AIR EMISSIONS FROM LANDFILL GAS FIRED ELECTRIC POWER GENERATION FACILITIES PAST, PRESENT AND FUTURE

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INTRODUCTION

In November 1992, the author published a paper titled "Air Emissions at Landfill Gas Fired Electric Power Generation Facilities." The paper summarized what was then Best Available Control Technology (BACT) for reciprocating engines, combustion turbines and steam cycle power plants. The 1992 paper provides a convenient historic benchmark for the paper which follows. The paper which follows will discuss historic trends in BACT, current BACT and where BACT may be headed in the future.

While not particularly relevant to the current paper, the 1992 paper made several interesting observations on the state of the landfill gas fired power generation industry at that time. There were about 85 operating landfill gas fired power plants in the United States. At the present time, there are about 250 operating landfill gas fired power plants. The 1992 paper pre-dated the "European invasion" into the landfill gas power generation market. Caterpillar, Superior and Waukesha engines were employed at virtually every reciprocating engine installation. Superior is no longer in the business, and Waukesha has a limited market presence. Jenbacher and Deutz now compete with Caterpillar for the landfill gas fired reciprocating engine market. In 1992, Solar Turbines dominated the landfill gas fired combustion turbine market, as they do today. The 1992 paper mentioned that siloxane was an issue of concern with both landfill gas and digester gas. The paper made the observation that combustion of siloxane compounds could form silicon dioxide, and render emission control post-combustion catalyst systems inoperable after very short periods of operation. It is believed that the 1992 paper is one of the earliest papers citing siloxane as a potential problem for landfill gas fired power generation.

POWER GENERATION TECHNOLOGIES

Reciprocating engines currently dominate the landfill gas to energy market, both on an installed capacity basis, and on a new orders basis. Important engines currently being deployed include:

- Caterpillar -- 3516 (820 kW); 3520 (1,600 kW); and 3516 (3,050 kW);
- Jenbacher -- 320 (970 kW); and 620 (2,400 kW); and
- Deutz -- TBG 620 V16 (1,360 kW).

Combustion turbines most frequently being deployed include the following machines manufactured by Solar Turbines:

- Taurus -- 5,600 kW; and
- Centaur -- 3,500 kW.

The Solar Saturn (1,200 kW) is still available, but is not being ordered for use in the landfill gas market. Solar is currently planning on introducing its high-efficiency Mercury (4,600 kW) into the landfill gas market.

The author is aware of six landfill gas steam cycle power plants currently in operation in the United States. The last one was built in 1993.

The only new power generation technology to be commercially deployed for landfill gas service over the last fourteen years is the microturbine. There are about a dozen landfill gas fired projects currently operating in the United States. Available microturbines include:

- Capstone -- 30 kW and 60 kW; and
- Ingersoll-Rand -- 70 kW and 250 kW.

AIR POLLUTANTS OF CONCERN

In general, air quality regulatory agencies are concerned with five conventional pollutants, which are also called criteria pollutants:

- Nitrogen Oxide (NO_x);
- Carbon Monoxide (CO);
- Volatile Organic Compounds (VOCs);
- Particulates (PM); and
- Sulfur Oxides (SO_x).

The terms VOCs, NMOCs (non-methane organic compounds), NMHCs (non-methane hydrocarbons) and ROGs (reactive organic gases) are used somewhat interchangeably in the regulatory world, and for purposes of this paper, it is not particularly important to dwell on the slight differences in definitions between these terms. Suffice it to say that NMOCs and NMHCs are virtually the same, and VOCs and ROGs are close to being the same. VOCs and ROGs are a subset of NMOCs and NMHCs. The difference between the two groups is that the latter group excludes certain compounds (such as ethane) which are relatively non-reactive (e.g., do not contribute to ozone formation in the atmosphere).

NO_x is the obsession of most regulatory agencies. NO_x and VOCs photochemically react to form ozone in the atmosphere. Ozone is the principal compound causing non-attainment in air districts in the United States. Non-attainment classifications vary from "extreme" non-attainment to "marginal" non-attainment. Ozone problems are not specific to the area where the air emissions are sourced. Ozone can be transported hundreds of miles with the prevailing wind. NO_x is generally present in the form of NO_2. NO_2 is the major contributor to the brown haze seen in urban areas. Ozone and NO_x are generally of greatest concern to air regulators, even when an area is in attainment for ozone. NO_x, rather than VOCs, have been targeted for more strict control, despite the fact that both contribute to ozone formation. NO_x is generally emitted in much larger quantities.

