the content of oxygen, carbon dioxide and hydrogen sulfide. Short, infrequent spikes in contaminant levels may not be cause for concern, but frequent spikes or a persistent upward trend may indicate a need to change lube oil maintenance practices. Siloxane measurement requires separate sampling; an upward trend in these impurities may signal a need for more frequent overhauls. The key to long term success in siloxane management and progressive analysis is to stay with the same sample and analysis techniques.

Impacts on Performance

Fuel quality affects essentially all aspects of a low-energy fuel project, most notably the cost of maintenance. A conservative rule of thumb for maintenance cost on a well-designed project using pipeline natural gas is 0.7 cents to 1 cent per kWh. That cost may increase to 1.2 cents with relatively clean (or effectively treated) low-energy fuel; costs of up to 1.8 cents or even higher have been observed for especially challenging fuels.

Fuel quality may also affect power quality – variations in energy content may mean some oscillation in power output and possibly frequency and voltage deviations. This is not a concern where the electric output is sold to the utility grid but must be considered where the power is used at the host facility, especially if sensitive electronic equipment will be affected.

Some fuel impurities also can lead to changes in emissions. Specifically, siloxane buildup on the cylinder heads, pistons and liners reduces cylinder volume, effectively increasing the compression ratio and driving up carbon monoxide (CO) emissions, possibly beyond regulatory limits. This may make it necessary to clean the combustion chambers. The increased compression ratio also heightens the risk of detonation (“knocking”), an uncontrolled and destructive combustion process in the cylinders.

Efficiency on low-energy fuel depends on the fuel quality and on engine design features, notably compression ratio. Engines that use the same compression ratio on low-energy fuel as on natural gas tend to be slightly less efficient in low-energy applications. On the other hand, engines custom designed for a specific site based on fuel analysis may be able to use a higher compression ratio and be slightly more efficient. That higher compression is possible because low-energy fuel typically contains elevated carbon dioxide, which adds detonation resistance. Higher compression ratio engines are more efficient, but may not handle the gas quality swings as well as lower compression ratio engines. These higher efficiency engines may require additional or more frequent engine adjustments.

Making Low-Energy Fuels Work

The first rule of operating low-energy–fueled engines is to know that the recommended maintenance intervals in the owner’s manual are typically quite conservative, based on essentially worst-case fuel conditions, according to our maximum allowable gas quality limits. In reality, low-energy fuels are highly site-specific and variable, so that a one-size-fits-all maintenance regimen is doomed to fail economically for any given site. The operators’ key task is to optimize maintenance intervals by carefully applying engine-specific trend analysis. Here’s a look at essential items to monitor.

Lubricating oil

Lube oil is an engine’s lifeblood, and monitoring its condition is critically important, both for what it does to protect your engines and for what it reveals about engine condition.

Oil selection

Good maintenance starts with choosing the right oil – one that delivers the necessary oil life and component protection in a challenging low-energy fuel application. Engine manufacturers issue model- and application-specific oil specifications.

Oils contain a variety of additives designed to add oil stock stability under a range of operating conditions, resist acidification, and extend oil life. These additives in the right combination are especially important in low-energy-fuel engines. It is prudent to choose an oil supplier that has a history with your engine manufacturer and understands the lubrication requirements of your engine in your specific application.

As the gas quality changes at a site, the optimum formula for lube oil also may need to change. An oil that works on one site may not provide the same operating results on another site. In fact as the gas at one site continues to evolve over time, it may be necessary to alter the oil formula on site as well.

Oil analysis

Oil analysis is valuable in any application but especially where low-energy fuel is used. Oil analysis is similar to medical blood testing. The results provide vital information that helps you set the most appropriate oil change and component maintenance interval. It also provides early warning of contaminant buildup that could lead to component damage and catastrophic failure.

A key engine health indicator found in gas engine oil is wear metals. Iron, chromium and copper will always be present in oil, and the levels, typically stated in parts per million (ppm), help indicate which components are wearing as expected and which are experiencing abnormal wear, from fuel impurities or some other cause.

Analysis also detects glycol, indicating coolant leakage, and silicon, likely signaling an air leak in the air intake system or a damaged air filter. Especially important, analysis can also detect the presence of harmful acids, indicated by declining total base number (TBN), a measure of buffering capacity; and rising total acid number (TAN), a measure of acid content. TAN is an extra-cost option not typically included in basic oil analyses and must be specifically requested.

Oil life is a function of the volume of oil in the engine, engine operating load, ambient conditions, and the quality of the fuel. Oil can safely remain in the engine until some measurement reaches its condemning limit as set by the engine manufacturer. In engines using low-energy fuel, low TBN and high TAN are usually the first condemning limits reached. Oil analysis can be used to trend both conditions. Tests for TBN and TAN may not be standard in an oil sample analysis, so you may need to ask for these tests.

