PM10 Emissions from LM6000 for Mariposa Energy, LLC

This memo is with reference to the proposed PM10 BACT standards for 4xLM6000 PC Sprint engines for the Mariposa Energy Project. Based on Preliminary Determination of Compliance for a 200 MW gas turbine in the Marsh Landing Generating Station1, BAAQMD is proposing an emissions rate of 0.0041 lb/MMBtu for PM10 emissions. This amounts to a limit of about 2 lbs/hr of PM10 emissions for a 50 MW gas turbine out of the stack. This document explains GE's position with respect to gas turbine PM10 emissions and our guarantee policy.

Background

The LM6000PC is a gas turbine engine derived from GE's proven CF6-80C2 aircraft engine. Aero-derivative engines such as the LM6000 have several distinguishing features. The LM6000 has a 2-shaft architecture that permits the low speed shaft to continue to rotate at 3600 rpm while the air-flow and the high-speed shaft speed modulate with power. Aero-derivative engines also have higher operating pressure ratios (OPR 28-30). The higher pressure-ratios result in a greater pressure drop and consequently greater temperature drop across the turbines. Thus, while the firing temperatures of the Aeroderivative engines are on the same order of magnitude as the frame engines, the higher temperature drop results in a lower exhaust temperature for these engines. These unique features result in a superior simple-cycle efficiency (40-44%) with unmatched operational flexibility (10min start, 30 MW/min ramp rate).

Aeroderivative and frame gas turbines have evolved with different design philosophies. Aeroderivative gas turbines have been derived from flight engines and are optimized for high simple-cycle efficiencies. The design heritage based on flight requirements provides for limited space for the combustion system and hence these engines have typically used annular combustor designs with residence times in the 3 to 5 millisecond range. Frame gas turbines in general have been designed for higher combined-cycle efficiencies and consequently operate at lower pressure ratios and lower simple-cycle efficiency than aeroderivative gas turbines. Since frame gas turbines have been designed for land-based applications, they are typically heavier and also have lower output per unit mass flow of air than aeroderivative gas turbines. The combustion systems in Frame machines are in general of the can-annular type with residence times of the order of tens of milliseconds. While both types of gas turbines have their unique strengths, Aeroderivative gas turbines are ideally suited for simple cycle applications with unmatched operational flexibility requirements such as in peaking power, while maintaining best in class efficiency. Due to different design philosophies, there are some fundamental differences in achievable emissions between these two types of gas turbines.

The LM6000 gas turbine offers Best-in-Class performance in the 50 MW size class. Spray Intercooling technology (SPRINT) is offered to increase the output on hot days and increase the operational flexibility. The LM6000 PC-SPRINT model has high operational flexibility and output that is of particular interest for highly dispatchable simple-cycle power.

PM10 Emissions

PM10 emissions refer to particulate matter emissions that are less than 10 microns in diameter. GE believes that the combustion process by itself does not play a major role in the PM10 emissions from gas turbines operating on clean natural gas.

The main sources of PM10 are as follows:

a) Formation of SO3 from Sulfur in the fuel
b) Formation of ammonium sulfates from trace ammonia in the SCR system and trace sulfur in the fuel.
c) Particulate matter in the ambient air that gets past the inlet filtration systems
d) Contaminants in water used for NOx control
e) Contaminants in tempering air and other bypass air used for after-treatment purposes
f) Uncertainties in measurement system contributing to positive bias and variance

PM10 emissions in the US typically include both filterable and condensable emissions that are measured separately. Filterable emissions are measured using US EPA method 5B, which uses a heated filter placed out of the stack to collect PM, which is then weighed to determine the concentration of PM. However this method does not separate PM by size. In order to separate PM emissions by size, US EPA method 201A uses a cyclone that is placed in front of the filter. All these components are placed inside the stack so that the PM is collected at the temperature of the stack. PM10 emissions from gas turbines burning natural gas are typically very low. Hence the recommended sample times must be extended to collect a quantifiable amount of PM. A typical test run may last more than 6 hours[1] and for small gas turbines can be required to run even longer.

