# EXHIBIT S

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White Paper

# Revisiting BACT for Lean Burn Landfill Gas Fired Internal Combustion Engines

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February 26, 2009

NDEP558

## REVISITING BACT FOR LEAN BURN LANDFILL GAS FIRED IC ENGINES

### Background

Within the Bay Area Air Quality Management District there are currently twenty-four lean burn (LB) landfill gas (LFG) engines in operation at nine facilities. Lean burn engines are designed to be operated at high excess air levels (up to 65:1 in some pre-stratified systems) resulting in lower combustion temperatures and therefore lower $NO_x$ emissions. In addition to these existing engines, six new lean burn LFG engines, located at the Ameresco facility in Half-Moon Bay are in the process of commissioning with another two identical engines in the construction phase at Ameresco-Keller Canyon. Besides the above-mentioned lean burn engines, there are eleven rich burn LFG engines, which must be replaced by January 1 of 2012 in order to comply with Regulation 9, Rule 8 $NO_x$ requirements.

### Changes in BACT for $NO_x$ and CO

The 1995 BAAQMD published BACT[1] levels for nitrogen oxides ($NO_x$) and carbon monoxide (CO) from waste gas fired spark ignition engines ≥250 horsepower (hp) are as follows:

**Table 1 $NO_x$ and CO BACT for Waste Gas Engines (g/bhp-hr)**

| POLLUTANT | BACT1 (Technologically Feasible, Cost-effective) | BACT2 (Achieved in Practice) |
|---|---|---|
| $NO_x$ | 1.0 | 1.25 |
| Technology | Not specified | Lean Burn Technology |
| CO | 2.1 | 2.65 |
| Technology | Not specified | Lean Burn Technology |

Since 2000, the BAAQMD has received and approved eleven permit applications for a total of twenty-seven LFG engines. Seven of these engines (5 of the 11 permit applications) have been installed and have been operating for at least two years. Eight engines (2 permit applications) are now undergoing construction or initial commissioning. For the remaining twelve approved engines (4 permit applications), the Authorities to Construct have expired, and the engines were never installed due to performance, maintenance, and emission limit compliance concerns about the proposed engines. In the course of performing top down BACT analyses on these applications, the respective $NO_x$ and CO BACT standards have simultaneously become more stringent, as illustrated by the three projects discussed below.

[1] See Appendix A for 1995 Landfill and Digester Gas-Fired IC Engine BACT Standard

Sonoma County Landfill: In 2001 the Sonoma County Landfill requested a permit condition change revising the $NO_x$ and CO limits on the existing 8 engines to be consistent with the two new additional engines which were currently being permitted at the site. As a result of this, the current limits at Sonoma are 0.8 grams $NO_x$ per brake-horsepower hour (g/bhp-hr) and 2.1 gram CO per brake horsepower hour. Based on this determination it was felt that a CO BACT limit of 2.1 g/bhp-hr could be achieved in practice. These emission limits were requested by the facility operator in order to avoid a time-consuming PSD evaluation resulting from the application for the two additional engines. Based on the past performance of the existing engines, the facility operator felt the new limits could be achieved.

Ameresco-Half Moon Bay: The established BACT-based limits for the 2007 permit application for six LB LFG engines at Ameresco-Half Moon Bay was 0.6 g/bhp-hr for $NO_x$ and 2.1 g/bhp-hr for CO. It should be noted that Ameresco-HMB proposed and has installed state of the art LFG cleanup systems, which include high level filtration, refrigeration and temperature swing adsorption (TSA) carbon adsorption in order to reduce siloxanes, water and other impurities thereby greatly improving the LFG quality and consistency. In addition, Ameresco-HMB has also installed catalytic oxidation (CO) units on the exhaust of all engines and selective catalytic reduction (SCR) on the first engine to reduce $NO_x$ emissions. These catalytic systems are experimental; stable, long-term operation of similar waste gas systems has not, to date, been achieved in practice. The hoped-for maximum emission level of CO from all catalytically controlled engines is 0.52 g/bhp-hr and the $NO_x$ level from engine 1 with SCR, is 0.15 g/bhp-hr. These lower standards using add-on pollution control technology, if proven successful, would be in the category of technologically feasible-cost effective or BACT1.

This paper is mainly concerned with BACT2 - the emission levels achieved in practice for engines >250 hp. Based on a recent BACT review (BAAQMD Permit Application 14433), only rich burn engines exist for engines $\leq$ 250 hp.

Ameresco-Keller Canyon: The Ameresco facility at Keller Canyon (KC) is currently installing a pair of new engines identical to those at Ameresco-HMB, but without the CO oxidation catalysts. Initially, Ameresco-KC planned to use a more economical filtration system for water and particulate reduction. However, Ameresco-KC decided that the substantially more expensive TSA siloxane removal system would be necessary to ensure compliance with the BACT-based limits for these engines, which are: 0.6 g/bhp-hr for $NO_x$ and 2.1 g/bhp-hr for CO.

Conclusions: The BAAQMD BACT-based emission limits for both $NO_x$ and CO have become increasingly more stringent since 1995, as shown in bold in Table 2, and compared with other BACT determinations.

**Table 2 Achieved in Practice (BACT2) for $NO_x$ and CO**

| | $NO_x$ | CO |
|---|---|---|
| **BAAQMD BACT – 1995** | **1.25 g/bhp-hr** | **2.65 g/bhp-hr** |
| **Sonoma Co Landfill (2002)** | **0.8 g/bhp-hr** | **2.1 g/bhp-hr** |
| **Waste Management at Altamont Landfill (2002)** | **0.6 g/bhp-hr** | **2.1 g/bhp-hr** |
| Michigan (12-23-2003) | 1.87 g/bhp-hr | 3.02 g/bhp-hr |
| **ALZA Corp. (2004)** | **0.6 g/bhp-hr** | **2.5 g/bhp-hr** |
| SCAQMD (12-3-2004) | 0.6 g/bhp-hr | 2.5 g/bhp-hr |
| Vermont (12-16-2004) | 0.5 g/bhp-hr | 2.75 g/bhp-hr |
| Rhode Island (1-5-2006) | 0.5 g/bhp-hr | 2.75 g/bhp-hr |
| New Jersey (10-6-2006 | 0.6 g/bhp-hr | 2.75 g/bhp-hr |
| **Ameresco-HMB (2006)** | **0.6 g/bhp-hr** | **2.1 g/bhp-hr** |
| **Ameresco-KC (2007)** | **0.6 g/bhp-hr** | **2.1 g/bhp-hr** |

## Discussion: Lean Burn LFG Engine $NO_x$ & CO BACT Limits

Although it may be feasible to achieve lower emission levels for either $NO_x$ or CO from internal combustion engines, source test results and operator experience indicate that it is impractical to expect reductions in both $NO_x$ and CO emission levels simultaneously ad infinitum, without the use of downstream controls. The reason for this is because emission levels of $NO_x$ and CO from waste gas combustion are only independent to a point; thereafter, they are inversely proportional. That is to say, as adjustments are made to the engine operation in order to achieve a lower $NO_x$ emission rate, the CO emission rate will increase.

