LANDFILL GAS TO VEHICLE FUEL: ASSESSMENT OF ITS TECHNICAL AND ECONOMIC FEASIBILITY

Jeffrey L. Pierce
SCS Energy
Long Beach, California

ABSTRACT

One of the more interesting potential uses for landfill gas (LFG) is the production of vehicle fuel. LFG can be used to produce a compressed natural gas (CNG) or a liquefied natural gas (LNG) equivalent. CNG or LNG can be used to: 1) fuel vehicles at the landfill (water trucks, earthmoving equipment, light trucks, autos, etc.); 2) refuse hauling trucks (long haul refuse transfer trailers and route collection trucks); and 3) supply the general commercial market.

The paper will discuss: 1) technology; 2) performance; 3) LFG supply issues; 4) fuel quality issues; and 5) economics.

GAS FUELS VERSUS LIQUID FUELS

Liquid fuel currently dominates the vehicle fuel market. Diesel and gasoline are the liquid fuels now in use. Diesel is generally used to fuel buses, heavy duty trucks and heavy equipment. Gasoline is generally used in automobiles, vans and light trucks. Diesel is sometimes used in light trucks, vans and automobiles.

Gas fuels are beginning to displace liquid fuels. Gas fuels include compressed natural gas (CNG) and liquefied natural gas (LNG). Gas vehicles burn fuel in a gaseous state and require a pressure of 75 psig to 125 psig. If CNG is stored on the vehicle, its storage pressure is typically 3,000 psig. Its pressure is reduced prior to delivery into the engine. If LNG is stored on the vehicle, it is stored at 75 psig to 125 psig and the LNG is vaporized prior to delivery to the engine. The performance of the engine is indifferent to whether the gas being used is supplied by CNG or LNG.

The principal advantage of gas fuels versus liquid fuels is in the area of air emissions. Gas fuels have lower air emissions. The actual reduction in air emissions depends on whether the displaced fuel is gasoline or diesel and on the specific engine the comparison is based upon. Typical air emission reductions that can be expected for gas fuels versus diesel fuel are as follows:

TABLE 1
TYPICAL AIR EMISSION REDUCTIONS

Air Pollutant	Reduction
Nitrogen Oxides (NO_x)	60% to 85%
Particulates	60% to 80%
Carbon Monoxide (CO)	10% to 70%
Non-Methane Organic Compounds (NMOC)	10% to 85%

Gas fuels have benefits beyond reductions in air emissions. Natural gas is less expensive than liquid fuel (on an energy content basis). To some extent this is due to taxation policies; however, natural gas is generally less expensive than liquid fuels prior to tax. Gas fuels are arguably safer than liquid fuels since gas fuels are carried in stronger tanks, have a higher ignition temperature, have a higher lower flammability limit, and will dissipate to the atmosphere rather than stay on the ground.

Some proponents of gas fuels argue that gas fuels lower long-term engine maintenance costs; however, limited information is presently available in support of this claim.

The principal drawbacks to gaseous fuels are as follows:

- The engines are more expensive; and
- Liquid fuels are more readily available.

Liquid fuels can be purchased virtually anywhere. Gas fuels fueling stations are difficult to find. Gas

fuels have made its greatest inroads in the fleet market (buses, taxis, etc.) where the fleet owner can establish his own fueling network.

LNG VERSUS CNG

The principal advantage of LNG over CNG is that it has a higher "energy density." The same volume of LNG has 3.5 times the energy as CNG. The benefit is, of course, that much less volume is required to store an equivalent amount of energy as LNG. The reduction in volume has three benefits: 1) vehicles using LNG require less volume for on board fuel storage; 2) it is less expensive to store LNG than CNG at the point of production and at remote distribution stations; and 3) it is less expensive to transport LNG than CNG from the point of production to remote distribution stations. The characteristics of the currently available vehicle fuels are as follows:

TABLE 2
VEHICLE FUEL CHARACTERISTICS

	Gasoline	Diesel	CNG	LNG
Btu/ft^3	16,710	18,980	3,230	11,310
Btu/gal	125,000	142,000	24,160	84,570
Btu/lb	20,000	19,410	23,890	23,890

Note: CNG as a gas at 3,000 psig. Other fuels as liquids.