An oil analysis regimen should begin with the testing of a clean (unused) sample of the oil you plan to use. All oils have different additive packages and oil chemistries; they need to be evaluated and the resulting chemistries known before the oil is used in an engine. The results of the clean-oil test provide a baseline against which to compare analyses of future used oil samples.

Used oil then should be analyzed every 250 operating hours up until the first oil change to establish the parameter that will set the condemning limit and to identify the trend for the specific oil formulation. Technicians should take samples while the oil is warm and well mixed to ensure that the sample truly represents the condition of oil in the crankcase.

Next, oil should be analyzed at a minimum of one-half the expected life to verify the trend initially seen. After the number of operating hours to the condemning limit is verified, it is prudent to reduce the oil change interval slightly to establish a safety factor. Once you document clear trends, sample the oil at every change to verify that the trends are holding.

Be sure to note the total number of hours on the oil sampled – the age of the oil will greatly influence the analysis results. High-quality analysis laboratories list the latest test results side-by-side with the previous. They also have trained and certified oil technicians who know the specific engine model reviewing the results, looking for abnormalities, and advising on how things are trending.

One way to extend the oil change interval is to install a higher-capacity oil sump or an additional oil reservoir. A larger volume of oil circulating in the engine has the effect of diluting contaminants and extending the time it takes to reach the condemning limit. In this scenario, filtration must be sized appropriately, and it’s important to monitor the pressure differential across the filters to make sure they are not becoming plugged.

A few other key points to remember about oil and analysis:

- In reviewing oil analysis reports, consider contaminants that may come not from within the engine but from the surrounding environment. For example, operating in a dirty area may elevate silicon; operating near a chemical plant that emits chlorine compounds could speed up oil acidification.
- Before sending an oil sample, examine it carefully. If you see large wear particles or anything else abnormal, let your laboratory know and look for clues to the cause.
- No two engines run the same – not even two of the same model on the same site. What is normal for one engine may not be for another, so trend engines individually. In particular, a series of engines fed by the same fuel line may take in different levels of some contaminants. For example, as fuel moves down the line, the engines readily take in the lighter gas molecules, but the heavier siloxanes and grit may rush by until they "hit the wall" and are taken in by the last engine in the series.
- There are benefits to using original equipment oil filters and subscribing to your engine manufacturer's oil analysis service. In that event, factory-qualified technicians perform the analysis and warranty support is enhanced: If an engine manufacturer's oil filter should fail through defect, the manufacturer may cover not only the failed filter but also consequential damage to the engine.

Company Name: Green Energy
Customer Equip Number: L6G00101
Equipment: Engine Natural Gas
Serial Number: L6G00101
Manufacturer: Caterpillar
Model: G3516

Sample Type: Oil
Sample Ship Time: 3
Sample Label Number: Option III Prepaid
Fluid Brand/Weight: Cat NGEO Adv. 40

Dealer Name CAT

Lab Control Number	Sample Date	Process Date	Equipment Meter	Meter on Fluid	Fluid Changed	Make Up Fluid	Make Up Fluid Units	Filter Changed
B030-44021-0024	1/18/14	1/21/14	2234HR	936 HR	No			No
Action Required	Wear metal analysis results are normal. Infrared analysis results are acceptable. Water/Fuel/Glycol physical tests are negative. Total acid number (TAN) shows very significant increase. Total base number (TBN) has dropped to less than half of new.With the decrease in alkalinity, oil is at the end of the service interval. Please change oil and filter(s) if you have not already at your earliest convenience. Resample next service interval.							
B030-44009-0003	1/8/14	1/9/14	2092 HR	704 HR	Unknown			Unknown
No Action Required	Wear metal analysis results are normal. Infrared analysis results are acceptable. Water/Fuel/Glycol physical tests are negative. No problems presently associated with the sample. Contine sampling at the normal interval.							
B030-44002-0006	12/30/13	1/2/14	1873 HR	485 HR	No			No
No Action Required	Wear metal analysis results are normal. Infrared analysis results are acceptable. Water/Fuel/Glycol physical tests are negative. Total acid number (TAN) is acceptable. Total base number (TBN) is acceptable. Resample next service interval.							
B030-43354-0016	12/20/13	12/20/13	1650 HR	262 HR	Yes			No
No Action Required	Wear metal analysis results are normal. Infrared analysis results are acceptable. Water/Fuel/Glycol physical tests are negative. Total acid number (TAN) is acceptable. Total base number (TBN) is acceptable. Resample next service interval.							