$NO_x$ formation is favored by higher temperatures, which, as long as there is an acceptable or excess level of oxygen, also encourages complete combustion, and therefore low CO concentrations. CO on the other hand is formed as an intermediate compound in the combustion process and normally, given the appropriate kinetics, reacts further with oxygen to produce $CO_2$. Therefore, employing good combustion practices to ensure complete combustion normally controls CO emissions. In general, adjustments in engine operation to achieve lower $NO_x$ do not result in the most efficient combustion.

Discussions with engine owner/operators/emission testers support this. Experienced operators and emission test engineers[2] report that when an engine is adjusted to achieve very low $NO_x$ concentrations, the engine operating stability is reduced and in the words of some operators "the engines then run very rough—barely functioning". With engine combustion stability compromised, CO conversion to $CO_2$ is reduced as $NO_x$ is reduced. This will continue until a point is reached where further engine adjustment to effect

[2] Independent conversations between the author and a) Scot Campbell of Bay Power LLC, January 6, 2009; b) Pat Sullivan of SCS Engineers, December 11, 2008; c) Robert Bartley, BAAQMD Source Test Engineer, Februrary 4, 2009.

additional $NO_x$ reduction results in an exponential CO increase. The additional fact that the landfill gas is highly variable and tends toward lower Btu content also hinders good combustion and impairs CO conversion to $CO_2$.

The central idea of lean burn technology is to provide an environment that will efficiently combust the available fuel at low temperatures thus reducing the potential for $NO_x$ formation. Although more than adequate oxygen is present in lean burn operation, the lower temperatures and greater air flow can tend toward less than ideal kinetic conditions for full conversion of CO to $CO_2$. In addition, engine deposits which build up over time in waste gas fired engines may adversely affect the CO to $CO_2$ kinetics. Heywood[3] indicates, "for fuel-lean mixtures, measured CO emissions are substantially higher than predictions from any of the models based on kinetically controlled bulk gas phenomena. One possible explanation [for] this lean-mixture discrepancy is that only partial oxidation of CO may occur if some of the unburned hydrocarbons emerge during expansion and exhaust from crevices in the combustion chamber and from any oil layers or deposits on the chamber walls".

Landfill gas contains contaminants in the form of siloxanes, sulfur compounds and halides, which form deposits on the pistons, valves, cylinder walls and engine heads. Since the simultaneous goals of minimizing $NO_x$ formation and attaining complete combustion to minimize CO emissions from the firing of landfill gas in lean burn engines appear to be somewhat at odds with each other, emissions priorities must be established.

$NO_x$ is an ozone precursor and the San Francisco Bay Area is classified as non-attainment for the federal and state ozone standards. The Bay Area *is*, however in attainment with federal and state CO standards. Therefore $NO_x$ control is of primary importance over CO control. This is not to say that there is no interest in CO emissions. This paper revisits the BACT standards for $NO_x$ and CO for landfill gas fired lean burn engines with the goal of creating emission limits that are realistic and which represent BACT, yet are attainable—throughout a normal engine operating cycle.

<u>Other Landfill Gas Combustion Challenges Affecting $NO_x$ and CO Emissions</u>: In addition to the inherent existence of contaminants in landfill gas, which affect combustion, there are additional factors specific to landfill gas, which should be mentioned.

Landfill gas methane concentrations can vary greatly depending on the age of the landfill, the types of wastes processed, how the landfill gas system is designed and operated, and daily weather conditions. For a number of reasons landfill gas methane levels can easily range from 35% to 60%. One major factor that plays an important role is the fact that landfills and the energy recovery operation are separate entities with different day-to-day interests. In some cases the landfill and the energy recovery facility are not simply different divisions of the same enterprise, but many times are operated by completely different companies, with each having their own operating issues. A landfill is naturally focused primarily on the efficient day-to-day refuse operations, with the condition of the

[3] *Internal Combustion Engine Fundamentals*, John B. Heywood, 1988, McGraw Hill

landfill gas system and the consistency of the gas being a secondary consideration. The energy recovery facility operator, however, is very interested in the quality and consistent volume of landfill gas, but has little to do with the maintenance and day-to-day operation of the landfill gas collection system. With landfill gas being produced, transported and converted to energy in real time, it is easy to see how landfill gas quality, quantity, and therefore engine emissions can vary significantly over a short period of time.

## Landfill Gas to Energy (LFGTE) Coalition Recommendation

Because of the increasing stringency of both $NO_x$ and CO standards as well as the variability of landfill gas as discussed above, in July of 2007, the Landfill Gas to Energy Coalition met with District engineering staff to express their concerns regarding the permitting of new LFGTE projects. The major issue discussed was their inability to proceed with LFGTE projects on the basis of having to ensure long-term compliance with the increasingly stringent $NO_x$ and CO BACT standards. Furthermore, the coalition indicated they were unable to obtain financing for engines with District-imposed standards that were beyond the manufacturer guarantees. The Coalition recommended the following approach:

1) Condition engine owner/operators to meet either of the following initial startup BACT limits:
   a) Low-$NO_x$ Bias Option: 0.5 g/bhp-hr $NO_x$ and 2.5 g/bhp-hr CO, or
   b) Low-CO Bias Option: 0.6 g/bhp-hr $NO_x$ and 2.1 g/bhp-hr CO
2) Allow the emission limits to float up to *Not to Exceed* (NTE) emission limits for CO between 3.0 and 4.2 g/bhp-hr. The choice of which NTE limit would be established based on the relative level of landfill gas contaminants at the site in question.
3) Require regular top end or major maintenance events and non-CEM based periodic monitoring.

Engineering staff was agreeable to the general concepts but concluded that additional data was necessary to verify the recommended emission limits. The balance of this paper presents source test data, conclusions, and recommends a revised BACT standard for LFG-fired LB IC Engines.

## Source Test Discussion

In order to determine if the LFGTE Coalition Proposal was reasonable, an engineering study needed to be undertaken to look at the performance of typical modern LB LFG engines. This section will discuss this study and will present our conclusions.

The source test data evaluated in this study addressed emissions from modern engines manufactured by Caterpillar (3516), Jenbacher (J-320) and Deutz (TBG 620). These particular engines were selected because they are considered representative of current lean burn engine technology and also because source test data was available for these engines. The remainder of the LB LFG engine models in the Bay Area were not included in this survey either because source test data was limited or because the engines are considered older technology and therefore inappropriate to include in a statistical study for a BACT determination.

The source test data represents 5 facilities burning landfill gas collected from 3 different landfills in a total of 15 engines. A total of 68 compliance source tests were considered with 6 tests eliminated from consideration because of data reconciliation problems. Therefore, 62 tests were used in this study.

It should be noted that since these source tests were to demonstrate compliance with permit conditioned BACT limits, the facilities prepared for the tests in advance of the test date. Hence, the tests in most cases may be deemed to represent the facility operator attempting to "put his best foot forward" and pass the source test, if possible, by as wide a margin as possible. This is important to note since the basis for the higher CO limit (NTE or Not To Exceed limit) is to address the difference between annual source tests for compliance and day-in- day-out operation.