Because of its greater energy density, LNG is more often employed for larger, heavy use vehicles. LNG is sometimes transported to fuel distribution stations where it is vaporized and pressurized to CNG. LNG can be delivered in tank trucks containing 2,000 to 10,000 gallons. CNG must be transported in tube trailers which can carry a maximum of 100,000 standard cubic feet of CNG.

Given the advantages of LNG, why is more CNG in use than LNG? LNG costs more to produce. CNG requires only equipment and energy to compress natural gas. LNG requires equipment and energy to liquefy natural gas. The compression equipment required to produce CNC is relatively inexpensive and simple, and it can easily scale down to small production rates. The problem of transportation of CNC to the point of use is mitigated by the ubiquity of natural gas distribution piping in the United States. Natural gas can be compressed at its point of use.

LANDFILL GAS AND GAS FUEL QUALITY ISSUES

The principal component of landfill gas (LFG) is methane. The principal component of CNG and LNG is methane. For this reason, LFG can provide a feedstock for CNG and LNG production.

Typical LFG composition is as follows:

TABLE 3
TYPICAL LFG COMPOSITION

Component	Range
Methane	35% to 55%
Carbon Dioxide	20% to 45%
Oxygen	0.5% to 5%
Nitrogen	2% to 45%
Carbon Monoxide	<10 ppmv
Hydrogen Sulfide	20 to 500 ppmv
Non-Methane Organic Compounds	200 to 2000 ppmv

Pure LFG has a methane content in the range of 55 percent to 57 percent, and contains virtually no oxygen or nitrogen. Oxygen and nitrogen are introduced into LFG by air drawn into the landfill during LFG's extraction from decomposing refuse and/or due to air leakage into LFG collection piping.

Fuel quality standards governing gas fuels are set by regulatory agencies such as the California Air Resources Control Board (CARB) or by independent organizations such as the Society of Automotive Engineers (SAE). It is necessary for gas fuels produced from LFG to satisfy gas fuels standards in order for LFG-derived fuels to be considered interchangeable with gas fuels. CARB[1] standards as follows:

TABLE 4
CARB STANDARDS

Methane	$\geq$ 88%
Ethane (C2)	$\leq$ 6%
C3 and higher	$\leq$ 3%
C6 and higher	$\leq$ 0.2%
Hydrogen	$\leq$ 0.1%
Oxygen	$\leq$ 1%
Carbon Monoxide	$\leq$ 0.1%
Inert Gas ($CO_2 + N_2$)	$\leq$ 4.5%
Sulfur	$\leq$ 16 ppm

[1]California Code of Regulations, Title 13, Division 3, Chapter 5, Article 3 (Specifications for Alternate Motor Vehicle Fuels).

Water content is controlled by a dewpoint temperature standard. The dewpoint at vehicle fuel storage container pressure is to be at least 10° F below the 99.99 percent winter ambient air temperature for the region.

Methane contents of 95 percent to 97 percent are generally expected by engine manufacturers and 88 percent should be considered the absolutely minimum acceptable methane percentage. It is also important to consider market perception. LFG-produced CNG and LNG is competing against high methane content CNG and LNG produced from "real" natural gas.

Landfill gas contains low levels of ethane and C2+ compounds, low levels of hydrogen and low levels of carbon monoxide; thus, the CARB standards for these compounds are easily satisfied. The virtual lack of ethane and C2+ compounds in LFG-derived CNG and LNG benefits engine performance, and in this regard, LFG-derived CNG and LNG are better fuels than gas fuels from natural gas.

The challenge in converting LFG to CNG and LNG is to reduce carbon dioxide, moisture, nitrogen, and oxygen to relatively low levels.