CO is extremely dangerous and is deadly in relatively low concentrations in confined areas. Its public health implications in very low concentrations in ambient air are not quite as clear, but many urban areas are in non-attainment for CO, particularly in the winter months. Concern over CO has led to the requirement to oxygenate gasoline, both year round or seasonally, through the addition of ethanol or MTBE. MTBE has, of course, been implicated in groundwater contamination, and is being phased out. Over the last three years, SCS has seen air regulators placing a much higher emphasis on CO control. The simultaneous emphases on NO_x and CO is a problem since NO_x and CO are inversely related in combustion. As combustion is tuned to lower NO_x, CO increases, and vice versa. The NO_x/CO relationship makes clear theoretical sense. If you tune a system to reduce oxidization of N_2 to NO_x, you will generally have the undesired consequence of making it more difficult to complete the oxidization of methane (CH_4) to carbon dioxide (CO_2). More of the carbon stops at carbon monoxide (CO).

An issue with VOCs, unique to landfill gas fired power generation, is the impact of NSPS Subpart WWW. A landfill gas control device (flare or engine) must achieve either a 98 percent reduction in NMOCs or emit less than 20 ppmv as hexane (at three percent O_2). While the landfill gas "treatment exemption" can provide a work around to prevent the imposition of NSPS Subpart WWW on power generation equipment, this does not prevent an air regulator from proposing this same limit on the power generation equipment, using his general regulatory authority.

Particulate and SO_x emissions are generally viewed as being out of the control of landfill gas fired combustion technologies. Sulfur, in the landfill gas, will be oxidized to SO_x (SO_2 and small amounts of SO_3). The prevalent form of sulfur in landfill gas is hydrogen sulfide (H_2S). H_2S generally accounts for more than 85 percent of the sulfur in landfill gas. If SO_2 must be controlled, it must be removed from the landfill gas prior to combustion using non-regenerative and regenerative technologies (iron sponge, SulfaTreat or LO-CAT). SO_x is an air quality concern because it contributes to acid rain, and because locally SO_x can react with other compounds in the atmosphere to form particulates. To the author's knowledge, there are no air districts or regions in the United States which are in non-attainment for SO_x.

Very few air districts or regions are in non-attainment for particulates; however, there are some districts or regions where naturally occurring particulates, and smoke from woodburning fireplaces and stoves are causes of non-attainment for particulates. The particulate concentration in raw landfill gas is very low, and some particulate removal is achieved in landfill gas moisture removal, which usually involves application of a coalescing filter. Inert particulates pass through combustion without a change in mass. Organic particulates may be somewhat reduced in mass by combustion, and small quantities of particulate can be added to the exhaust by the combustion of siloxane compounds.

Since SO_x and particulates are beyond the control of the power generation equipment itself, and since most air regulators accept air emissions for particulates and SO_x "as proposed," in air permit applications, neither particulate nor SO_x will be discussed herein.

BEST AVAILABLE CONTROL TECHNOLOGY (BACT)

Reciprocating Engines

Table 1 lists what the author felt represented BACT for landfill gas fired reciprocating engines in 1992.

TABLE 1
BACT FOR RECIPROCATING ENGINES IN 1992

Parameter	Gross Power Output		Net Power Output
NO_x	1.5 g/bhp-hr	0.41 lbs/mmBtu	4.62 lbs/MWh
CO	2.7 g/bhp-hr	0.74 lbs/mmBtu	8.34 lbs/MWh
NMOC	0.5 g/bhp-hr	0.14 lbs/mmBtu	1.58 lbs/MWh

Notes:

1) The lbs/mmBtu conversions assume a gross heat rate of 10,800 Btu/kWh (HHV).
2) The lbs/MWh conversion assumes a generator efficiency of 96% and a parasitic load of 7%.

In the mid 1990's, NO_x had worked its way down to 1.0 g/bhp-hr to 1.2 g/bhp-hr in California, but some air regulators in other parts of the United States were accepting 1.0 g/bhp-hr as late as 2003. California air districts began routinely permitting engines at 0.6 g/bhp-hr in 1998, and at this point in time, 0.6 g/bhp-hr is widely recognized as BACT. NO_x emissions have been reduced by about 60 percent over the last fourteen years.

Caterpillar has been guaranteeing 0.5 g/bhp-hr on its recently introduced 3520. Jenbacher, for one, appears to be ready to match that number; however, as will be discussed below, a simultaneously tight CO limit can prevent 0.5 g/bhp-hr, or even 0.6 g/bhp-hr, from being reliably achieved.

It appears as if 0.5 g/bhp-hr may be the limit achievable through engine combustion controls alone. Post-combustion NO_x reduction through the application of urea-based, selective catalytic reduction (SCR) is a proven technology for natural gas fired engines. In such applications, the engine's raw NO_x emissions are typically 1.0 to 1.3 g/bhp-hr, and the SCR is added to achieve a 90 percent reduction in NO_x. The final NO_x emission rate is in the range of 0.1 to 0.2 g/bhp-hr. Uncontrolled NO_x emissions are lower, when an engine is fired on landfill gas, than when fired on natural gas. Natural gas engines are also frequently fitted with an oxidization catalyst to achieve a 75 percent reduction in CO. Final CO emissions are in the range of 0.2 g/bhp-hr. Because of the issue of catalyst blinding, the landfill gas utilization industry has successfully avoided having SCR and oxidizing catalysts established as BACT.