Wear Metals (ppm)	Cu	Fe	Cr	Al	Pb	Sn	Si	Na	K	B	Mo	Ni	Ag	Ti	V	Mn	Cd	Ca	Mg	Zn	P	Ba
B030-44021-0024	1	3	0	1	0	1	2	1	1	35	1	0	0	0	0	0	0	15554	4	4	1	0
B030-44009-0003	0	2	0	0	0	0	1	0	1	58	0	0	0	0	0	0	0	1570	3	5	2	0
B030-44002-0006	0	1	0	0	0	0	0	0	1	73	0	0	0	0	0	0	0	1487	3	0	0	0
B030-43354-0016	0	1	0	0	0	0	0	0	1	10	0	0	0	0	0	0	0	1487	2	0	0	0

Oil Condition/Particle Count (cu/ml)	ST	Oxl	NIT	SUL	W	A	F	V100	TAN	TBN
B030-44021-0024	0	9	4	20	N	N	N	14.6	3.41	1.8
B030-44009-0003	0	8	5	18	N	N	N	14.7	2.19	2.4
B030-44002-0006	0	7	4	16	N	N	N	14.4	1.82	3.3
B030-43354-0016	0	6	4	10	N	N	N	14.8	1.80	3.5

Figure 5: Sample S·O·S^{SM} report.

A good maintenance objective is to match the oil change interval to the spark plug service interval. This means the engine is shut down only once for both maintenance tasks – oil is drained and replaced while the plugs are changed. If you have trouble reaching 2,000 hours or your target level, it may be worth considering different oil formulations. Talk to suppliers, show them the oil you have been using, and share your fuel and oil analysis results. A supplier then may be able to choose or even formulate an oil with an additive package that can help achieve the desired life.

Spark plugs

Properly performing spark plugs are critical to performance, fuel economy and emissions in engines operating on low-energy fuels. Today’s advanced lean-burn engines may use traditional J-gap spark plugs or prechamber plugs. In the pre-chamber design, the spark plug admits air and fuel to a small chamber around the electrode by way of small orifices. Upon ignition, the prechamber protects the flame from being “blown out” by turbulence in the cylinder. The growing flame is then ejected through the orifices to ignite the full cylinder’s air-fuel charge. Because fuel impurities (especially siloxanes) can readily foul prechamber plug orifices, J-gap plugs are generally preferred in low-energy fuel applications.

Spark plug life varies greatly with fuel quality. In applications involving clean natural gas, J-gap plugs typically last 3,000 to 5,000 hours in low-compression engines and 2,000 to 4,000 hours in high-compression engines. In low-energy applications, plugs often need cleaning or replacing sooner.

Figure 6: J-gap (left) verses prechamber (right) spark plugs.

Good trend data is especially helpful in setting the optimum plug change or service interval for a specific installation. Operators can monitor and track trends in spark plug wear by measuring and recording the gap at each service and by observing the plugs' general condition. Plug performance also can be trended by monitoring secondary transformer output, which usually reads out as percentages on the engine control panel or through the SCADA system. A new spark plug typically registers 25 percent. As the plug ages, the electrode deteriorates, increasing the gap and thus the voltage required for the spark to jump across. The required voltage also increases when electrodes become fouled by fuel impurities. Plug failure begins as secondary voltage surpasses 90 percent – this makes it easy to arrive at the optimum time for cleaning, re-gapping or replacement.

If the engine is unstable or running poorly, a check of exhaust port temperatures is a good start to troubleshooting. A temperature drop indicates a failed or misfiring plug. Deciding when to replace all plugs is a judgment call. In general, if just one plug fails, especially if it fails far from the expected change interval, it is more cost-effective to replace only that plug. However, when three or more plugs have failed, especially within a short time, that is a reliable sign that all plugs are approaching end of life.

Valves

Engine valves are designed to recede into the valve seat with every day wear, and valve lash gaps need to be adjusted regularly to maintain an effective combustion seal in the cylinders. The rate of recession varies with operating conditions, fuel quality and other

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factors. Measurement of valve stem projection is especially important to trend analysis in low-energy-fuel engines.