In addition to the annual test data, one facility is required to perform daily handheld monitoring of CO emissions as a surrogate to ensure NMHC destruction efficiency. This data will also be addressed, as it is valuable in developing the NTE limit. Table 3 presents a summary of the type of source test data obtained from the facilities and engines studied.

**Table 3 Source Test Data Monitoring/Collection Frequency**

| Engine Manufacturer | # of Tests | Pollutant | Annual Compliance Test Data | Daily Test Data |
|---|---|---|---|---|
| **Jenbacher** | 12 tests | $NO_x$ | **Yes** | No |
| (3 engines) | | CO | **Yes** | No |
| **Deutz** | 16 tests | $NO_x$ | **Yes** | No |
| (2 engines) | | CO | **Yes** | **Yes** |
| **Caterpillar** | 34 tests | $NO_x$ | **Yes** | No |
| (10 engines) | | CO | **Yes** | No |

Figure 1 presents a graphical image of the CO and $NO_x$ test results for all of the annual compliance source tests, including statistical data while Table 4 presents a summary table of individual engine facility performance.

**Figure 1 Lean Burn Landfill Gas Engine Survey Results**

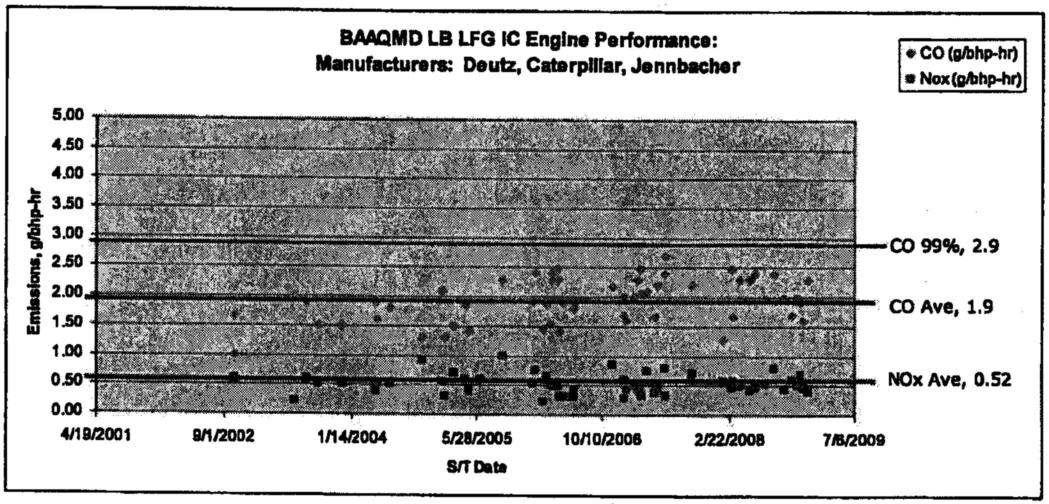


**Table 4 Tabulation of Annual LB LFG Engine Source Tests by Engine Type**

| Engine Type | Pollutant | Permit Limit (g/bhp-hr) | # of Source Tests | Mean | Upper 99% (3 sigma) Bound | Variability (ave to 99%) |
|---|---|---|---|---|---|---|
| **Low $NO_x$ Bias** | | | | | | |
| Jenbacher | $NO_x$<br>CO | 0.6<br>2.5 | 12 | 0.45<br>2.3 | 0.62<br>2.9 | 38%<br>25% |
| **Low CO Bias** | | | | | | |
| Caterpillar | $NO_x$<br>CO | 0.8<br>2.1 | 34 | 0.53<br>1.8 | 1.1<br>2.8 | 110%<br>56% |
| Deutz | $NO_x$<br>CO | 0.6<br>2.1 | 16 | 0.53<br>1.9 | 0.76<br>2.7 | 23%<br>11% |

Table 4 presents the averages of the data for each engine type. Although the Jenbacher shows a fairly low variation between the 3-sigma upper bound and the mean, it should be noted that there were only 12 data points available for the Jenbacher engines. There are many reasons which can be suggested for the variabilities from the engines shown in Table 4. It is beyond the scope of this paper to explore all the possible reasons for this variability.

In addition, some engines appear to be predisposed to achieve low $NO_x$ emission levels (with a predilection toward higher CO levels) while other engines may be biased toward achieving low CO levels and higher $NO_x$ emissions. The averages presented on Table 4 indicate that the Caterpillar and Deutz engines may be biased toward lower CO, while the Jenbacher may be biased toward lower $NO_x$. For this paper, we considered any engine with an average $NO_x$ of 0.5 or less, where CO averaged greater than 2.1 to be biased



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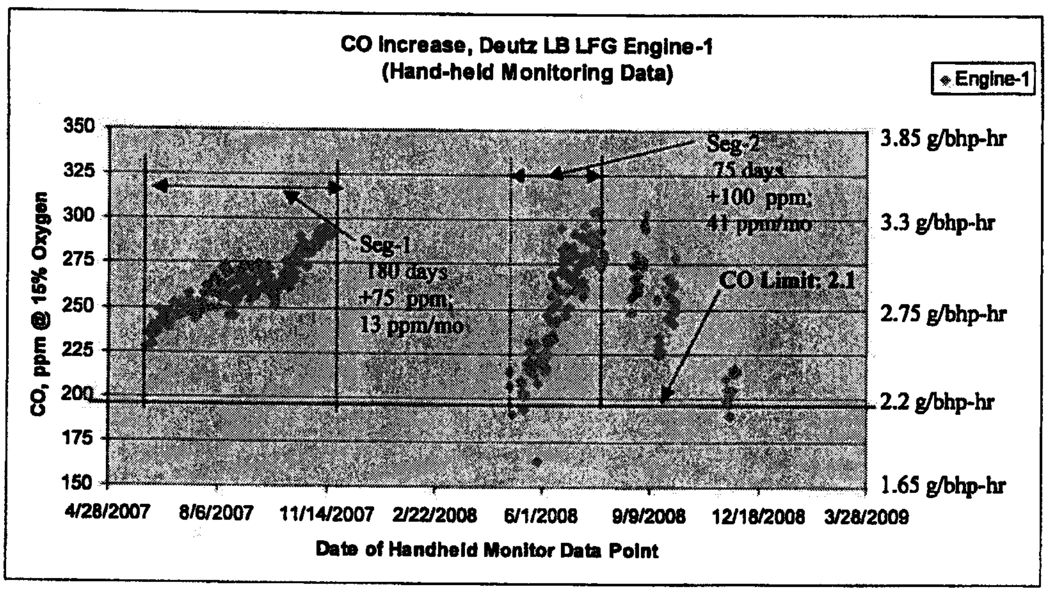
toward low $NO_x$. Likewise, any engine with an average CO of 2.1 or less, where the average $NO_x$ was greater than 0.5 to be biased toward lower CO. Additional support for these cases is provided in the figures in Appendix B, which show emission tendencies for the three engine manufacturers considered in this study. These biases are consistent with the LFGTE Coalition recommendation for initial $NO_x$/CO emission standards based on the $NO_x$ or CO bias of the chosen engine. The BAAQMD finds this approach, with a custom tailored BACT combo ($NO_x$/CO paired initial nominal emissions standard) to be a reasonable approach for landfill gas fired engines.