The gas fuels specification does not address other trace compounds present in LFG which may cause problems in engines, including siloxanes and chlorinated non-methane organic compounds (NMOC's). Based on reciprocating engine experience in LFG-fired electric power generation, it would be prudent to remove these substances, even if not required by published gas fuels specification.

CONVERSION OF LANDFILL GAS TO CNG

The principal task in converting LFG to CNG is to increase its methane content or, conversely, to reduce its carbon dioxide, nitrogen and oxygen content. Three methods have been commercially employed in the United States (i.e., beyond pilot testing), to remove carbon dioxide from LFG:

- Membrane separation;
- Molecular sieve; and
- Amine scrubbing.

There is only one LFG to CNG conversion plant now operating in the United States. It is located in Los Angeles. It employs membrane separation. SCS Energy (SCS) is currently installing a small membrane separation vehicle fuel project in Sonoma County, California. There are three other membrane separation plants operating in the United States which convert LFG to pipeline quality gas. Two projects are currently operating, which produce high-Btu gas from pipeline quality gas, which employ molecular sieve technology. Four other pipeline sale projects employ amine scrubbing. The product gas specifications governing pipeline gas sale are similar to those governing CNG.

All three of the above methods are focused on carbon dioxide removal, and do not remove oxygen and nitrogen. The oxygen and nitrogen limitations of the fuel specification must be satisfied by wellfield operation and design. Air intrusion into the wellfield must be minimized. In some instances, this may require that LFG from interior wells be directly sent to the vehicle fuel plant, and that LFG from perimeter wells be sent to another outlet for use or disposal.

Membranes can achieve some incidental oxygen removal, but nitrogen is not removed, and nitrogen represents the bulk of the non-methane/non-carbon dioxide fraction of landfill gas. A molecular sieve can be configured to remove nitrogen by proper selection of media. Nitrogen removal, in addition to carbon dioxide removal, would require a two-stage molecular sieve. Another name for molecular sieve technology is pressure swing adsorption (PSA).

Selexol has been the most common amine used in LFG service. A typical Selexol-based plant employs the following steps:

- Landfill gas compression (using electric drive, LFG fired engine drive, or product gas fired engine drive);
- Moisture removal (using refrigeration);
- Hydrogen sulfide removal in a solid media bed (using an iron sponge or a proprietary media (such as Sulfatreat) ;
- NMOC removal in a primary Selexol absorber; and
- Carbon dioxide removal in a secondary Selexol absorber.

In the Selexol absorber tower, the LFG is placed in intimate contact with the Selexol liquid. Selexol is a physical solvent which preferentially absorbs gases into the liquid phase. NMOC's are generally hundreds to thousands of times more soluble than methane. Carbon dioxide is about 15 more times soluble than methane. Solubility is also enhanced

with pressure. The above principles are exploited to remove NMOC's and carbon dioxide from the landfill gas to yield a purified methane stream. The Selexol vessels operate at pressures in the range of 500 psi. The Selexol liquid is regenerated by lowering its pressure (flashing) and then running air through the depressurized Selexol to strip off the NMOC's and carbon dioxide. The stripper air from the NMOC removal step is normally sent to a thermal oxidizer where all or part of the thermal energy required to support combustion is supplied by the NMOC's and methane in the stripper air. The stripper air from the carbon dioxide removal step is normally vented to the atmosphere.

A typical molecular sieve plant employs the above-described compression, moisture removal and hydrogen sulfide removal steps, but relies on vapor phase activated carbon and a molecular sieve for NMOC and carbon dioxide removal, respectively. The activated carbon removes NMOC's and protects the molecular sieve. The molecular sieve is a vessel which contains a media which preferentially adsorbs certain molecules (in this case, carbon dioxide) when contacted with a gas stream which is under pressure. When the media is exhausted, the vessel is brought offline and is regenerated through a depressurization and purge cycle. The activated carbon can also be regenerated on site through a depressurization, heating and purge cycle. The process is known as thermal swing adsorption. The purge streams are generally disposed of in a thermal oxidizer. The thermal oxidizer generally requires some supplemental energy which can be provided by LFG or product gas.