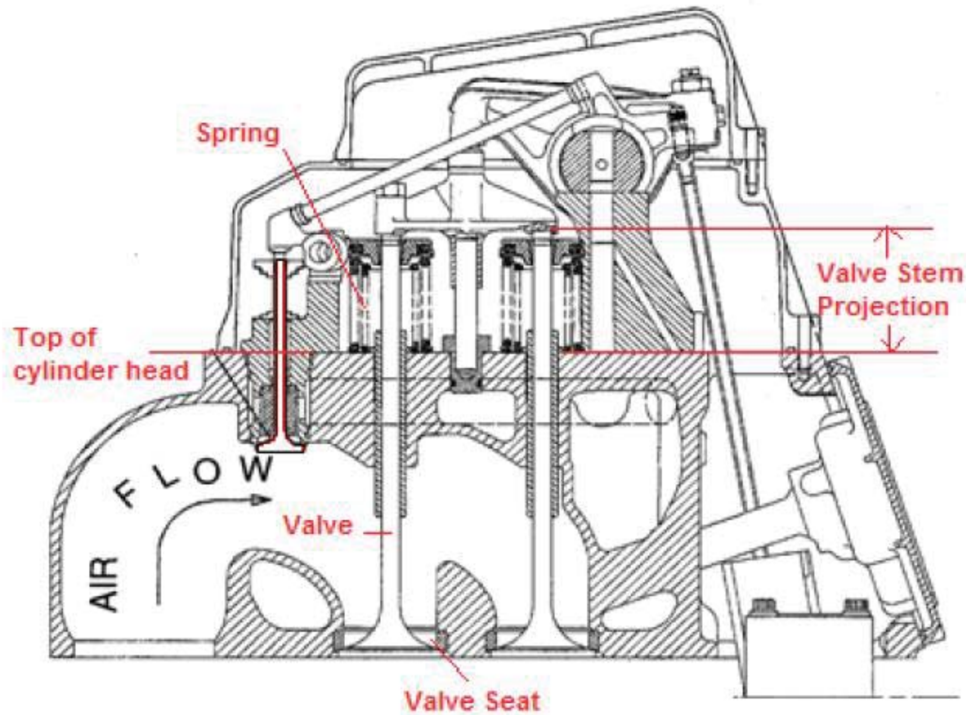

Figure 7: Valve stem projection measurement.

Valve stem projection indicates the amount of wear that has taken place between the valve faces and valve inserts. Measure the initial valve stem projection at 250 hours, and then again at 1,000 hours on new cylinder heads – the normal “beat-in” period in which the valve becomes seated on the insert. This establishes a wear baseline. After that, take measurements at spark plug changes.

Valves in low-energy fuel engines are vulnerable to acid erosion that can accelerate wear. They are also subject to the buildup of siloxane deposits on the valve and seat faces that can hold valves open and cause burning. Valve stem projection measurement will help detect either condition.

Figure 8: New valve recession measurement tool for Cat® G3500C/E engines.

Buildup on the valve face also changes valve lash and therefore valve timing, in turn affecting airflow and the air/fuel ratio in the cylinder. An incorrect valve open/close sequence may cause loss of compression, a richer fuel mixture leading to detonation, or excessive inert exhaust gases in the cylinder at ignition, reducing power output.

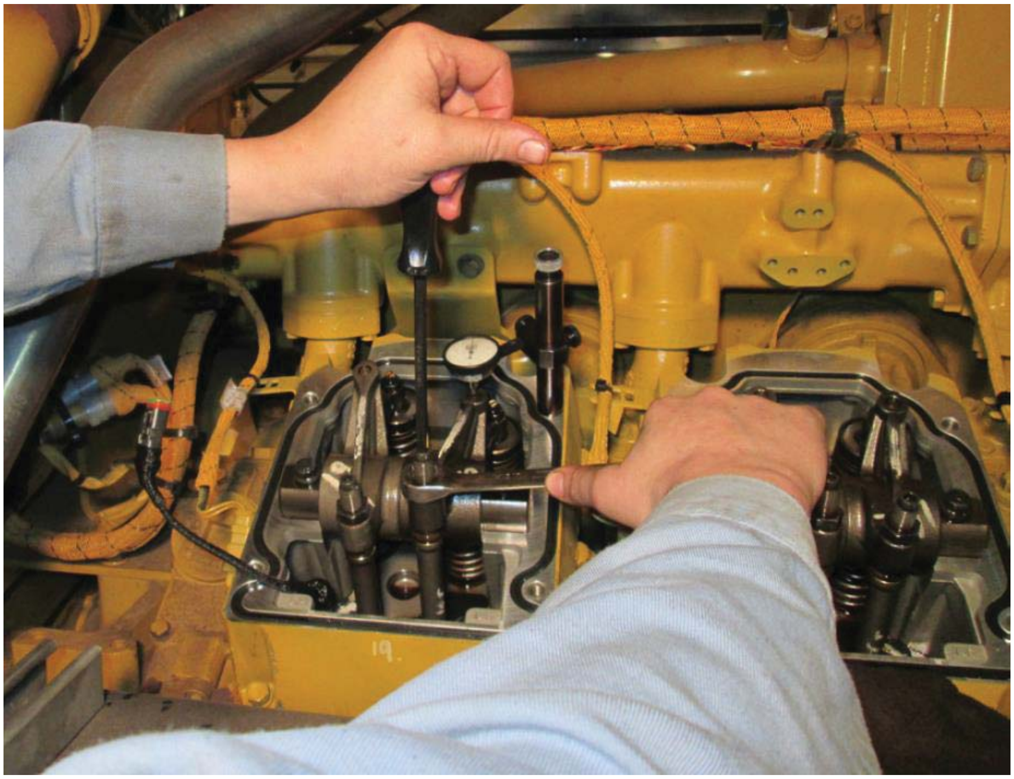

Figure 9: Valve lash adjustment.