## Development of Not To Exceed Emission Standards

Daily Monitoring Data: The facility operator of the Deutz engines is required to perform daily monitoring of the LFG engines (using a portable analyzer) to demonstrate compliance with the NMHC destruction requirements of BAAQMD Regulation 8 Rule 34-301.4. This data is presented in Figures 2 and C-1, with the calculations (and Figure C-1) shown in Appendix C.

**Figure 2 Deutz Engine-1: Daily CO emission Trends, ppm CO at 15% Oxygen**[4]




As mentioned previously, the daily CO monitoring is performed as a surrogate to ensure destruction of NMOC as required by BAAQMD Regulation 8 Rule 34 which requires the establishment of a monitoring surrogate to ensure a minimum NMOC destruction efficiency of 98% or an outlet concentration of 120 ppm NMOC as methane at 3 percent oxygen. Most municipal landfills have chosen the ppm standard over the percent destruction since the initial loading of NMOC in the landfill gas is relatively low.

[4] Conversion between g/bhp-hr and ppm @ 15% oxygen based on average LFG methane content of 50% and

In the present case, to ensure that the 120 ppm NMOC limit is achieved, the Deutz engines are conditioned to a maximum exhaust CO concentration of 330 ppm at 15% oxygen. For the permitting of new LB LFG engines going forward, this limit will be allowed as a surrogate for NMOC destruction, unless the owner/operator chooses a different monitoring surrogate or can demonstrate compliance with the 120 ppm NMOC limit at a different CO level. Specific locations may need to be evaluated based on the current and projected conditions. This BACT analysis is designed to allow for some flexibility to address site specific landfill conditions, where needed.

## Actual Emissions vs Historical Source Test Emissions

A comparison of the daily CO concentrations vs the averages of the data collected during source tests for the Deutz engines indicates the engines may be out of compliance with the 2.1 g/bhp-hr limit a good portion of the time. Whereas the source test-derived data (shown in Table 3 and Appendix B indicates the engines are *generally* in compliance with the 2.1 g/bhp-hr limit, the daily monitoring shows a different story—according to the daily CO emissions data gathered with the hand-held monitor, the Deutz engines are, in actuality, mostly *out of compliance* with the 2.1 g/bhp-hr standard.

This analysis assumes that the hand-held monitor is providing a reasonably accurate estimate of engine emissions. The technical literature for the hand-held analyzer model used by the Deutz engine operator specifies a standard range for CO of 0 to 2,000 ppm with accuracy of plus or minus 2%. In light of the fact that the data shown in Figure 2 and Appendix C-1 indicates a steady trending, we conclude that the hand-held data is reasonable. Based on the data gleaned in this study, it is apparent that: 1) it is normal for CO emissions to increase as the engines are operated, and 2) establishment of not to exceed limits based on a nominal rate of CO increase would seem to be a reasonable approach for these engines, and 3) additional monitoring is needed to ensure that the engines get needed maintenance in a timely fashion. Engine maintenance events may not have a significant impact on $NO_x$ emissions, but for landfill gas engines, regular maintenance is of paramount importance for minimizing CO emissions.

The daily emissions monitoring of the 2 identical Deutz engines produced 5 CO emission increase intervals, totaling 400 ppm for both engines combined over 736 days. Based on an analysis of the CO emissions increase during each interval, the emissions performance deterioration ranged from 9 ppm per month to 41 ppm per month, depending on the interval. Summing all the CO increases over all intervals combined gives an average increase rate of 16 ppm CO (@15% oxygen) per month. In the case of these Deutz engines, we note that daily $NO_x$ monitoring is not required, since the CO is only tracked for NMOC destruction surrogacy. In order to get a more complete picture of engine performance, the $NO_x$ emissions data needs to be gathered concurrently with the CO data.

The economics of landfill gas to energy projects indicate that the minimum economic average between engine turnarounds is one year. One year of operation at 16 ppm CO increase per month yields 192 ppm CO increase per year. At an average LFG methane concentration of 50% and an assumed IC engine efficiency of 30%, the CO increase of

192 ppm @ 15% oxygen is equivalent to a CO increase of 1.5 g/bhp-hr. For the low $NO_x$ bias the proposed NTE limit is 3.9 g/bhp-hr and for the low CO bias, the proposed NTE limit is 3.6 g/bhp-hr. Appendix D presents the calculations showing these not to exceed (NTE) standards for CO emission increases.

## Summary and Recommendation

Our discussions with waste gas engine operators leads us to believe that engines generally perform at their best after overhaul events and that combustion performance tends to deteriorate as siloxane deposits form throughout the combustion surfaces. Notwithstanding this, source test histories are not extensive enough to show consistent trends demonstrating this deterioration, although there is ample evidence that significant variation exists around the Bay Area mean of 2.44 g/bhp-hr.

The current 2.65 g/bhp-hr standard appears to have been established based on early, limited source test data for digestor gas fired engines. Lean burn engines effectively have only 1 control variable at their disposal – engine timing. The air to fuel ratio may be adjusted, but it is difficult to guarantee a consistent ratio due to ongoing variation in gas composition and ambient conditions. Additionally lower BTU fuel such as landfill gas combined with excess air generally result in less stable combustion which may also tend to increase CO emissions compared to digestor gas fired engines. Thus, separate BACT determinations are necessary for different types of waste fuel.

Rather than completely scrap the current BACT standards for waste gas fired IC engines, we propose the following changes for CO and $NO_x$ BACT for lean burn landfill gas fired IC engines:

1) BACT for $NO_x$ and CO should be paired standards, and no longer evaluated separately.

2) Since some engines seem to be biased toward low $NO_x$ operation, and some toward low CO operation, establish a nominal BACT standard for each operating bias. Although CO would be allowed to drift upward, compliance with this nominal standard for $NO_x$ and CO would have to be demonstrated after every engine turnaround.

| | | |
|---|---|---|
| Low $NO_x$ Bias: | $NO_x$: | 0.5 g/bhp-hr |
| | CO: | 2.5 g/bhp-hr |
| Low-CO Bias: | $NO_x$: | 0.6 g/bhp-hr |
| | CO: | 2.1 g/bhp-hr |

3) Establish NTE or Not To Exceed limits for CO, based on 1 year of CO increase increment of ~192 ppm or 1.5 g/bhp-hr. All emission calculations would be based on the NTE value chosen.

4) Allow operation beyond the 1 year economic minimum operating cycle, as long as CO emissions are less than 80% of the NTE, up to a maximum

time of the lesser of 26,000 hours of engine operation or 36 calendar months of operation.

5) Require monthly handheld monitoring events to closely watch engine performance and plan appropriately for turnarounds.

6) Annual source testing would continue to be required.

