INGAA Emissions Data Collection: Carbon Monoxide Emissions from Natural Gas-Fired Two-Stroke Cycle and Four-Stroke Cycle Lean Burn Reciprocating Internal Combustion Engines

Emissions Data for Reciprocating Internal Combustion Engine National Emission Standard for Hazardous Air Pollutants (RICE NESHAP): 2010 Amendments for Existing Engines

Technical Report: CO Emissions Data for Lean Burn Engines and MACT Floor Analysis

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1.0 Project Objectives and Data Sources

A rule to amend the Reciprocating Internal Combustion Engines (RICE) National Emission Standards for Hazardous Air Pollutants (NESHAP) was proposed on March 5, 2009. The proposed rule addresses standards for existing major source engines 500 horsepower (hp) and smaller and existing area source engines of all sizes. The Interstate Natural Gas Association of America (INGAA) is a trade association of the interstate natural gas transmission industry, and INGAA member companies operate stationary natural gas-fired spark ignition internal combustion (IC) engines. These engines are installed at compressor stations along the pipelines to transport natural gas to residential, commercial, industrial and electric utility customers. INGAA submitted comments on the proposed rule on June 3, 2009, and a primary concern was the basis of proposed emission standards for gas-fired IC engines. This concern was primarily due to deficiencies in the data used to establish emission standards for a regulation that will impact thousands of engines. These deficiencies include both a lack of emissions data and data quality issues. INGAA's concerns are detailed in its comments, which are available in the rule docket (Docket Document No. EPA-HQ-OAR-2008-0708-0155).

The proposed rule addresses existing engines; thus, emissions data for existing equipment are of interest. INGAA conducted an emissions data collection effort, gathering data from its members to supplement the emissions data available for the rulemaking. The proposed rule includes carbon monoxide (CO) emission standards for lean burn engines, with CO emissions a surrogate for HAP emissions. Formaldehyde emission standards were proposed for rich burn engines. CO testing has been completed for many engines, typically associated with NOx compliance tests. Thus, it was anticipated that CO data would be available for lean burn engine categories. Formaldehyde testing is relatively rare, but formaldehyde data were also solicited. The objective of this effort was to:

- Assess the availability of emissions data for the three primary natural gas-fired IC engine subcategories: 2-stroke lean burn (2SLB), 4-stroke lean burn (4SLB), and 4-stroke rich burn (4SRB) engines;
- Collect available emissions data, including CO data for 2SLB and 4SLB engines and formaldehyde data for 4SRB engines;
- Compile and organize the data into a report for transmittal to EPA; and,
- Review and analyze the data to assess implications for the emission standard, including the basis for the minimum standard required under the Clean Air Act. This minimum standard is referred to as the "MACT floor". The Clean Air Act requires that the emission standard for existing units be based on the average emission limitation achieved by the best performing 12% of engines in a subcategory. In recent Court cases, it has been clearly delineated that NESHAP standards can take into account emissions variability, which considers emissions at adverse operating conditions that are reasonably likely to recur. Thus, INGAA analysis considered the MACT floor and emissions variability. As discussed in Sections 3, 4, and 5, this review concludes emissions variability warrants CO standards over 370 ppmv (at 15% O_2) for both 4SLB and 2SLB engine subcategories and specific recommendations are discussed in those sections.

Since CO data are relatively common, INGAA members provided data summaries for review and compilation. A significant amount of CO data were collected for lean burn engines, especially 2SLB engines, which are the most common units used in gas transmission. Formaldehyde data for 4SRB engines were generally not available. Since formaldehyde data are sparse, INGAA understands that other efforts are underway to test 4SRB engines and recommends that EPA consider those data for establishing 4SRB standards.

This report presents the results of the INGAA emissions data collection effort and provides CO emissions data for 2SLB and 4SLB engines. A summary of the engine types and collected data presented in this report includes:

- CO emissions test data from over 400 natural gas-fired engines, including 85 four-stroke lean burn engines and 325 two-stroke lean burn engines;
- Over 3,000 test runs and 1,000 individual tests (i.e., 3 test runs are common for many compliance tests);
- Most engines are larger than 500 hp, consistent with the population of existing gas transmission engines, but test data are included for engines 500 hp and smaller.