Engine manufacturers set specifications for maximum allowable valve stem projection. Measurements must be taken consistently and accurately. Ideally, the same person should always measure projection on a given engine, using the same tool and method. Projection is typically measured in millimeters, and different measuring devices and techniques can meaningfully skew the trend data.

Cooling system

Coolant is an essential fluid that serves multiple purposes. Its most obvious benefit is freeze protection, but it also elevates the boiling point of cooling water, enhancing cooling efficiency. Just as important, it contains additives that prevent mineral scale formation in coolant channels, lubricate water pump seals, inhibit rust, and prevent cylinder liner cavitation erosion.

Select a coolant type recommended by the engine manufacturer and mix it with deionized water in the appropriate proportion for the site (50-50 is typical for colder climates, but warmer climates year-round may call for other mixes). A simpler approach is to use a premixed coolant product. In any case, too weak or too strong a coolant mix for the location will hurt engine performance and life. Even engines in tropical areas where antifreeze is not used need conditioners to maintain the coolant for optimal performance.

Figure 10: Coolant level sensor on a radiator for a Cat G3406 engine.

Like oil, coolant should be analyzed regularly. An effective analysis program can help verify proper coolant chemistry, monitor cooling system condition, and signal opportunities to correct coolant or cooling system problems before failures happen. Analysis can detect symptoms of trouble such as improper system pH, unacceptable water hardness, presence of precipitates, low or high glycol level, oil in the coolant, and elevated lead, copper, and aluminum levels.

Cooling system pressure is also important. A leaking pressure-control cap will lower the coolant boiling point, allowing water to boil off and escape. In addition, steam flashing off the cylinder heads can limit cooling capacity and lead to premature component wear.

All maintenance that applies to ordinary cooling systems also applies to combined heat and power installations – the essential function of heat recovery remains the cooling of the engine.

Other trends

Other engine trends bear watching for their potential impact on performance and for what they indicate about low-energy-fueled engine status.

Engine load. Heavy-duty industrial gas engines are designed to operate at or near full rated load for extended periods. Owner's manuals generally specify that turbocharged engines operated at 60 percent load or less for a specified period be restored to near full load to burn off oil and deposits. Engine-generators that regularly operate at lighter loads use significantly more fuel per kWh than they would at full load. Maintenance costs also tend to be higher on a cost per operating hour basis on lightly loaded engines.

Ambient conditions. Hot weather accelerates component wear and the breakdown of oil and coolant. Hot ambient temperatures make the air less dense and may also require derating the power of the engine. The same is true of operating at high altitude. On the other hand, cold ambient temperature is a concern in low-energy fuel applications: Cold inlet air and a cooler engine encourage harmful impurities, like acids, to condense. The same is true for cold air around the engine block. For this reason, heated engine rooms or, at the minimum, engine enclosures are advisable in cold climates. In addition, a source of warm air for crankcase ventilation is essential to preventing condensation of corrosive acids in the lube oil.

Inlet and exhaust manifold pressure and temperature. Normal trending should establish the expected pressure and temperature values; any deviation in one or multiple cylinders is grounds for investigation. To cite just one example, increased exhaust manifold temperature and / or changes in intake manifold pressure could indicate a plugged or malfunctioning jacket water aftercooler is hindering heat rejection. Keep in mind that trending may be influenced by ambient conditions. An extremely hot ambient temperature, for example, may elevate exhaust manifold temperatures and could require an engine derate, timing change or require and engine shutdown.

Oil temperature and pressure. Here again, deviations from normal measured pressure and temperature values merit investigation.

Engine Overhauls

The basic purpose of engine overhauls is to restore the equipment to like-new working condition. Trending can help in tailoring intervals for top-end, in-frame and major overhauls to the application and the fuel quality. Conservative intervals for engines burning clean biogas without siloxanes are typically listed in the neighborhood of 20,000 hours for a top-end, 40,000 for an in-frame, and 80,000 for a major. However, depending on fuel characteristics and the quality of maintenance, intervals in low-energy fuel applications can be significantly shorter or longer. For example, an engine operating with siloxanes near condemning limits may have top-end overhauls at 12,000 hours. The top-end overhaul would be repeated again before the in-frame overhaul at approximately 36,000 hours.

Top-end overhaul

Top-end overhauls replace the cylinder head assemblies or rebuild them with new valves and valve seats, guides, springs, rotators, keepers and other components. Spark plugs are replaced and oil changed at the same time.