Condensable PM emissions are measured using US EPA method 202. A series of water-filled, glass impingers are connected downstream of the filter and placed in an ice bath. The hot stack gas passes through these impingers and any PM10 that is not solid is condensed out in the water. These are recovered and sent to a laboratory for gravimetric analysis. The water in the impingers of Method 202 is known to create a positive bias due to formation of pseudo-particulates from oxidation of SO2 in the impinger water. This bias can be significant when compared to the low levels expected from GTs. A revision to method 202 that looks to reduce this bias is currently being evaluated.

Regarding sulfur emissions from natural gas-fired combustion turbines, the gas turbine does not create new SO_x emissions, other than the sulfur oxides resultant from the level of sulfur present in the fuel. The gas turbine will oxidize the sulfur present in the natural gas to SO_2 during the combustion process. Sulfur can be accounted for by calculating the amount supplied in the gas.[2]

In order to illustrate the different contributions to PM10 emissions from gas turbine power plants, a statistical simulation model for predicting PM10 emissions from gas turbines follows. The model is described in further detail in the Appendix. This model only considers three sources for PM10 emissions – fuel, water, and air, assuming that the fuel, water, and inlet air all meet GE requirements for use in gas turbines. Several reasonable assumptions are made on the degree of conversion of sulfur to SO2 and SO3 and resulting conversion to ammonium bisulfate in the SCR. Since there is significant uncertainty, the model takes a statistical approach to predicting expected PM10 emissions. The model also considers the contribution of the measurement and sampling uncertainty, which is assumed to be normally distributed with a standard deviation (sigma) of about 0.5 - 0.7 lb/hr. Due to several sources of uncertainty, a Monte Carlo type approach is adopted, which gives a statistical prediction on expected PM10 emissions.

A sample prediction from the model is shown in Fig. 1 for a 50 MW gas turbine (like the LM6000 PC sprint) and a generic 200 MW gas turbine, assuming sulfur content in the fuel of around 0.65 g/100 SCF of fuel. If we assume a 95% test pass rate (which is a 2-sigma level), the predicted emissions level for a 50 MW gas turbine is around 3 lb/hr, while for a 200 MW gas turbine it is around 9 lb/hr. This is in good agreement with measured emissions levels and consistent with our emissions policy. It is important to note the significant spread in the predicted values considering the uncertainties in fuel quality, ambient air quality, water quality, and conversions of S to SO3 and ammonium bisulfate and sulfuric acid mist. With a measurement uncertainty of 0.7 lb/hr (based on variation in test data), the range of values is from 0 to 3.5 lb/hr for 50 MW unit and 0 to 10 lb/hr for 200 MW unit.

Next, the effect of measurement uncertainties on the predictions is explored for both gas turbine size classes. In Fig. 2a, b, the model is exercised assuming that there is no measurement and sampling uncertainty and with 0.25 g/100 SCF of fuel. As shown, 2-sigma levels for 50 MW gas turbine class is around 1.4 lb/hr, while for 200 MW gas turbine class, it is around 4.6 lb/hr. In Fig 3a, and 3b, the model is exercised assuming a measurement uncertainty of around 0.7 lb/hr. The 2-sigma level for 50 MW gas turbine is found to be about 2.5 lb/hr, which is 80% higher than without measurement uncertainties. For the 200 MW gas turbine, the 2-sigma level is around 5.3 lb/hr, which is only 14% higher than without any measurement uncertainty. Thus, the presence of measurement and sampling uncertainties affects the guarantee-able emissions for a 50 MW gas turbine higher than it does for a 200 MW gas turbine. Although PM10 emissions levels will scale down with size, the measurement uncertainties do not typically scale down. Hence, it is unrealistic to apply the same emissions rate for a 200 MW and a 50 MW gas turbine.