While the proposal to change from an achieved in practice (BACT2) CO standard of 2.65 g/bhp-hr to NTE CO standards of either 3.6 g/bhp-hr for low-CO biased engines or 3.9 g/bhp-hr for low $NO_x$ biased engines may – on the surface – appear to be a relaxation of the CO BACT standard, this is not the case. Compliance with the current CO BACT2 standard is typically evaluated only once per year during a compliance demonstration test. Operators typically conduct engine overhauls or other maintenance procedures prior to this source, but the engine is typically not monitored for CO between these annual tests. Therefore, the CO deterioration during the year is not typically detected nor limited in any fashion. The proposed initial CO limits will be subject to the same source testing frequency as the current CO standard, and the two proposed initial CO limits are both lower than the current CO BACT2 standard. The proposed NTE CO limits are additional limits that will apply where no limit currently exists. Thus, these NTE standards are clearly not a relaxation of an existing limit. The proposed addition of monthly monitoring and maintenance frequency requirements will ensure that $NO_x$, CO, and NMOC emissions from these engines remain as low as possible throughput the entire year. Overall, these additional NTE CO standards, monthly monitoring, and maintenance frequency requirements are expected to reduce the annual average $NO_x$, CO, and NMOC emissions from landfill gas fired IC engines compared to engines that are subject to the current BACT2 standards with compliance demonstrate by an annual source test.

The proposed revised BACT standard for lean burn landfill gas fired IC engines is shown in Appendix A.

## Proposed Sample Conditions for Implementation of Revised BACT Standard

The following conditions would be applied to all projects for LB LFG engines evaluated under new source review. These conditions only deal with issues pertaining to $NO_x$ and CO emissions and the monitoring and compliance with these pollutant emission standards. These conditions may be modified as needed to address site-specific permitting situations.

The sample presented as follows represents the permitting of an engine with operation biased toward low-CO, hence the nominal baseline $NO_x$/CO emission standards are 0.6 g/bhp-hr-$NO_x$ and 2.1 g/bhp-hr CO.

1. Nitrogen Oxide ($NO_x$) Emission Limits: Nitrogen Oxide ($NO_x$) emissions from each engine shall not exceed 0.6 grams of $NO_x$ (calculated as $NO_2$) per brake horsepower-hour (g/bhp-hr). The owner or operator may demonstrate compliance with this part by having a $NO_x$ concentration at the engine exhaust of no more than 36 ppmv of $NO_x$, corrected to 15% oxygen, dry basis. An exhaust

concentration of more than 36 ppmv of $NO_x$ shall not be deemed a violation of this part, if the owner or operator conducts a Part 4 Compliance Demonstration Source Test within 30 days of measuring the $NO_x$ concentration excursion, and this source test demonstrates that $NO_x$ emissions did not exceed 0.6 g/bhp-hr during the test period. (Basis: BACT)

2. Carbon Monoxide (CO) Emission Limits:
   a) Initial and/or Post Overhaul CO Limits: Upon initial startup and after either a top-end or major overhaul, carbon monoxide (CO) emissions from each engine shall not exceed 2.1 grams of CO per brake horsepower-hour (g/bhp-hr).
   b) Not to Exceed (NTE) Limits: Ongoing CO emissions from each engine shall not exceed 3.6 g/bhp-hr. The owner or operator may demonstrate compliance with this part by having a CO concentration at the engine exhaust of no more than 385 ppmv of CO, corrected to 15% oxygen, dry basis. An exhaust concentration of more than 385 ppmv of CO shall not be deemed a violation of this part, if the owner or operator complies with one of the following requirements within 30 days of measuring the CO concentration excursion.
      i) Conduct a Part 4 Compliance Demonstration Source Test, which demonstrates that CO emissions do not exceed 3.6 g/bhp-hr during the test period, or
      ii) Shutdown the engine as soon as possible and perform either a top-end or major overhaul.

   (Basis: BACT)

3. NMOC Emission Limits: Each engine shall comply with either the destruction efficiency requirements or the non-methane organic compound (NMOC) outlet concentration limit specified in Regulation 8-34-301.4. In order to satisfy the requirements of Regulation 8-34-509, the APCO deems outlet CO concentration to be the key emission control system operating parameter for each engine. For the Part 4b monthly monitoring tests only, compliance with the Part 2b CO concentration limit shall be a surrogate for demonstrating ongoing compliance with the 8-34-301.4 NMOC concentration limit. Measuring an exhaust concentration greater than the Part 2b CO concentration limit shall not be deemed a violation of this part, if the owner or operator complies with one of the following requirements within 30 days of measuring the CO concentration excursion.
   a) Conduct a Part 4 Compliance Demonstration Source Test, which demonstrates that NMOC concentration (expressed as methane) does not exceed 120 ppm at 3% oxygen, dry basis, or
   b) Shutdown the engine as soon as possible and perform either a top-end or major overhaul.

   (Basis: BACT and Regulations 8-34-301.4 and 8-34-509)

4. Testing and Monitoring Requirements: In order to demonstrate compliance with Parts 1 through 3, the owner or operator shall comply with all of the following testing and monitoring requirements.

a) Compliance Demonstration Source Test (initial, annual or post overhaul source test): The owner or operator shall ensure that a District-approved compliance demonstration source test is conducted within 60 days of each initial startup or post overhaul startup of each engine and annually thereafter. Annual source tests shall be conducted no later than 12 calendar months after the previous source test. Compliance demonstration source tests shall be conducted while the engine is operating at conditions representative of normal operation and shall determine all items identified in Parts 4a(i-vii), below. The owner or operator shall contact the District Source Test Section at least 7 days in advance of each source test. Compliance demonstration test reports shall be submitted to the Source Test Section within 60 days of the test date. The compliance demonstrate source test shall determine and report the following information:

   i. Total flow rate of gaseous fuel to each IC Engine (dry basis);
   ii. Concentrations (dry basis) of carbon dioxide ($CO_2$), nitrogen ($N_2$), oxygen ($O_2$), methane ($CH_4$), and total non-methane organic compounds (NMOC) in the combined gaseous fuel burned in each IC Engine;
   iii. Exhaust gas flow rate from each IC Engine (dry basis);
   iv. Concentrations (dry basis) of $NO_x$, CO, $CH_4$, NMOC, and $O_2$ in the exhaust gas from each IC Engine;
   v. Emissions rate of $NO_x$ and CO in units of grams of pollutant/brake horsepower-hour.
   vi. NMOC destruction efficiency achieved by each IC Engine; and
   vii. CO, $NO_x$ and $O_2$ concentrations in the exhaust from each engine shall be measured in tandem using the portable gas analyzer method used for the monthly emissions monitoring required by Part 4b.

b) Monthly (Portable Analyzer) Emission Monitoring Test: The owner or operator shall conduct an initial monthly emissions monitoring test during the Part 4a initial compliance demonstration source test and on a calendar month basis thereafter. The interval between required monthly monitoring events shall be at least 15 days. This monthly test shall determine concentrations of $NO_x$ and CO in units of ppmv @ 15% oxygen using a District approved portable analyzer. All emission monitoring tests shall be conducted with the engine operating either at conditions representative of normal operations unless otherwise specified. The analyzer shall be calibrated, maintained, and operated in accordance with the manufacturer's specifications and recommendations. $NO_x$ and CO readings at 15% oxygen shall be averaged over a consecutive 15-minute period. Monthly CO monitoring satisfies the monitoring requirements of 8-34-509.