Key trend indicators of time for top-end overhaul include valve stem projection, oil volume from the blowby recovery system, and oil consumption – generally in that order of importance. Another contributor to top end overhauls has been emissions slip (primarily CO) due to the buildup of siloxanes, ash from oil consumption or other contaminants in the combustion chamber. Engine manufacturers specify maximum allowable growth in valve stem projection. One valve out of specification (sometimes called a "flyer") is not necessarily grounds for a complete top-end overhaul – it may be an aberration caused by one softer valve or insert. However, if two or more valves on different cylinder heads exceed the specification, a top-end overhaul may be indicated depending upon the number of hours on the component. On the other hand, a loss of valve stem projection indicates deposits forming on the valve and inserts and may also indicate the need for top-end maintenance.

For top-end overhauls, remanufactured cylinder heads can be a cost-effective alternative to new components – especially where low-energy fuel demands overhauls at shorter intervals. In this arrangement, the engine manufacturer or a dealer supplies heads rebuilt with a combination of new and/or remanufactured parts that meet the original equipment specifications and carry the same warranty as new. The engine owner then receives credit for the replaced heads and components.

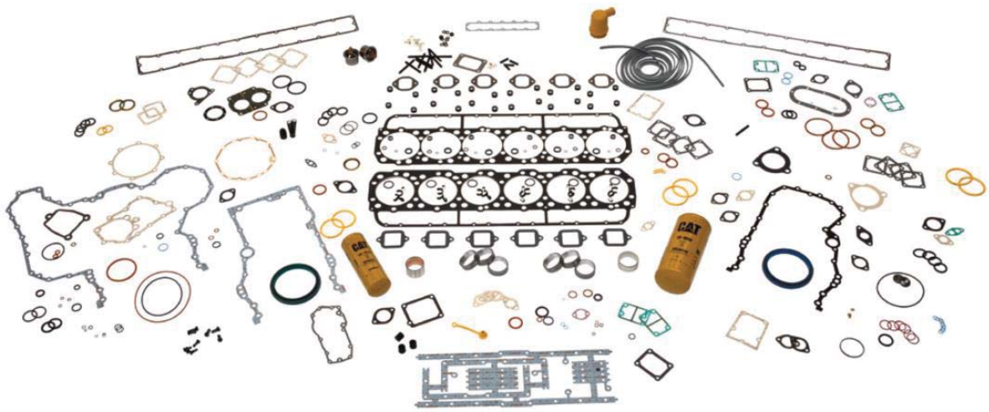

Figure 11: G3406 complete foundational overhaul kit.

In-frame overhaul

An in-frame overhaul reconditions many of the engine's internal systems in place, without removing the engine cylinder block from the generator or base rails. In-frame overhauls usually include many of the activities done at top-end overhaul, including replacement of the cylinder heads. An in-frame also typically includes replacing the pistons and connecting rod groups, cylinder liners, turbochargers, and main and connecting rod bearings. With good planning, the process can be completed in 24 to 48 service hours, depending upon engine service access. Indicators for an in-frame overhaul include oil consumption commonly caused by glazing of cylinder liners (easily identified by bore-scoping) and elevated levels of wear metals (aluminum, copper, chromium, iron) in the oil, as detected through oil analysis.

Major overhaul

A major overhaul is essentially a complete rebuild. It replaces the same components as for an in-frame overhaul but also includes a rebuild of the front gear train (bearing replacement, gear inspection and replacement if worn), a change-out of the damper pulley, camshaft bearing replacement, a line bore inspection on the engine block (making sure that the crank and cam bores are still parallel to each other), and possibly more, including camshaft and crankshaft reconditioning.

A major overhaul requires uncoupling of the engine from the generator, removal from its building or housing, and transport to the controlled environment of an overhaul shop. The process can take 200 to 250 service hours for a typical 170 mm bore, 16-cylinder engine, or longer if there are more cylinders or if abnormal wear exists.

Indicators of time for a major overhaul include a 300 percent increase in oil consumption, or a 200 percent increase in oil volume to the blowby recirculation system, as measured from a baseline set at the 1,000-hour mark. A major change in exhaust emissions also may signal time for an overhaul, although that alone can indicate merely a need to adjust the engine emissions system or the control strategy.

Where possible, it is prudent to schedule overhauls of any kind around other expected outages. For example, if the electric utility plans to take its feed-in line down for service or repair about 2,000 hours before the time of in-frame overhaul, it may make economic sense to complete the overhaul then, instead of restarting and then shutting down again a few months later.

Counting the Costs

The success of a power generation project with engine-generators using low-energy fuel comes down to the cost of electricity per kWh. Profit margins can be slim – tenths of a cent in cost per kWh can mean huge dollars over a project’s life. Typical capital costs are 3 to 3.5 cents per kWh and are largely inflexible. Maintenance costs, on the other hand, are largely under the owner’s control.

How much does poor maintenance cost? There is essentially no upper limit – and low-energy fuel tends to multiply the consequences of neglect and error. Engine failures, premature overhauls caused by rapid component wear, long spells of unplanned downtime – all these together can amount to many thousands and, in the case of large projects, even millions of dollars in hard expenses and lost revenue, significantly increasing the cost per kWh.