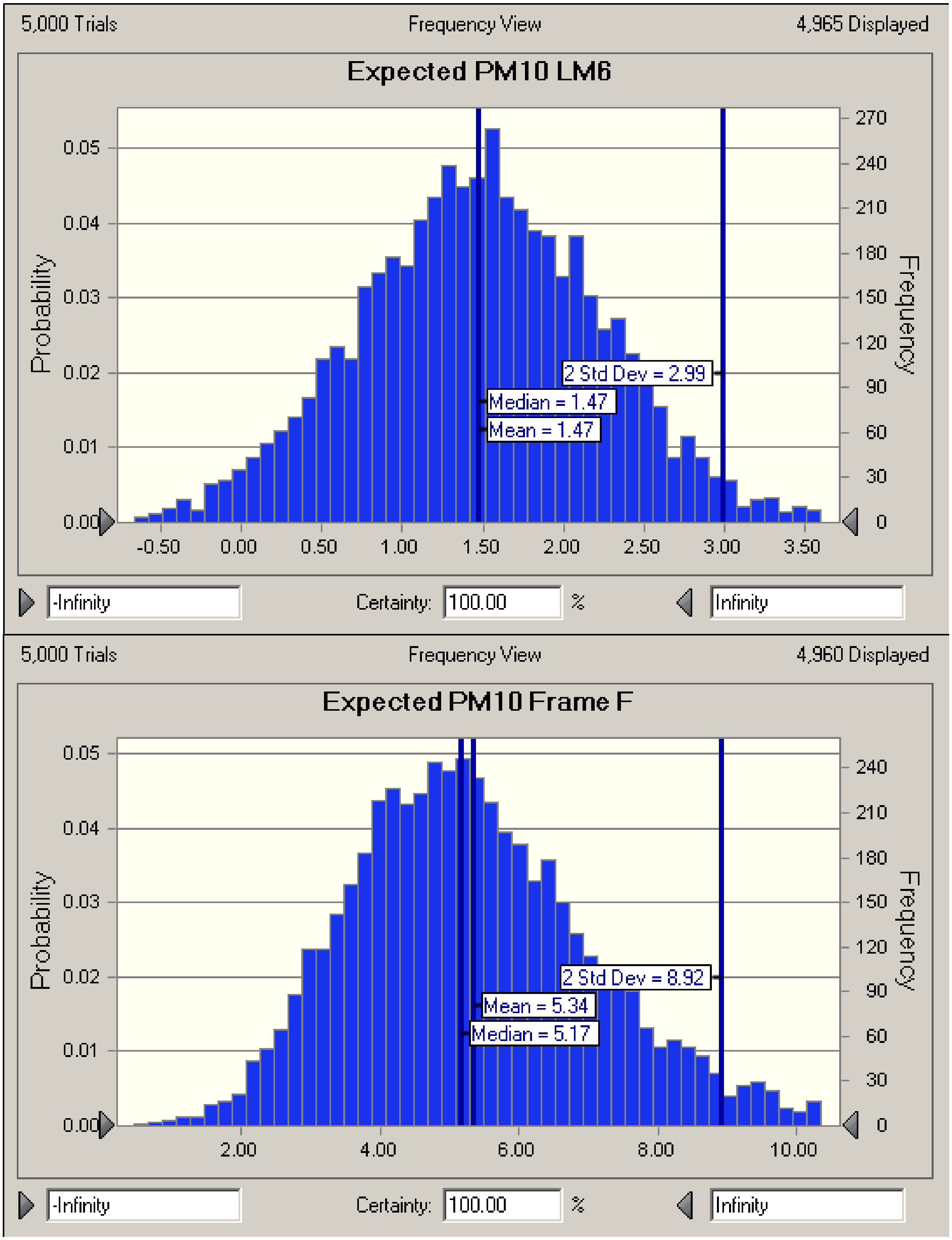


Fig. 1a (top) and 1b (bottom): Predictions from a statistical model on expected PM10 emissions from 50 MW gas turbine and 200 MW gas turbine with Sulfur content of 0.65 g/100 SCF.