(Basis: Regulations 2-1-403, 8-34-412, 8-34-509, 9-8-501, and 9-8-503)

5. Maintenance Requirements: The owner or operator of each IC engine shall conduct a top-end or major overhaul of the engine in accordance with the following maintenance frequencies:

a) Overhaul Frequency when CO emissions > 80% NTE standard: In the event that the monthly emission monitoring test indicates emission levels greater than 80% of the NTE equivalent value in ppm @ 15% $O_2$, the owner or operator may either accept the test result and comply with the overhaul frequency in this subpart, or elect to perform a compliance demonstration source test to determine the engine emission levels in g/bhp-hr. If a compliance demonstration source test is performed, the results in units of g/bhp-hr shall be used in preference to monthly ppm monitoring results for determining if engine emission levels are greater than 80% of the NTE limit. If the engine emissions exceed 80% of the NTE limit, a top-end or major overhaul shall be performed within 12 calendar months of the source test date (or accepted monthly monitoring test date) showing CO emissions greater than 80% of the NTE standard.

b) Overhaul Frequency when CO emissions ≤ 80% of the NTE standard. A top-end or major overhaul shall be conducted at a frequency not to exceed 26,000 hours or 36 calendar months of operation, whichever comes first. For the purpose of complying with this part, the engine shall be considered to operate for a calendar month if the engine operates for more than 372 hours in any calendar month.

(Basis: Regulation 2-1-403)

## APPENDIX A

**BAY AREA AIR QUALITY MANAGEMENT DISTRICT**
**Best Available Control Technology (BACT) Guideline**

Source Category

| | | | |
|---|---|---|---|
| **Source:** | **IC Engine – Landfill Gas Fired** | **Revision:** | **4** |
| | | **Document #:** | **96.2.2** |
| **Class:** | **> 250 Hp Output** | **Date:** | **2009** |

| | Pollutant | BACT<br>1. Technologically Feasible/ Cost Effective<br>2. Archived in Practice | TYPICAL TECHNOLOGY |
|---|---|---|---|
| | **POC** | 1. n/s<br>2. 120 ppm @ 3% $O_2$ [b] | 1. Lean Burn Technology + LFG Trtmt: filtration + refrigeration + carbon adsorption [h]<br>2. Lean Burn Technology [a] |
| Low-Nox Engine Bias | **$NO_x$** [Low-$NO_x$ Engine Bias] | 1. n/s<br>2. 0.5 g/bhp-hr [c, g] | 1. n/d<br>2. Lean Burn Technology [c] |
| Low-Nox Engine Bias | **CO** [Low-$NO_x$ Engine Bias] | 1. n/s<br>2. a) Initial Standard: 2.5 g/bhp-hr [g, h]<br>b) Not to Exceed Standard: 3.9 g/bhp-hr [e, h]<br>c) CO emissions based overhaul schedule [c, e, f] | 1. Lean Burn Technology + LFG Trtmt: filtration + refrigeration + carbon adsorption [h]<br>2. Lean Burn Technology [c, h] |
| Low-CO Engine Bias | **$NO_x$** [Low-CO Engine Bias] | 1. n/s<br>2. 0.6 g/bhp-hr [d, g, h] | 1. n/d<br>2. Lean Burn Technology [d, h] |
| Low-CO Engine Bias | **CO** [Low-CO Engine Bias] | 1. n/s<br>2. a) Initial Standard: 2.1 g/bhp-hr [c, d, g]<br>b) Not to Exceed Standard: 3.6 g/bhp-hr [e, h]<br>c) CO emissions based overhaul schedule [c, e, f] | 1. Lean Burn Technology + LFG Trtmt: filtration + refrigeration + carbon adsorption [h]<br>2. Lean Burn Technology [c, d, h] |
| | **$SO_2$** | 1. n/s<br>2. n/s | 1. LFG Treatment with >80% $H_2S$ Removal [a]<br>2. n/d |
| | **$PM_{10}$** | 1. n/d<br>2. n/s | 1. n/d<br>2. LFG Filtration [a] |

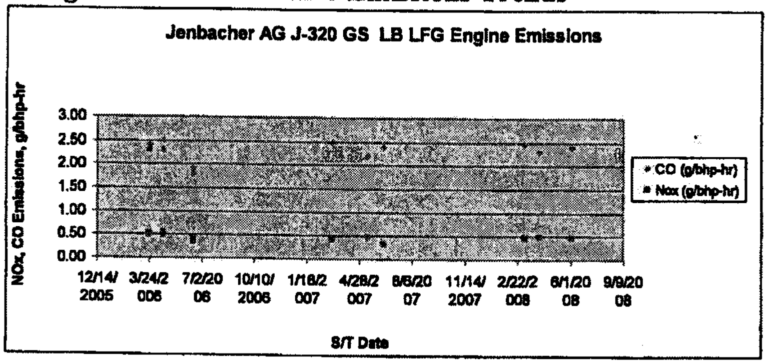
| | | |
|---|---|---|
| **NPOC** | 1. n/a<br>2. n/a | 1. n/a<br>2. n/a |

References and notes for LFG IC Engine BACT Determination

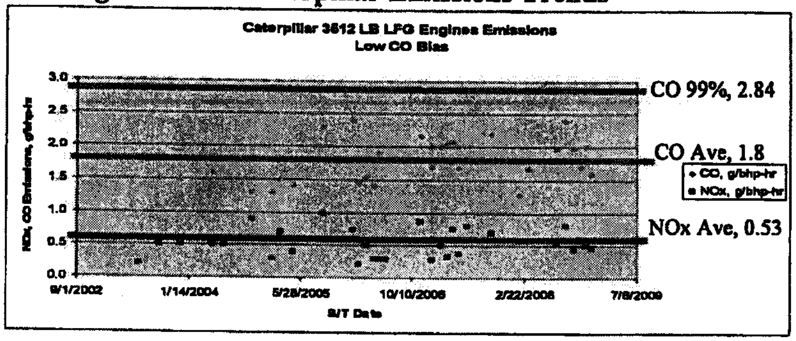
| | |
|---|---|
| a. | BAAQMD Published Waste Gas IC Engine BACT Determination, 6-2-1995, Revision 3. |
| b. | BAAQMD Regulation 8-34-301.4. 120 ppm as methane at 3% $O_2$ (equivalent to 360 ppm @ 15% $O_2$. Equivalent to 98% NMOC destruction. Compliance with CO NTE limit may be used as a surrogate for NMOC destruction for the purpose of showing compliance on a monthly basis. |
| c. | LFGTE Coalition LFG BACT Proposal, 7-3-2007 |
| d. | AN 12649 (Ameresco-Half Moon Bay), AN 14265 (Ameresco-Keller Canyon). |
| e. | 3.9 g/bhp-hr equivalent CO Limit = 420 ppm CO at 15% $O_2$. 3.6 g/bhp-hr equivalent CO Limit = 385 ppm CO @ 15% $O_2$. Ongoing compliance demonstrated by monthly monitoring with handheld analyzer for $NO_x$ and CO. Exceeding 420 ppm CO (or 385 ppm CO, if appropriate) triggers either 1) compliance source test to determine g/bhp-hr $NO_x$ and CO emissions or 2) operator must shutdown engine within 30 days for maintenance. If 80% of NTE limit is exceeded, engine must be shutdown for maintenance within 12 months of date of the CO excursion. NOTE: The ppm CO to g/bhp-hr CO conversions are based on LFG methane content of 50% and engine mechanical efficiency of 30% (gross heat input to shaft horsepower). The owner or operator may request a revised ppm equivalent level based on site specific engine and landfill gas characteristics. |
| f. | Engine maintenance may be deferred until 26,000 hours or 36 calendar months of operation, whichever comes first, if all standards are met (with CO $\leq$ 80% of NTE). |
| g. | Source test required within 60 days of engine startup after top-end or major maintenance event. |
| h. | White Paper, Revisiting BACT for Lean Burn Landfill Gas Fired Internal Combustion Engines, BAAQMD, 2-26-2009. |