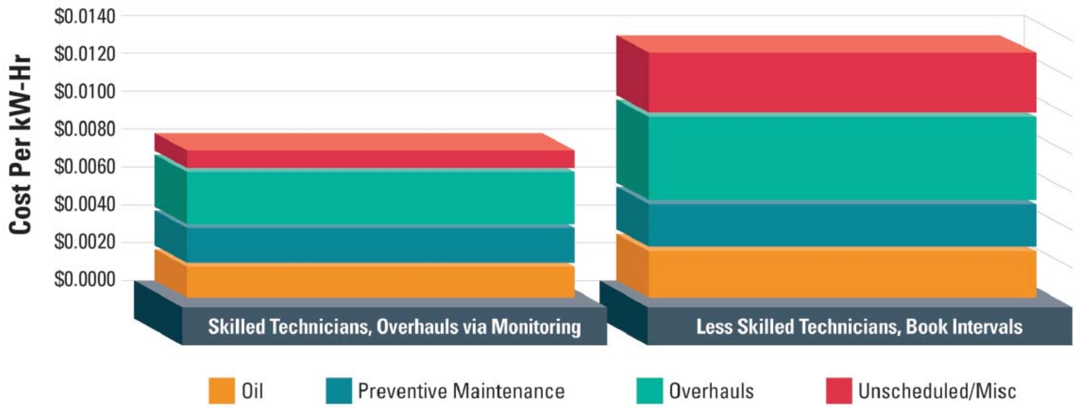

Figure 12: Maintenance and repair costs variance.

Good maintenance is more challenging in low-energy fuel applications, but the basic procedures are the same and are not difficult to master. The requirements include knowledge of trending methods, effective scheduling, well-trained people, quality replacement components and consumables, and access to technical support from your engine manufacturer. Trend-based maintenance will help keep productive hours up and costs down for the full duration of a low-energy-fuel power generation project.

Sidebar

The B-Life Concept: Comparing Apples to Apples

With engines as with any industrial product, manufacturers make claims about reliability and durability: how long something will last without failing. To evaluate these claims – to compare “apples to apples” – it helps to have some objective measure.

One such measure is B life, a scale from zero to 100 that refers to the percentage of items that will survive to a given service life. For example, engine components are often designed on the basis of a B10 life. This is the age (in operating hours) at which 10 percent of the components will need to be serviced or replaced, and 90 percent of the components will still be in service. (Figure 13)

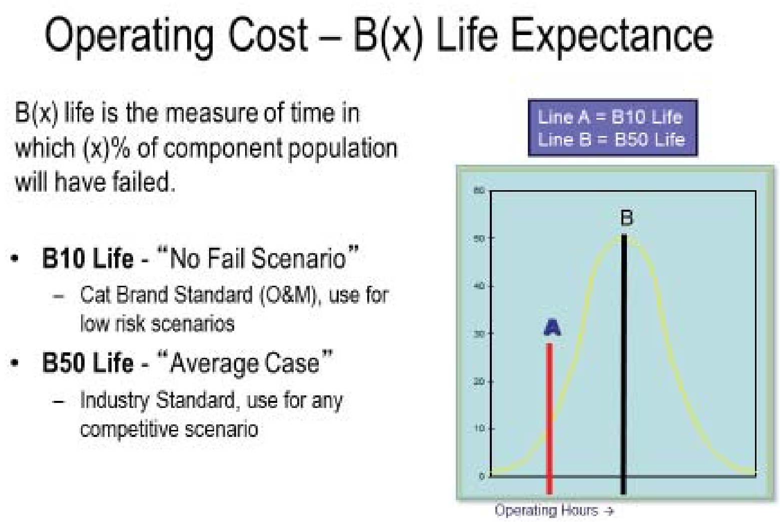

Figure 13: Maintenance and repair costs variance.

The design of machinery, such as engines, always includes a compromise between durability and cost. To illustrate, in space exploration or airline travel, critical components are manufactured to a B life approaching zero – nearly 100 percent will survive to the designed life. This is extremely expensive, but necessary because failures are not acceptable and often mean that people die.

On the other hand, in industrial engines, component failures are undesirable and costly, but are usually not life-threatening. If built to a near-zero B life, engines would be so expensive that few users could afford to buy them.

Instead, engine components are typically built to an expected design life based on B10. For example, cylinder head components are designed and manufactured to standards such that 10 percent will need to be serviced at or before a given time to top-end overhaul – say, 20,000 hours. Conversely, 90 percent of the components will meet or exceed that service life.