A typical membrane plant employs the above-described compression, moisture removal and hydrogen sulfide removal steps, but relies upon activated carbon and membranes for NMOC and carbon dioxide removal, respectively. Activated carbon removes NMOC's and protects the membranes. The membrane process exploits the fact that gases, under the same conditions, will pass through polymeric membranes at differing rates. A "fast" or highly permeable gas such as carbon dioxide will pass through a membrane approximately 20 times faster than a "slow" or less permeable gas such as methane. Pressure is the driving force for the separation process. The feed gas (LFG) and product gas (predominantly methane) enter and exit the membrane modules at approximately the same pressure. The permeate gas (predominantly carbon dioxide) exits at a lower pressure. The operating pressures, number of membrane stages in the series, and provisions for gas recycle depends on desired methane recovery percentage and desired product gas methane purity. In natural gas processing applications, both methane recovery percentage and desired product gas methane purity are highly important. In LFG applications, product gas methane purity is of importance; however, methane recovery as a percentage of methane in the raw LFG is of less importance. The membrane configuration employed for an LFG utilization project should strike the optimal balance between capital cost and methane recovery. The activated carbon regeneration stream and the reject carbon dioxide stream from the membranes are typically directed to a thermal oxidizer for disposal.

Early membrane plants used "high" pressure membranes. Newer plants are using "low" pressure membranes. The current generation of membrane plants use a combination of an NMOC-selective, molecular sieve, coupled with non-regenerative activated carbon polishing, instead of thermal swing adsorption.

The membrane process and the molecular sieve process scales down more economically to smaller sized plants, and for this reason these technologies are more likely to be used for CNG production than Selexol.

The Los Angeles County Sanitation District (LACSD) owns the only operating LFG to CNG facility in the United States. The LACSD facility is located at their Puente Hills Landfill in Whittier, California, and has been in operation for over ten years. It converts an inlet flow of 250 scfm at 55 percent methane to 100 scfm of CNG at 96 percent methane. The product is equal to about 1,000 gallons of gasoline equivalent (GGE) per day. While the facility is rather small from an LFG perspective, it is significant from a vehicle fuel perspective. At a fuel economy of 20 miles per gallon, this facility could support 20,000 trip miles per day. If a fleet vehicle traveled 200 trip miles per day, the LACSD facility could support 100 vehicles. About 70 percent of the methane in the landfill gas is converted to product CNG, with about 30 percent of the methane lost in the waste gas stream. Higher methane recoveries would be possible with a more expensive membrane configuration. A 30 percent loss of feedstock would be unacceptable in other industries; however, LFG is a low or no cost feedstock and relatively poor methane recovery is an acceptable trade-off for lower construction costs. LACSD's experience with the operation of the Puente Hills facility and their

experience with vehicles running on CNG has been summarized in two papers by Wheless, et. al.[2] [3] LACSD considers the CNG project to be a technical success.

The process chain for CNG production at Puente Hills is as follows:

- Landfill gas compression and moisture removal. Compression is undertaken in multiple stages to reach 525 psi;
- Vapor phase activated carbon;
- Gas heating to 140° F;
- Three stages of membrane separation;
- Multi-stage compression of the product gas to 3,600 psi;
- Compressed gas storage facilities; and
- A fuel dispenser to dispense 3,000 psi CNG.

The permeate gas (waste gas) from the first stage and part of the gas from the second stage of membranes contains 25 to 30 percent methane and is blended with other LFG now being fired in a steam cycle power plant, which is located on-site and which pre-existed the CNG facility. At a typical CNG installation, the waste gas would be flared. The permeate gas from part of the second stage and the third stage membrane is relatively rich in methane (about 80 percent) and is recycled back to the inlet of the LFG compressors. The activated carbon is regenerated on-site.