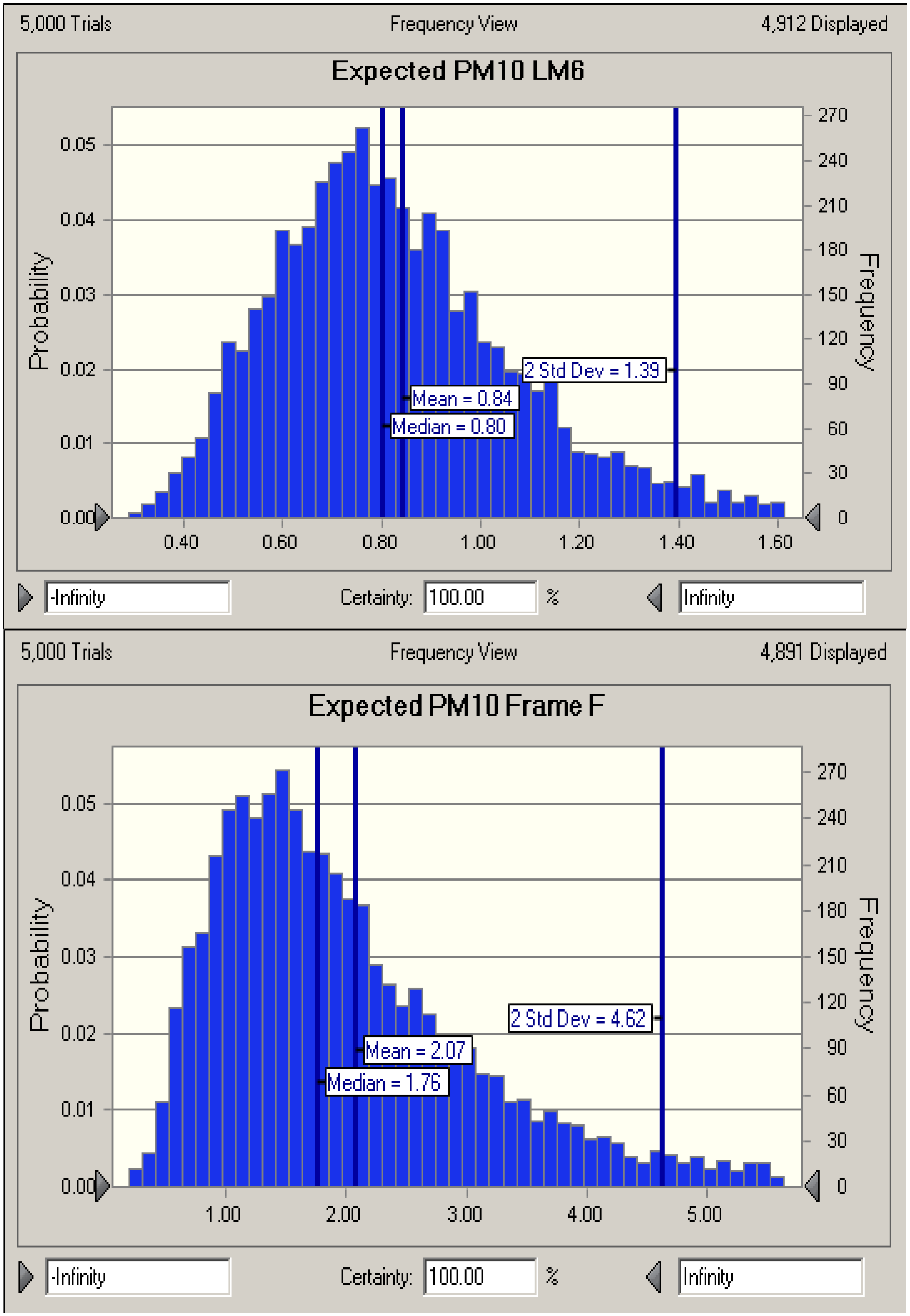


Fig. 2a (top) and 2b (bottom): Predictions from a statistical model on expected PM10 emissions from 50 MW gas turbine and 200 MW gas turbine with 0.25 g/100 SCF of Sulfur.