Engines with multiple tests and multiple test conditions across the operating envelope are of special interest for assessing emission variability. Data review indicates that many engines had four or fewer test runs (i.e., a single "test" often includes 3 or 4 "test runs" at a single operating condition). The number of test runs per engine varied from one to over fifty. Based on Court decisions, EPA's approach for standard development assesses variability on emissions from the best performing 12% of sources (i.e., "MACT floor units"). Thus, it is informative if MACT floor units have emissions data at multiple test conditions and across the operating range.

In addition, INGAA and its members have actively engaged in other emissions testing programs for over 15 years. These include projects at the Colorado State University (CSU) Engines and Energy Conversion Laboratory (EECL) engine testbed, which includes a 2SLB engine common in gas transmission. For example, in 1999 EPA funded testing on the CSU 2SLB engine to develop data for the original RICE MACT standard, and gas transmission stakeholders participated in that effort through the Pipeline Research Committee International (PRCI) and Gas Research Institute (GRI). Compared to engines in field operations where tests are predominantly high load compliance tests, this 2SLB engine provides data over a broader range of standard operating conditions. As noted in the June 2009 INGAA comments, these tests may provide data to assess emissions variability. Thus, data from the CSU 2SLB engine are included in this report, and the test data from the 1999 EPA study are supplemented with additional CSU data. EPA also funded 4SLB engine tests at CSU. Unfortunately, that engine was sited at the test bed for only a sort time and additional data beyond the EPA program are not available for the 4SLB engine. The EPA test data are already in the rule docket. The CSU 2SLB data are discussed in Section 4. In addition, 2SLB data from recent testing completed by compression service providers is included in this report, as discussed in Section 4.

While this is primarily a “data report”, the document includes analysis and discussion that provide a technical summary of the collected data. In addition to this introduction, Section 2 of this report discusses the process associated with the “MACT floor” analysis based on INGAA’s understanding of Clean Air Act requirements and recent Court cases. This “process” includes identifying the best performing 12% of engines and assessing variability from that engine population. Section 3 presents summary data and tables for the 4SLB engine subcategory. Section 4 presents summary data and tables for the 2SLB engine subcategory. Section 5 summarizes the results and conclusions. Detailed data and quality assurance information are provided in appendices. Appendix A provides data tables for the 4SLB engines and Appendix B provides data tables for the 2SLB engines. The table format includes a unique engine identifier, test run identifier, engine information (e.g., make, model, type), test information (e.g., test date, engine load), emissions data, and averages of multi-run tests if more than one test-run is completed at a single operating condition (e.g., compliance tests). In addition to these appendices, supplementary information such as test reports and test validation documentation for engines that populate the MACT floor will be provided to EPA separately.

2.0 MACT Floor Determination: Basis and Analysis Approach

Appendices A and B provide the data from the INGAA collation of reciprocating engine emission tests. Appendix A presents 4SLB data and Appendix B presents 2SLB data. For tests (e.g., compliance tests) with multiple test runs (typically three runs) at the same engine operating condition, the average of the runs is presented and each test run is shown as a separate row. These data are summarized in Sections 3 and 4, and INGAA includes analysis and discussion of our perspective of this dataset, including identification of the “MACT floor” and consideration of variability. This section discusses the basis for the analysis in this report.

Section 112(d)(3)(A) of the Clean Air Act requires that emission standards for existing engines be based on “the average emission limitation achieved by the best performing 12% of the existing sources…”. This emission level is typically referred to as the “MACT floor”. As discussed below, decisions from the D.C. Circuit Court support the consideration of variability in establishing the emission standard. The analysis and discussion in Sections 3 and 4 focus on the engines that comprise the MACT floor with data for all engines in the Appendices. The methodology for defining the MACT floor engines is discussed below.

For this analysis, INGAA considered the Clean Air Act, Court decisions regarding the basis for determining Section 112(d) emission standards, EPA’s analysis for existing compression ignition engines in the March 3, 2010 RICE NESHAP amendments, and recent EPA MACT floor analysis from other NESHAP rules. In addition, this analysis is supplemented by INGAA’s understanding of reciprocating engine emissions, the inherent variability in emissions from natural gas-fired reciprocating engines, and operating conditions such as load that can affect lean burn engine CO emissions.

For lean burn gas-fired engines, the proposed rule establishes CO as a surrogate for HAP emissions such as formaldehyde. In discussions with INGAA, EPA has indicated that it is acceptable to complete the MACT floor analysis based on CO emissions data, and companion HAP data (e.g., formaldehyde) are not necessary. Since CO measurement is common in compliance tests, available test results offer considerable data and the INGAA data collection focused on CO emissions data. Since formaldehyde emissions testing typically has not been required and formaldehyde is more difficult to measure than CO, it was expected that very little formaldehyde data would be available from previously conducted tests. This was verified in the data collection effort.