Now, suppose that one engine manufacturer promotes a top-end overhaul interval of 20,000 hours, and a competitor with a similar engine promotes a top-end overhaul at

30,000 hours. Both claims may be true – but based on different B life standards. That is, the claim of 30,000 hours may be based on B50: just half the components will survive to the advertised life.

So, in comparing reliability claims, it is legitimate and prudent to ask each manufacturer: On what B life is the claim based? In this way, B life enables buyers to tell whether apples are truly being compared to apples. In fact, the service intervals in some manufacturers’ operation and maintenance manuals are listed at B10, while others are listed at B50.

Uptime vs. Efficiency

In assessing the performance of a biogas-to-energy project, the equipment’s efficiency is important – but not nearly as important as its availability (uptime). Simply stated, anytime the generating equipment is offline, it produces zero revenue. Its *kilowatts* of capacity are devalued when its *hours* of operation are reduced.

Of course, no generator can operate around the clock for a year. Real revenue is determined by the theoretical revenue multiplied by capacity factor – the percent of its total potential output the units actually achieves. The key items that affect capacity factor and revenue are:

- **Availability.** Revenue is lost anytime the generator does not operate. This includes downtime for maintenance and repairs. Unavailable periods also include any times when the digester is not producing gas.
- **Load factor.** Revenue is lost if the generator is unable to operate at full load. That can happen if the fuel supply is temporarily limited, or if fuel quality declines.
- **Derates.** High temperature and high altitude could keep the generator set from achieving its nameplate capacity rating.

It is also important to understand how tradeoffs between generator set capacity factor and generator set electrical efficiency affect revenue. A simple scenario illustrates the trade-off between generator set electrical efficiency and availability, as they affect revenue. Assume two 1 MW units, an electricity sale price of $70 per MWh, and a fuel production cost of US$70.63/MJ/Nm^3 (US$2/MM Btu). Now assume that both units operate at 96 percent availability, but that Unit A is 39 percent efficient while Unit B is 42 percent efficient. In that scenario, the more efficient Unit B has a 2.2 percent net revenue (Figure 14).

Same Capacity Factor, Different Efficiency

	UNIT A	UNIT B
Generator set kW	1000	1000
Gas Price $/mmbtu	$ 2.00	$2.00
Value of Energy Produced $/MW-hr	$70.00	$70.00
Generator Efficiency	97.0%	97.0%
Engine Heat Rate BTU/min	145,000	135,000
Capacity Factor	96.0%	96.%
Generator Set Electrical Efficiency	39.2%	42.1%
Fuel Consumed/year mmbtu	73,163.52	68,117.76
Cost of Fuel/year	$146,327	$136,236
MW-Hour Produced	8,410	8,410
Fuel Cost/MW-hour	$17.40	$13.20
Value of Power Produced	$588,672	$588,672
Net Revenue (Fuel Cost vs Power Produced)	$442,345	$452,436

2.23% revenue advantage

Figure 2: Revenue improvement with same capacity factor, different engine efficiency.

Now for the same two units, assume that electrical efficiency is the same at 42 percent, but that Unit A’s availability is 90 percent and Unit B’s is 96 percent. In this scenario, the more available Unit B has a 6.25 percent revenue advantage (Figure 15).

Same Efficiency, Different Capacity Factor

	UNIT A	UNIT B
Generator set kW	1000	1000
Gas Price $/mmbtu	$ 2.00	$2.00
Value of Energy Produced $/MW-hr	$70.00	$70.00
Generator Efficiency	97.0%	97.0%
Engine Heat Rate BTU/min	135,000	135,000
Capacity Factor	96.0%	90.%
Generator Set Electrical Efficiency	42.1%	42.1%
Fuel Consumed/year mmbtu	68,117.76	63,860.40
Cost of Fuel/year	$136,236	$127,721
MW-Hour Produced	8,410	7,884
Fuel Cost/MW-hour	$16.20	$16.20
Value of Power Produced	$588,672	$551,880
Net Revenue (Fuel Cost vs Power Produced)	$452,436	$424,159

6.25% revenue advantage

Figure 3: Revenue improvement with same engine efficiency, different capacity factor. Better efficiency does not always equal better revenue.

This fact argues forcefully for selecting power generation equipment with a proven track record for reliability and with design characteristics that extend routine maintenance intervals, thus reducing annual scheduled downtime. Additionally, any rotating equipment requires preventive maintenance and will certainly see unplanned shutdowns during its service life. It is therefore paramount to ensure that qualified service technicians and service/repair parts are available locally. For projects that required continuous operations (e.g. 8,000 hours per year) with high availability, a well-structured product support and maintenance program is required. Appropriate parts must be stocked at all levels – by the client on site, by the equipment manufacturer’s’ local distributor or dealer, by the manufacturer's regional warehouses, and by the manufacturer’s main centralized depot.

Service references
SEBU6400-05
SEBU8554-03
SEBU7681-17

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