The construction cost of the Puente Hills CNG facility was $1.8 million (cost escalated to 2007 dollars). The Puente Hills project is a relatively small demonstration project, and its costs are not representative of a larger project. Wheless, et. al estimates the total cost of CNG production for a membrane facility to be as follows:

TABLE 5
COST OF CNG PRODUCTION

Inlet LFG (scfm)	Plant Size (GGE/day)	Cost ($/GGE)
250	1,000	$1.40
500	2,000	$1.13
1,250	5,000	$0.91
2,500	10,000	$0.82
5,000	20,000	$0.68

Note: Wheless' costs escalated to 2007 dollars. GGE means gallons of gasoline equivalent.

In a recently completed feasibility study, SCS estimated the capital cost of a 900 scfm LFG inlet LFG to LNG membrane plant to be $3.2 million, and the "all in" cost of CNG production (i.e., capital plus operation/maintenance cost) to be $6.60/mmBtu or $0.85/GGE.

4.2

CONVERSION OF LANDFILL GAS TO LNG

If LFG is first converted to CNG, it could then be liquefied to produce LNG using conventional natural gas liquefaction technology; however, there are two considerations that must be addressed if this approach is employed. The first is that carbon dioxide freezes at a temperature higher than methane liquefies. To avoid "icing" in the plant, the product CNG must have as low a level of carbon dioxide as possible. This preference would favor the molecular sieve over the membrane process or to at least favor polishing the membrane product gas with a molecular sieve.

The second consideration is that natural gas liquefaction plants have generally been "design to order" facilities which process large quantities of LNG. Smaller, pre-packaged liquefaction plants have begun to be offered by a few manufacturers. Even these "small" plants have design capacities of 10,000 gal/day or greater.

The inlet LFG to the LFG to product gas step must have a very low nitrogen and oxygen content. If the LFG does not have a very low nitrogen and oxygen content it will be necessary to add nitrogen and oxygen removal steps to the process chain. Liquefier manufacturers have advised SCS that they desire an inlet gas to the liquefier having less than 0.5 percent oxygen, citing an explosion concern, present in the cold box, when oxygen is in excess of 0.5 percent. The need to limit nitrogen in the inlet LFG is driven

[2]Processing and Utilization of Landfill Gas as a Clean Alternative Vehicle Fuel, SWANA 17th Annual Landfill Gas Symposium, March 22-24, 1994, Long Beach, California, USA.
[3]Converting Landfill Gas to Vehicle Fuel: The Results of Over 30 Months of Operation, SWANA 19th Annual Landfill Gas Symposium, March 19-21, 1996, Research Triangle Park, North Carolina, USA.

by the desire to achieve a minimum LNG methane content of 96 percent.

In a recent feasibility study, SCS estimated the "all in" cost of LNG production to be $0.65/gallon for a plant producing 15,000 gallons/day of LNG. It should be noted that a 15,000 gallon per day facility would be an unusually large LFG to LNG project. It would require about 3,000 scfm of LFG and would involve a capital investment approaching $20 million. The sale of 15,000 gallons per day of LNG in most market areas in the United States would also represent a challenge. The loss of economy of scale in downsizing to 5,000 gallons per day would probably increase the "all in" cost to the vicinity of $0.90/gallon. Under certain circumstances, and for a limited time, a tax credit may be available to support LNG projects.

At least one equipment supplier, Prometheus Energy Company, has targeted the LFG to LNG market, using a proprietary process chain. They have recently installed a facility at Frank R. Bowerman Landfill in southern California. Prometheus is delivering a paper in this same session, and they are expected to report on the initial operating experience of this full-scale facility. Prometheus may be able to lower the price of production below $0.90/gallon at the smaller facility sizes required at a typical landfill.

CONCLUSION

LFG can be, and has been, successfully converted to CNG. Membrane or molecular sieve technology can be employed, and in SCS's opinion, neither technology offers a clear advantage over the other. CNG produced from LFG can compete economically with liquid fuels. A commercial-scale facility (inlet capacity over 1,000 scfm) can compete with CNG produced from natural gas at today's natural gas prices.

At this point, it is not clear if LFG to LNG is commercially practical. The Frank R. Bowerman facility should answer this question.