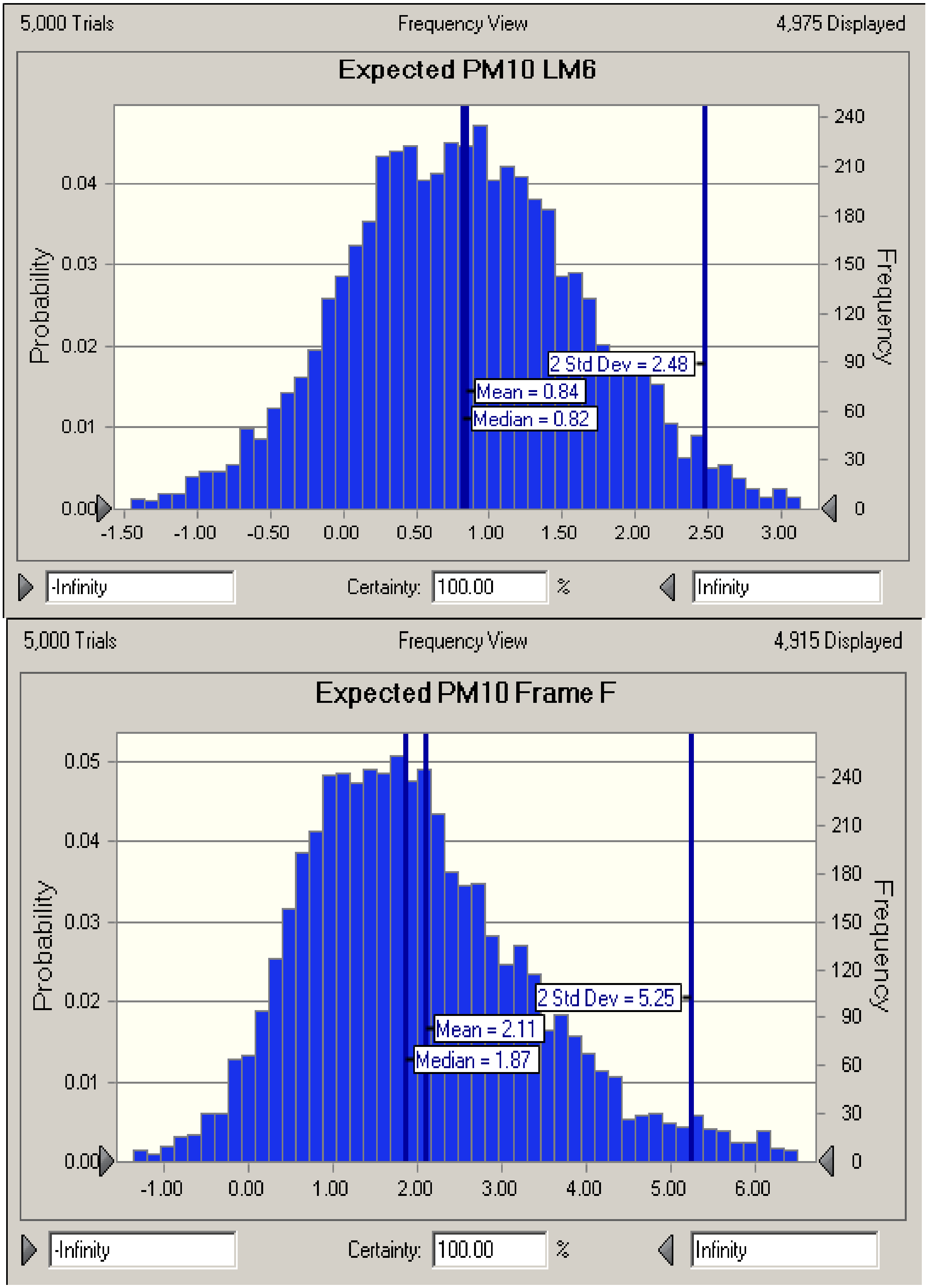


Fig. 3a (top) and 3b (bottom): Predictions from a statistical model on expected PM10 emissions from 50 MW gas turbine and 200 MW gas turbine with measurement and sampling uncertainty of 0.7 lb/hr, and 0.25 g/100 SCF of Sulfur in fuel.

It is important to note that the above model is to be used for illustration purposes only and should not be construed as implying any guarantee-able value. Consideration of higher degree uncertainty with the measurement and sampling system will show that higher PM10 emissions values are likely to be observed in the field. GE recommends only the use of experimental data for PM10 emissions in order to arrive at guarantee-able emissions.

Proposed BACT

Data from Table 11 in the Marsh Landing PDOC is shown in Fig. 4 below. The data refers to PM10 emissions from source data. It can be seen that there is significant variation in the data. The main sources of variation are as follows a) ambient air quality conditions, b) fuel quality, c) water quality, and d) measurement uncertainty. Since the combustion process by itself does not create any PM10 emissions, the contribution of the gas turbine to the variation in PM10 is negligible. Although in many cases the emissions are lower than 0.0041 lb/MMBtu, a facility may not meet these levels on a consistent basis. Based on the data, it is apparent that 5 out of the 42 conditions exceed the proposed BACT limit of 0.0041 and 7 out of 42 exceed the corresponding BACT limit of 2.0 lb/hr. Such an emissions level has not been consistently demonstrated in practice and it should not be the basis for BACT determination.