INGAA understands that EPA will complete a MACT floor analysis based on available data, including the data in this report. INGAA is compelled to provide its perspective of the MACT floor analysis and consideration of variability based on Clean Air Act requirements and recent Court decisions. Because there are many existing reciprocating internal combustion engines and it is not feasible to have a detailed understanding of emissions from all engines, any available dataset will have inherent limitations or deficiencies and those limitations need to be considered in the analysis. For example, although this report provides considerable data from many engines, there are limitations that could result in an unreasonable outcome depending upon the technical analysis of the data. INGAA compiled data from previous tests and some limitations include:

- The CO data are primarily from previous compliance emission tests. The CO emissions data were not collected as part of a comprehensive testing project with specific objectives to understand either "best performing" CO levels or emission variability. Thus, the dataset characteristics strongly reflect compliance test criteria;
- Almost all the test data are from compliance tests such as annual performance tests or quarterly portable analyzer tests. These tests are typically driven by NOx concerns that require high load tests. The proposed rule requires compliance at all operating conditions including low load, and it is commonly understood that lean burn engine CO emissions increase at lower load. CO test data at low load are sparse; thus, the collective data set significantly under-represents low load operating conditions and bias the data, on average, towards high load conditions with lower characteristic CO emissions and higher NOx emissions.
- The number of tests for any particular engine varies from one test , which often includes three test runs at one operating condition, to numerous tests conducted over a period of years and/or at various operating conditions. As discussed below, this influences the preferred approach for identifying best performing engines when comparing emissions in the dataset – i.e., which emissions data are used to determine the best performing engines when considering engines with multiple tests.

2.1 Identifying Best Performing Units

The March 2009 proposed rule established the "MACT floor" technology as an uncontrolled engine – i.e., no add on HAP controls are applied. INGAA supports that conclusion, and the analysis for RICE subcategories is not complicated by multiple HAP or CO control technologies within the INGAA data population. The INGAA CO emissions data are from engines that do not include CO controls – i.e., do not include an oxidation catalyst.

INGAA understands that EPA plans to focus on the best performing units (i.e., data from the best performing 12%) when assessing variability. However, different approaches can be considered, and have been used by EPA in NESHAP rules, to identify the best performing units in the dataset. Since the engines in this report include some engines with single or very few tests and other engines with multiple tests at various times and/or operating conditions, the basis of this comparison is important.

In addition, some tests include multiple test runs at a single operating condition – i.e., three tests runs that are averaged for a compliance test. Other tests in the data set are single runs. The analysis approach needs to identify how data will be treated for tests with multiple test runs completed at a single operating condition.

Based on docket documents, INGAA understands that for the March 2010 compression ignition NESHAP amendments, when multiple test *runs* are available for a *single test condition*, such as three "high load" test runs for a compliance test, EPA used the *average* of the multiple runs (i.e. the test average) when comparing emissions data between engines to identify the best performing 12%. If only a single run is available at a particular test condition (e.g., prevalent for test data from EPA-sponsored and other tests at the Colorado State University engine test bed), that single test result is used for the inter-engine comparison to identify the best performing 12%. INGAA uses this same approach in the Section 3 and Section 4 discussion.

The next step is to consider how to evaluate engines and compare data between engines when some engines have multiple tests. This comparison "ranks" the engines and identifies the best performing 12% of the engine population. In the INGAA data set, engines with multiple tests include engines tested at different times (e.g., annual or quarterly compliance tests over a period of time), and, to a lesser extent, engines tested at multiple operating conditions (e.g., multiple loads). As described below, INGAA recommends that for engines with multiple CO emission tests, the *lowest or best performing CO emissions* from each engine should be used for engine-to-engine comparisons to identify the best performing 12%. This approach bases the comparison on the best performance for each individual engine, and provides the best assurance that tests completed at similar operating conditions (e.g., tests at high load) are compared when defining the engines that comprise the top 12%.

To further explain, consider an alternative approach where the *highest* CO emissions are used for engine-to-engine comparisons when an engine has multiple tests. Since the CO data compiled from INGAA members are typically from compliance tests, high load is the norm. Thus, for engines in the data set with a single test, a high load test with lower characteristic CO emissions is most likely. Alternatively, an engine with multiple tests may have data over a broader array of conditions, including changes to load or other parameters that can impact CO such as the air to fuel ratio (i.e., AFR which reflects the amount of excess combustion air) or ambient conditions (e.g., summer versus winter tests). The prevalence of compliance test data also ensures that multi-test engines very likely include data at full load with lower characteristic CO emissions.