At the present time, there is at least one project with an air permit application pending which proposes to install SCR after a landfill gas fired reciprocating engine. It is a fairly large project, and the project developer has proposed to push the technology limit to keep his total NO_x emissions in tons/year below a limit that would trigger New Source Review (NSR). The project will incorporate a landfill gas treatment train which will remove virtually all sulfur, siloxanes, and halogens. A contaminant-free gas is required to protect the post-combustion catalyst. The capital and operation/maintenance costs of the entire pre- and post-combustion facilities will significantly increase the cost of power production. While this project may be able to absorb this financial impact, very few landfill gas fired projects could afford this impact. If this project is constructed and is successful, it will establish SCR as BACT for landfill gas fired applications.

CO is an even more immediate problem for reciprocating engines. CO was routinely permitted at 2.5 g/bhp-hr to 3.0 g/bhp-hr up until two years ago. It appears as if air regulators acknowledged that NO_x and CO could not be lowered simultaneously. It has been difficult to find an engine manufacturer who will simultaneously stand behind NO_x at 0.6 g/bhp-hr and CO at 2.5 g/bhp-hr. Despite the difficulty of getting a 2.5 g/bhp-hr guarantee, air regulators in many jurisdictions have been pushing for 2.0 g/bhp-hr, based on actual air emissions data from a handful of sites. SCS successfully permitted a project in California in 2004 and in Pennsylvania in 2005 at 2.5 g/bhp-hr, after a long battle with regulators. While project developers were able to live with weak guarantees from engine suppliers for 2.5 g/bhp-hr, they cannot accept permits written at 2.0 g/bhp-hr -- where no manufacturer guarantee is available, and there is little hope of meeting 2.0 g/bhp-hr.

Two post-combustion technologies are currently available to drive CO below 2.5 g/bhp-hr -- an oxidizing catalyst and Jenbacher's Cl.AIR process. The latter process relies on elevating the temperature of the engine exhaust and by providing increased detention time to encourage more complete conversion of CO to CO_2. One project in California has received a permit for construction, and has installed, a post-combustion oxidizing catalyst. The permitted CO level is 0.33 g/bhp-hr. The permitted VOC and NO_x levels are 0.15 g/bhp-hr, and 0.53 g/bhp-hr, respectively. The project developer agreed to add post-combustion control to break the permitting obstacle imposed by the air regulator's insistence on 2.0 g/bhp-hr. The addition of post-combustion CO control introduces the same questions as post-combustion NO_x control -- "will it work?" and "will the added cost kill the project?"

As has often been the case, since the beginning of the concept of BACT, BACT is driven by a single party, making a desperate attempt to solve a problem that is preventing his project from proceeding.

VOC emissions have been relatively unchanged over the last fourteen years, with permits being routinely written in the 0.5 to 1.0 g/bhp-hr range. Like CO, VOCs tend to be inversely related to NO_x emissions. The comparative lack of focus on VOCs might be attributable to:

- Air regulators continuing to accept the VOC to NO_x tradeoff, as they at one time had accepted for CO; and
- Realization that NO_x and VOCs are tied to atmospheric ozone formation, and that regulators have elected to preferentially emphasize NO_x over VOCs; or

More and more, air regulators are defaulting to the 98 percent destruction or 20 ppmv NSPS Subpart WWW limit to govern NMOCs. Landfill gas that would otherwise be flared is subject to this same limit. Unlike NO_x and CO, there is a zero net gain in VOCs (NMOCs), between a flare and an engine, and the regulators should be indifferent to where the landfill gas is burned. As a point of reference, 20 ppmv (as hexane) is roughly equivalent to 0.15 to 0.20 g/bhp-hr. The variability is due to the variation in engine heat rate and air-to-fuel ratio.

Combustion Turbines

Table 2 lists what the author felt to be BACT for landfill gas fired combustion turbines in 1992:

TABLE 2
BACT FOR COMBUSTION TURBINES IN 1992

Parameter	As-Fired	Net Power Output
NO_x	0.12 lbs/mmBtu	1.91 lbs/MWh
CO	0.11 lbs/mmBtu	1.75 lbs/MWh
NMOC	0.005 lbs/mmBtu	0.08 lbs/MWh

Notes:

1) The lbs/MWh conversion assumes a gross heat rate of 13,500 Btu/kWh (HHV) and a parasitic load of 15%.