GE Emissions guarantees are based on 85% confidence interval with 97.5% pass rate. Based on these criteria and also taking other sources of variation into consideration, it is our opinion that consistently testing PM10 emissions below 2.5 lb/hr cannot be achieved with certainty. It is important to note that the data shown here does not account for additional contributions due to natural deterioration in site conditions and decline in the effectiveness of SCR catalysts with time, which may lead to additional PM10 formation from trace ammonia. This is in line with recent PM10 permit limits that have been issued for the LM6000.

It is our assessment that PM10 emissions rates for LM6000 should be based on what has been achieved in practice using LM6000 engines after taking the various uncertainties into consideration. There are also differences between a 200MW F-class gas turbine and a 50 MW aeroderivative engine that necessitate applying individual standards. LM6000 has a nominal simple cycle efficiency of about 40% vs 36% for the F-class GT on an LHV basis. The LM6000 engine also utilizes air most efficiently by producing higher MW for a given amount of air. In spite of such efficient utilization of air, the source test data from the Bay Area Air Quality Management District indicates that an emissions rate of 0.0041 lb/MMBtu is exceeded 5 out of 42 times. Although there are several instances with much lower emission rates, significant variations in site, fuel, water, ambient air lead to wide variations in measured PM10 rates.

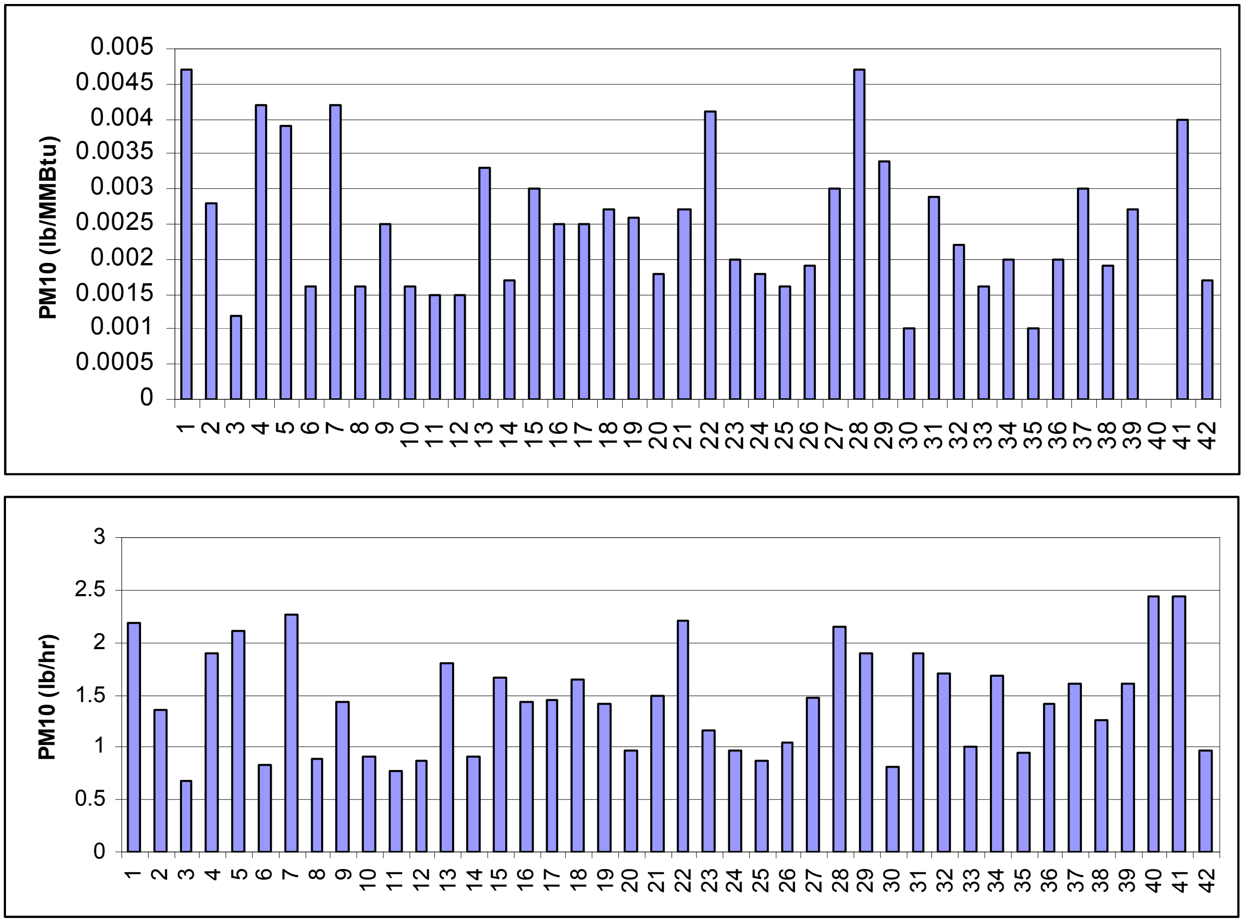


Fig. 4: PM10 Emission rates from GE LM6000 Simple Cycle engines[3]

In addition, a linear scaling of PM10 based on fuel flow rates is insufficient to account for differences in gas turbine cycle conditions as well as NOx mitigation techniques. The linear scaling based on lb/MMBtu penalizes higher efficiency aeroderivatives to reach lower PM10 on a lb/hr basis. The relation between PM10 in lb/hr and emissions rate is given below

PM10 (lb/hr) = Emissions rate (lb/MMBtu) * Fuel flow (MMBtu/hr).

Since an aeroderivative engine utilizes less fuel per unit MW of power, the above correlation implies that a higher efficiency engine needs to reach lower lb/hr PM10 emissions. This is only true if all the PM10 emissions are directly attributable to fuel. Since a component of PM10 emissions is from air, this linear scaling does not take into consideration differences in technology in establishing PM10 emissions. More importantly, as demonstrated above, the measurement uncertainties for PM10 measurement system do not scale down with fuel flow. It is thus unrealistic to impose the same emissions rates on a 50 MW gas turbine as for a 200 MW gas turbine.