If the top 12% is selected based on comparing the highest CO from multi-test engines, it is likely that an operating condition with higher characteristic CO emissions (e.g., lower load and/or higher AFR) from the multi-test engine would be compared to a full load test with lower characteristic CO emissions for the single-test engine. This is an inequitable comparison which will result in multi-test engines being precluded from or limited in the engine population that comprises the best performing 12%. In addition, this approach prevents the comparison of CO emissions at *common operating conditions* (e.g., high load and nominal AFR) for the multi-test versus single test engines, and also prevents consideration of operating conditions that reflect "best performance" for multi-test engines.

Based on this understanding of the emissions dataset and associated test conditions, INGAA believes that the most logical and technically preferred approach is to compare engine-to-engine data under similar operating conditions where feasible. Such a comparison has a higher probability of identifying the better performing engines. For example, comparing CO emissions from two engines at high load provides an indication of the better performer. However, comparing high load emissions (with lower characteristic CO) from one engine with low load emissions (with higher characteristic CO) from another engine does not provide a reasonable basis for assessing which engine is the better performer because there is a discrepancy in load, a key operating parameter that is known to impact lean burn engine CO emissions.

Engine emission characteristics also support the common operating condition comparison that is best achieved by comparing lowest emissions from multi-test engines. For example, for lean burn reciprocating engines, it is generally expected that CO emissions are more variable across the range of typical engine conditions (e.g., load and AFR) on an individual engine than the variability that would be reflected by comparing multiple similar engines at a common high load operating condition. If all engines in the dataset were tested under a similar range of operating conditions and had a similar number of test points, this issue would be less compelling. However, for the data provided in this report, where the number of tests per engine varies from a single test on many engines to more than ten tests on other engines, this analytical approach is important not only for defining best performers, but also for providing the ability to consider data from multiple tests to better understand emissions variability.

While the alternative approach (i.e., identifying MACT floor engines based on highest CO emissions) is not detailed in this report, INGAA review of the dataset confirms the concerns expressed here: sorting the data based on the best performing or lowest CO emissions for multi-test engines results in many engines with multiple tests in the MACT floor (as shown in Sections 3 and 4); in contrast, an alternative that sorts the engines based on maximum emissions results in nearly all of the MACT floor engines being single test engines (i.e., CO based on one test run or one, three run test at a single operating condition). The latter outcome hinders the ability to assess emissions variability for the best performing 12% of engines. It also fails to identify the engines with the best CO emissions performance.

Thus, INGAA strongly recommends that the "best performing" engines within a subcategory be based on selecting the lowest CO test from multi-test engines for comparison with other engines. INGAA believes that this approach is consistent with the Clean Air Act and has the most technical merit for equitably comparing engine emissions performance and identifying best performing engines. In addition, since this approach will limit the likelihood that multi-test engines will be inappropriately excluded from the "MACT floor" engine population, this approach also facilitates consideration of the range of emissions for best performing engines and CO emissions variability. INGAA analysis and discussion in Sections 3 and 4 use this approach for identifying the engines in the "MACT floor".

2.2 MACT Floor Variability

As noted above, EPA has indicated that review of emissions variability should be limited to the "MACT floor" units – i.e., the engine population in the best performing 12%. This report does *not* discuss possible alternatives to this interpretation for the variability assessment; however, the EPA approach does introduce limitations when considering the vast array of engine types and applications.

For example, it is commonly understood that ambient conditions (e.g., temperature, humidity or precipitation) and elevation can impact emissions. Both higher elevation and cooler ambient temperature can increase CO emissions. If data from the MACT floor engine population are limited to engines at lower elevation or from warmer weather tests, than variability associated with these factors will not be captured. In addition, some engines with multiple tests over a broad range of operating conditions may provide informative emissions variability data; however, if the lowest CO emissions are not within the best performing 12%, then that data set is not included in the analysis.

These factors, along with the fact that the CO data in this report are not based on a test program designed to characterize and understand variability but rather are primarily from high load compliance tests, indicate that the emissions variability in the data set is likely to be conservative and under-estimate the CO emissions variability that will occur on best performing engines in practice. The INGAA data represent a relatively large data set, and it is understood that there are practical limitations to the amount of data and emissions characterization studies that can be completed for an equipment category as diverse as reciprocating internal combustion engines. Nonetheless, it is important to consider these limiting factors when assessing variability.