BACT for NO_x, CO and NMOCs are currently as follows, based on recently approved air permits:

TABLE 3
CURRENT BACT FOR COMBUSTION TURBINES

Parameter	ppmv @ 15% O_2	As-Fired	Net Power Output
NO_x	25	0.07 lbs/mmBtu	1.11 lbs/MWh
CO	130	0.29 lbs/mmBtu	4.62 lbs/MWh
NMOC	20	0.025 lbs/mmBtu	0.40 lbs/MWH

Notes:

1) The lbs/MWh conversion assumes a gross heat rate of 13,500 Btu/kWh (HHV) and a parasitic load of 15%.

It appears as if regulators are willing to accept higher CO and NMOC emissions in exchange for lower NO_x emissions. Alternatively, the author may have somewhat "over committed" on CO and NMOCs in his 1992 paper.

Steam Cycle Power Plants

Table 4 lists what the author felt to be BACT for landfill gas fired steam cycle power plants in 1992:

TABLE 4
BACT FOR STEAM CYCLE POWER PLANTS IN 1992

Parameter	Gross Power Output	Net Power Output
NO_x	0.03 lbs/mmBtu	0.36 lbs/MWh
CO	0.01 lbs/mmBtu	0.12 lbs/MWh
NMOC	0.005 lbs/mmBtu	0.06 lbs/MWh

Notes:

1) The lbs/MWh conversion assumes a gross heat rate of 11,000 Btu/kWh (HHV) and a parasitic load of 7%.

Since no new steam cycle power plants have been permitted and built since 1993, the above values still represent BACT. The NO_x control technology employed by steam cycle power plants was low NO_x burners and recycle flue gas. Steam cycle power plants have the lowest air emissions of any of the three traditional power generation technologies.

Microturbines

Microturbines did not exist in 1992, and a 1992 benchmark does not exist. SCS installed the first commercial landfill gas fired microturbine power plant in 2001, and has designed or installed a total of ten other facilities since that time.

Recent air emissions test results for six microturbine installations are shown on Table 5.

TABLE 5
AIR EMISSIONS FROM MICROTURBINE POWER PLANTS

	Gross Power Output (lbs/mmBtu)			Net Power Output (lbs/MWh)		
Parameter	**Average**	**Max.**	**Min.**	**Average**	**Max.**	**Min.**
NO_x	0.0145	0.0237	0.0050	0.230	0.376	0.079
CO	0.0246	0.0473	0.0050	0.391	0.751	0.079
NMOC	0.0240	0.0465	0.0121	0.381	0.739	0.192

Notes:

1) The lbs/MWh conversion assumes a gross heat rate of 13,500 Btu/kWh (HHV) and a parasitic load of 15%.

OLD DOG LEARNS NEW TRICKS

The Penrose Power Station, located in Sun Valley, California, currently employs four Cooper Superior 16SGTA reciprocating engines. The engines were originally placed in service in May 1986. The nameplate capacity of each engine is 1,875 kW. SCS Energy operates and maintains this landfill gas fired power plant. South Coast Air Quality Management District (SCAQMD) Rule 1110.2 retroactively imposed more stringent NO_x emission standards on existing reciprocating engines, effective December 31, 2004. Working under the protection of an SCAQMD variance, granted by SCAQMD's Hearing Board, SCS Energy installed larger turbochargers; rebuilt the engines; installed, commissioned and tested a continuous emissions monitoring system; supervised installation of a new engine control system; and commissioned and tested the new engine control system. The new engine control system was supplied by Enginuity of Fort Collins, Colorado. Pre- and post-conversion emission test results are shown on Table 6.

The engine upgrade program at Penrose Power Station successfully brought 20-year old engines in compliance with current BACT.

TABLE 6
PRE- AND POST-CONVERSION AIR EMISSIONS FOR COOPER SUPERIOR 16STGA ENGINES

	Pre-Conversion	**Post-Conversion**
NO_x		
ppmv @ 15% O_2	68.4	25.2
lbs/mmBtu	0.33	0.12
g/bhp-hr	1.17	0.46
CO		
ppmv @ 15% O_2	99.9	152.3
lbs/mmBtu	0.46	0.59
g/bhp-hr	1.65	2.27
NMOC		
ppmv as hexane @ 3% O_2	12.39	14.3
lbs/mmBtu	0.04	0.04
g/bhp-hr	0.14	0.15

Notes:

1) Average of triplicate testing of all four engines.
2) All testing at 94% to 100% of engine full power.

GENERAL COMMENTS ON BACT

As can been seen in the foregoing discussion, BACT emissions vary greatly with technology. BACT is technology specific, not purpose specific. As of today, the application of BACT does not require that a project developer switch technologies to achieve a lower emission rate.

At any given time, BACT is supposed to be the same in any air district in the United States. BACT is, by its definition, the "best," and the definition does not have a geographic limitation. Nevertheless, there is some subjectiveness to the BACT determination, and every determination is not always made with the full benefit of the latest developments in all other air districts.