APPENDIX B

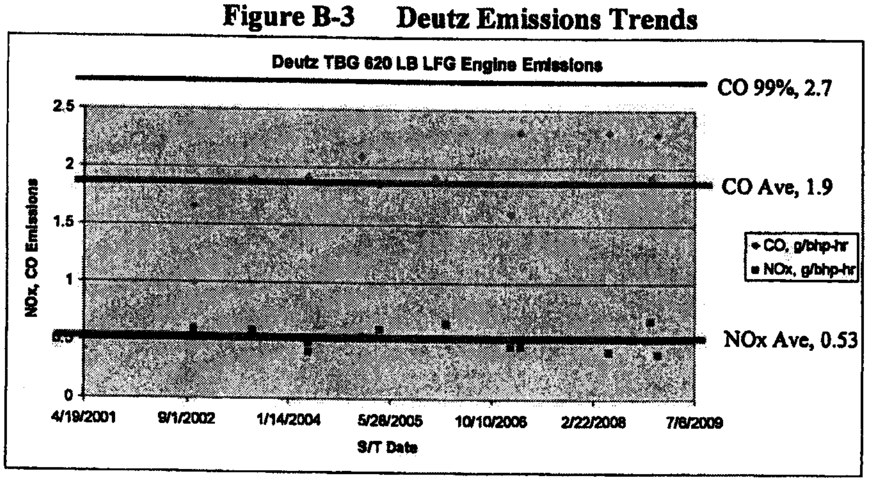
## Figure B-1 Jenbacher Emissions Trends




## Figure B-2 Caterpillar Emissions Trends




## Figure B-3 Deutz Emissions Trends



## APPENDIX C

**Deutz LB LFG Engine(s) Daily Monitoring CO Increase Calculations**

**Engine 1:**

Segment 1:
CO Increase: 300 ppm – 225 ppm = 75 ppm
Days Required: 65 + 100 + 15 = 180 days
Rate of Increase: [(75 ppm/180 days)*365]/12
= 12.7 ppm/month (0.42 ppm/day)

Segment 2:
CO Increase: 300 ppm – 200 ppm = 100 ppm
Days Required: 25 + 55 = 75 days
Rate of Increase: [(100 ppm/75 days)*365]/12
= 40.6 ppm/month (1.33 ppm/day)

**Engine 2:**

Segment 3:
CO Increase: 300 ppm – 225 ppm = 75 ppm
Days Required: 66 + 100 + 30 = 196 days
Rate of Increase: [(75 ppm/196 days)*365]/12
= 11.6 ppm/month (0.38 ppm/day)

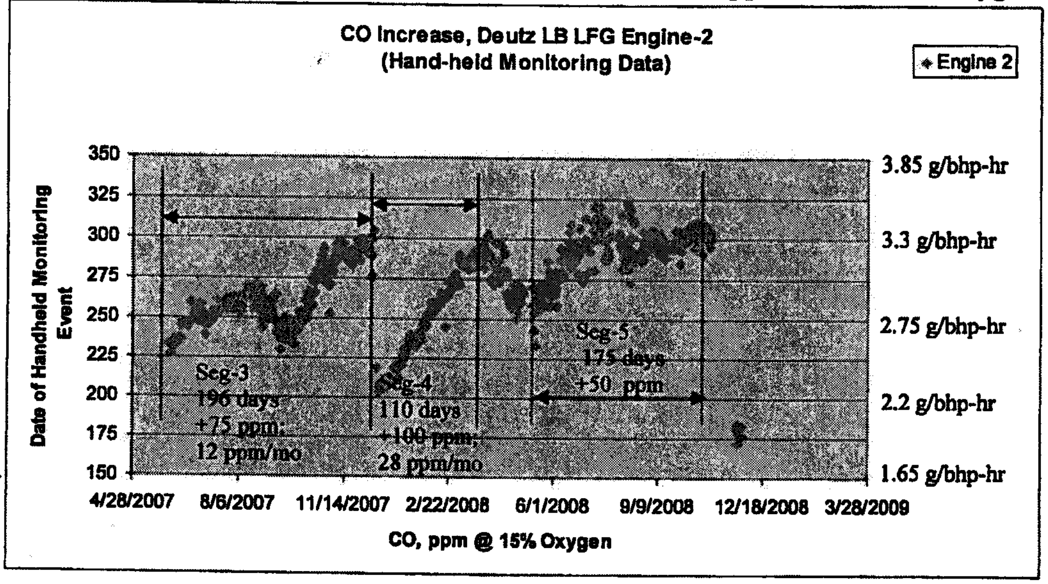
Segment 4:
CO Increase: 300 ppm – 200 ppm = 100 ppm
Days Required: 35 + 75 + 30 = 110 days
Rate of Increase: [(100 ppm/110 days)*365]/12
= 27.6 ppm/month (0.91 ppm/day)

Segment 5:
CO Increase: 300 ppm – 250 ppm = 50 ppm
Days Required: 15 + 100 + 60 = 175 days
Rate of Increase: [(50 ppm/175 days)*365]/12
= 8.7 ppm/month (0.29 ppm/day)

**Overall Average Change:**

CO Increase: 75 + 100 + 75 + 100 + 50 = 400 ppm
Days Required: 180 + 75 + 196 + 110 + 175 = 736 days
Rate of Increase: [(400 ppm/736 days)*365]/12
= 16.5 ppm/month (0.54 ppm/day)

**Figure C-1 Deutz Engine-2: Daily CO emission Trends, ppm CO at 15% Oxygen**



## APPENDIX D

### Development of NTE Standards

Basis: Economic minimum operating cycle of 1 year between engine turnarounds.