This report is an "emissions data report" with complementary technical discussion, and detailed citations and legal justification for considering variability are not provided. However, a review of recent Court decisions provides insight into assessing variability when establishing the MACT floor for existing engines. The 2007 Brick MACT encapsulates many of these decisions by referring to the recent record from other NESHAP challenges. Examples include:

- The Brick MACT decision reiterates a finding from the 2001 Cement Kiln MACT decision and a related 1999 decision where the D.C. Circuit Court explained, “EPA would be justified in setting the floors at a level that is a reasonable estimate of the performance of the ‘best controlled similar unit’ under the worst reasonably foreseeable circumstances.”
- “Cement Kiln” also acknowledges that it is acceptable for EPA to consider the range of emissions from the best performing sources and that results at more adverse conditions “are more helpful than normal operating data would be in estimating performance under a variety of conditions and thus in helping to assure that properly designed and operated sources can achieve the standard.”
- The Brick MACT decision also references the 2003 Mossville Environmental Action versus EPA decision in which the D.C. Circuit Court “…held that floors may legitimately account for variability because “each [source] must meet the [specified] standard every day and under all operating conditions.”
- A similar theme is evident in a 1999 Sierra Club versus EPA decision noting that the MACT floor standard must be achieved at all times and relevant factors should be considered, “under the most adverse circumstances which can reasonably be expected to recur.”

Thus, it is acceptable and expected for EPA to consider emission levels associated with normally anticipated and recurring operating conditions, and Court decisions acknowledge that data from more adverse operating conditions may better inform the basis of the standard. For the context of the lean burn engine emission standard considered in this report, higher CO emissions associated with reasonable operating conditions likely to recur are of special interest. These operating conditions and associated emissions are of interest due to the nature of the dataset, where high load compliance tests are prevalent due to the basis for historical engine tests. Thus, the data distribution is not indicative of actual day-to-day operations and more adverse conditions (for CO emissions) such as low load are significantly under-represented.

In addition, Court cases buttress EPA’s position that the floor should not be based on “worst performer” units with the MACT floor technology (i.e., lean burn engines without HAP/CO control for this standard) that are not within the best performing 12%. For example, the Brick MACT decision references a Cement Kiln MACT finding, “…that EPA may not use emission levels of the worst performers to estimate variability of the best performers without a demonstrated relationship between the two…”. Demonstrating a relationship could provide an avenue to consider variability from units outside the top 12% (e.g., a unit not within the floor that is the same make and model as a MACT floor unit but located at a different elevation). However, this is not pursued in the analysis in this report.

In summary, in considering variability, INGAA recommends that EPA:

- Identify “best performing” engines based on the lowest CO emissions for engines with multiple tests;

- Incorporate the range of emissions from best performing engines into the standard setting process;
- Consider whether the operating conditions associated with higher CO test results points are within the envelope of reasonable operations and likely to recur;
- Consider that the CO emission data distribution for this dataset is not indicative of actual day-to-day operations and more adverse conditions for CO emissions such as low load are under-represented;
- Consider that the units must meet the standard every day and under all operating conditions; and
- Establish a standard that MACT floor units can meet if operating "under the most adverse circumstances which can reasonably be expected to recur."

In Sections 3 and 4, data are summarized for the engines that comprise the best performing 12%. The analysis and discussion of the CO emissions data collected by INGAA are based on the principles discussed above.

3.0 Data Summary and Discussion: Four-Stroke Cycle Lean Burn Engines

This section discusses the CO emissions data for 4-stroke lean burn engines, and focuses on emissions for the best performing 12% of engines. CO emissions data are available from eighty-five 4SLB engines with over 1,000 test runs. Engine size ranged from approximately 600 hp to 7,800 hp and includes large bore, slow speed "integral" engines and higher speed separable engines. Integral engines are common in gas transmission and include the engine and compressor (i.e., driven equipment) in one package with both driven off a common crankshaft. For separable engines (e.g., Caterpillar and Waukesha engines), the driven equipment (e.g., compressor, pump, electric generator) is a separate package linked to the engine drive shaft.