In summary, the following points need to be considered in arriving at an acceptable emissions rate for PM10 for LM6000 units:

a) The largest contribution to PM10 emissions is from sulfur in the fuel, ambient air, and water. The gas turbine combustion process itself does not produce PM10 emissions.
b) Measurement uncertainties do not scale down with turbine size measured in MW. For this reason, it is unrealistic to impose the same emissions rates on a 50 MW gas turbine as a 200 MW gas turbine.
c) Based on source test data available for LM6000 units, PM10 emissions have exceeded 2 lb/hr in nearly 7 out of 42 instances.
d) There is significant variation in PM10 emissions from source test data and PM10 emissions limits below 2.5 lb/hr have not been consistently achieved across all ambient conditions, load points, and life cycles.
e) Utilization of a linear scaling based on lb/MMBtu penalizes higher efficiency aeroderivatives to reach even lower PM10 emissions on a lb/hr basis. This straight scaling based on fuel flow does not consider other contributions to PM10 emissions from ambient air and water used for NOx control.
f) Fundamental differences in technology between high efficiency aeroderivatives and frame technology require different emissions levels for aeroderivatives.

Due to these differences and also based on available source test data, it is unlikely that, with an appropriate level of confidence, a PM10 emissions rate of 0.0041 lb/MMBtu or 2 lb/hr can be achieved on a consistent basis across all ambient conditions and load points for 50 MW gas turbines.

Appendix

A: Model description and assumptions

In order to make some illustrative predictions, a simplified model that accounts for the main sources of PM10 emissions contributions from a gas turbine power plant has been developed. The model consists of three different modules. All the PM10 is assumed to come from either the Sulfur in the fuel, the ambient air, or the water. Due to the uncertainties in the chemistry of formation of PM10 from sulfur in the fuel, a statistical model based on the Monte Carlo methodology is adopted to predict PM10 emissions from a gas turbine system.

Sulfur module

The sulfur in the fuel is converted to oxides of sulfur in the gas turbine. The oxides are comprised of SO2 and SO3. The gas turbine is assumed to convert between 5 and 10% of sulfur to SO3. The CO reduction catalyst is assumed to convert between 20 to 40% of the remaining SO2 to SO3. The SCR is assumed to convert 20 to 30% of the remaining SO3 to ammonium bisulfate. The remaining SO3 is assumed to be converted to sulfuric acid mist. All these contributions are added to the PM10 emissions coming out of the stack.