Daily Monitoring Data: Deutz engines ppm to g/bhp-hr equivalence: 350 ppm = 3.85 g/bhp-hr or 91 ppm per g/bhp-hr (conversion calculation shown below) at average 57% methane content in LFG and engine efficiency of 25% (based on source tests)

1.1 g/bhp-hr = 191 ppm @ 15% $O_2$
2.5 g/bhp-hr = 227 ppm @ 15% $O_2$

Average monthly CO increase: 16 ppm/month (192 ppm/yr)

| | | | | |
|---|---|---|---|---|
| Low CO Bias NTE | = | 191 ppm + 192 ppm | = | 383 ppm (~385 ppm @ 15% $O_2$) |
| Low $NO_x$ Bias NTE | = | 227 ppm + 192 ppm | = | 419 ppm (~420 ppm @ 15% $O_2$) |

<u>Equivalent CO ppm @ 15% oxygen and g/bhp-hr for District Wide Assumptions:</u>

LFG methane content, ave, assumed in BAAQMD: 50%
LFG IC Engine efficiency, assumed in BAAQMD: 30%

| | | | | |
|---|---|---|---|---|
| Low CO Bias NTE | = | 385 ppm CO @ 15% $O_2$ | = | 3.6 g/bhp-hr of CO |
| Low $NO_x$ Bias NTE | = | 420 ppm CO @ 15% $O_2$ | = | 3.9 g/bhp-hr of CO |

<u>Sample calculation for conversion from ppm to g/bhp-hr</u>

Conversion from 420 ppm at 15% oxygen to g/bhp-hr

1) Convert ppm at 15% to ppm at 0% oxygen (stoichiometric)
2) Calculate F, scf Flue Gas (FG) per scf LFG (0.5)
3) Calculate g/bhp-hr based on engine efficiency (0.3)

1) ppm CO @ 0% $O_2$ = 420 ppm[(20.95 – 0)/(20.95 – 15)] = 1475 ppm @ 0% $O_2$

2) Stoichiometric Combustion, dry basis: F = {[(2)(0.7905)/0.2095](0.50 mole $CH_4$/mole LFG)} + 1 = 4.773 mole FG/mole LFG = 4.773 scf FG/scf LFG (dry basis)

Note: 1 scf LFG contains 0.50 scf of $CO_2$ and 0.50 scf $CH_4$ of which 30% actually goes to produce horsepower-in this example.

3) (1,475 scf CO/1E6 scf FG)(lb-mole CO/387 scf CO)(28.01 lb CO/lb-mole CO) (454 gram/lb)(4.773 scf FG/scf LFG)(scf LFG/0.50 scf $CH_4$)(scf $CH_4$/993.9 Btu) (1 Btu gross/0.3 Btu mechanical energy)(2544 Btu/hp-hr) = 3.9 g/bhp-hr

## APPENDIX E

### Emission Calculation Examples for Potential LFG Engine Projects

Proposed BACT2 Standards For a Low-CO Biased Engine: | Assumed Operating Time:

NOx_A 0.6 g/bhp-hr | 24 hours/day

CO_A 3.6 g/bhp-hr | 365 days/year

BHP 1138 Engine Type: Caterpillar 3516

| | Emissions per Engine | | Project Emissions (Tons/Year) for # of Engines | | | | |
|---|---|---|---|---|---|---|---|
| | Pounds/Day | Tons/Year | 2 | 3 | 4 | 5 | 6 |
| NOx | 36.13 | 6.593 | 13.187 | 19.780 | 26.373 | 32.966 | 39.560 |
| CO | 216.77 | 39.560 | 79.119 | 118.679 | 158.239 | 197.799 | 237.358 |

BHP 1877 Engine Type: Duetz TGB 620 V16

| | Emissions per Engine | | Project Emissions (Tons/Year) for # of Engines | | | | |
|---|---|---|---|---|---|---|---|
| | Pounds/Day | Tons/Year | 2 | 3 | 4 | 5 | 6 |
| NOx | 59.59 | 10.875 | 21.750 | 32.625 | 43.499 | 54.374 | 65.249 |
| CO | 357.53 | 65.249 | 130.498 | 195.748 | 260.997 | 326.246 | 391.495 |

Proposed BACT2 Standards For a Low-NOx Biased Engine: | Assumed Operating Time:

NOx_B 0.5 g/bhp-hr | 24 hours/day

CO_B 3.9 g/bhp-hr | 365 days/year

BHP 1341 Engine Type: GE Jenbacher AG J 320 GS

| | Emissions per Engine | | Project Emissions (Tons/Year) for # of Engines | | | | |
|---|---|---|---|---|---|---|---|
| | Pounds/Day | Tons/Year | 2 | 3 | 4 | 5 | 6 |
| NOx | 35.48 | 6.475 | 12.949 | 19.424 | 25.898 | 32.373 | 38.847 |
| CO | 276.72 | 50.501 | 101.002 | 151.504 | 202.005 | 252.506 | 303.007 |

BHP 2677 Engine Type: GE Jenbacher JGS 616 GS

| | Emissions per Engine | | Project Emissions (Tons/Year) for # of Engines | | | | |
|---|---|---|---|---|---|---|---|
| | Pounds/Day | Tons/Year | 2 | 3 | 4 | 5 | 6 |
| NOx | 70.82 | 12.925 | 25.850 | 38.775 | 51.700 | 64.624 | 77.549 |
| CO | 552.41 | 100.814 | 201.628 | 302.442 | 403.256 | 504.071 | 604.885 |

## APPENDIX F

### BAAQMD 1995 BACT DETERMINATION FOR LANDFILL OR DIGESTER GAS ENGINES

**BAY AREA AIR QUALITY MANAGEMENT DISTRICT**
**Best Available Control Technology (BACT) Guideline**

Source Category

| | | | |
|---|---|---|---|
| **Source:** | IC Engine – Landfill or Digester Gas Fired | **Revision:** | 3 |
| | | **Document #:** | 96.2.1 |
| **Class:** | **> 250 Hp Output** | **Date:** | 06/02/95 |

Determination

| Pollutant | BACT<br>1. Technologically Feasible/ Cost Effective<br>2. Archived in Practice | TYPICAL TECHNOLOGY |
|---|---|---|
| **POC** | 1. *0.6 g/bhp-hr*[a,T]<br>2. *1.0 g/bhp-hr*[a,T] | 1. *n/s.*<br>2. *Lean Burn Technology*[a,T] |
| **$NO_x$** | 1. *1.0 g/bhp-hr*[a]<br>2. *1.25 g/bhp-hr*[a] | 1. *n/s.*<br>2. *Lean Burn Technology*[a] |
| **$SO_2$** | 1. *n/s*<br>2. *0.3 g/bhp-hr*[a] | 1. *Fuel Gas Treatment w/ ≥ 80% $H_2S$ Removal*[a]<br>2. *Addition of iron salts to digester sludge to remove $H_2S$*[a] |
| **CO** | 1. *2.1 g/bhp-hr*[i]<br>2. *2.65 g/bhp-hr*[i] | 1. *n/s.*<br>2. *Lean Burn Technology*[i] |
| **$PM_{10}$** | 1. *n/d.*<br>2. *n/s.* | 2. *n/d.*<br>3. *Fuel Gas Pretreatment*[i] |
| **NPOC** | 2. *n/a*<br>3. *n/a* | 1. *n/a*<br>2. *n/a* |

References (BACT Determination)

i. BAAQMD
T. TBACT