Air module

A gas turbine power plant utilizes ambient air for several purposes. The inlet air is assumed to contain 80 micrograms/M3 of PM10. High quality air filters at the inlet of the gas turbine system capture most of the PM10. About 10-20% of the inlet particulate matter is assumed to slip through the inlet air filtration system.

Water module

Water used for NOx control may have a contribution to particulate matter. The water used for SPRINT and NOx control is demineralized water and as such, it contains very little (<5 ppm) impurities. Only 10% of the particles in water is assumed to contribute to PM10 formation.

Measurement Uncertainties

The sampling errors in the measurement system and instrument uncertainties are assumed to be normally distributed with a standard deviation of around 0.7 lb/hr. This is based on available sources of PM10 emissions. This is added to the predicted PM10 emissions.

B: Monte Carlo methodology

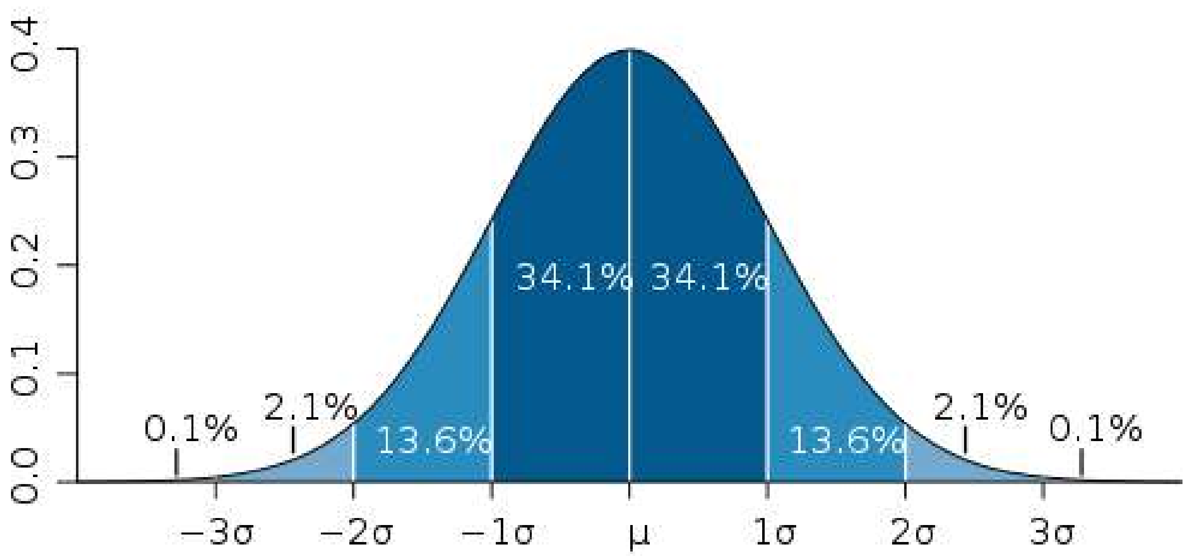
The main parameters used in the model are the following:

Sulfur in the fuel: mean value of 0.25 g/100 SCF, but assumed to be have a log-normal distribution with a standard deviation of around 0.2.
Percentage of Sulfur converted to SO3 in the gas turbine is uniformly distributed between 5 and 10 %
Percentage of remaining SO2 converted to SO3 in CO reduction catalyst is assumed to be uniformly distributed between 20 to 40%.

Percentage of remaining SO3 converted to SO3 in SCR is assumed to be uniformly distributed between 5 and 10%.
Percentage of SO3 converted to Ammonium bisulfate is assumed to be uniformly distributed between 20 and 30%
Percentage of PM10 in water contributing to PM10 is assumed to be uniformly distributed between 10 and 30%
Percentage of particulate matter in air that slips through the filtration system is assumed to be uniformly distributed between 10 and 20%.
Measurement uncertainty is assumed to be normally distributed with a mean of 0 and standard deviation of 0.7 lb/hr.

C: Statistics and Normal distribution

The model uses the Monte Carlo methodology, which is based on the theory of statistical distributions. A sample normal distribution is shown below. About 68% of the values drawn from a normal distribution are within one standard deviation away from the mean, about 95% of the values within two standard deviations and about 99.7% lie within three standard deviations.



Normal distribution curve[4]

References

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4. Wikipedia – Normal Distribution. http://en.wikipedia.org/wiki/Normal_distribution.