Because these data are from gas transmission, the most prevalent engine manufacturer in the data set is Ingersoll Rand, which is the primary 4SLB integral engine manufacturer. Other engine manufacturers represented within the data set include Cooper Bessemer, Caterpillar, Waukesha, Superior, and Wartsila. Since INGAA members participated in the EPA testing for the RICE MACT at the Colorado State University EECL, the CSU Waukesha 3521GL engine is included in this report. Emissions data are in Appendix A, but this 4SLB engine is not in the best performing 12%.

The emissions review and analysis, and data presentation are consistent with the discussion in Section 2. When a single test included multiple test runs (e.g., 3-run compliance test), the average of the three runs was used for comparison with other engines. This is consistent with the EPA diesel engines data presentation for the March 2010 RICE NESHAP amendments. When an engine has data for more than one test, the lowest (i.e., best performing) emissions level from the multiple tests was used for comparison with other engines. Based on this comparison, the engine population that comprises the best performing 12% was identified. Eighty six engines were evaluated and eleven engines comprise the best performing 12%. This evaluation is termed the "MACT floor" and these engines are referred to as "MACT floor units" or "MACT floor engines" in this report.

All of the 4SLB data are presented in Appendix A, with the individual tests associated with the eleven MACT floor engines presented in Appendix A-1 and the remaining engines in Appendix A-2. Each test run is shown in a single row in the data tables, and the average of multiple runs at a common operating condition is shown where applicable. INGAA members provided summary data and test reports for MACT floor engines will be provided to EPA separately.

For both 4SLB engines and 2SLB engines in Section 4, standard test methods were used. Tests were typically to demonstrate compliance with emission limits (e.g., annual tests, quarterly tests) or in some cases to collect data for initial Title V permits or define an engine specific emission rate. Standard methods were used including EPA reference methods (e.g., Method 10 for CO), the ASTM portable analyzer test method, or other standard portable methods (e.g., state sanctioned methods). Additional detail on test methods and data quality assurance for MACT floor engines is available in test reports that will be provided separately.

Table 1 presents summary information for the best performing 12% of the engines (i.e. the MACT Floor units), including the minimum emissions, maximum emissions, number of tests, and horsepower range for the tests. The engines are ranked based on the minimum emission level. In addition to the MACT floor units, the next two best performing engines are shown to indicate the next units that would be included in the MACT floor if the number of MACT floor units changes (e.g., other data are available that increases the number of MACT floor units). In addition, Table 1 indicates whether the engines are equipped with low emission combustion (LEC) technology for lower NOx emissions. LEC is a technology difference that could warrant a separate subcategory, but since both engine types are represented in the floor, this does not appear necessary.

Table 1. Summary of INGAA CO Emissions Data for 4SLB MACT Floor Units[A]

Performance Rank	ID No.	Make	Model	CO (ppm, 15% O_2) Min	CO (ppm, 15% O_2) Max	# Tests[E]	Min. Load Tested (%)	hp Range Tested[B]	LEC[C]
1	1	Ingersoll Rand	512 KVS	114	214	16	78	1,959 – 2,508	Yes
2	2	Cooper Bessemer	LSV-16	123	140	3	78	3,347 – 4,278	No
3	3	Ingersoll Rand	36 KVS	124	270	16	76	798 – 1,044	Yes
4	4	Ingersoll Rand	KVH-616	128	240	13	57	2,393 – 4,209	No
5	5	Ingersoll Rand	512 KVS	131	226	16	80	1,626 – 2,040	Yes
6	6	Cooper Bessemer	LSV-16	135	144	3	82	3,550 – 4,323	No
7	7	Ingersoll Rand	36 KVS-FT	137	375	11	47	472 – 990[D]	Yes
8	8	Ingersoll Rand	36 KVS	139	298	16	71	705 – 987	Yes
9	9	Caterpillar	G3516	141	196	5	76	659 – 861	Yes
10	10	Ingersoll Rand	KVT 512	149	226	6	67	2,024 – 2,921	No
11[A]	11	Ingersoll Rand	KVSR 412	153	223	2	88	1,793 – 2,044	Yes
12	12	Waukesha	3521GL	154	338	3	75	582 – 782	Yes
13	13	Superior	12SGTB	159	254	38	79[F]	1,611 – 2,026[F]	Yes

[A] The first eleven engines comprise the MACT floor from the INGAA data. The next two best performing engines are also listed.

[B] Maximum horsepower tested is at or near maximum rated load.

[C] Low (NOx) Emission Combustion configuration (e.g., enhanced ignition and/or mixing, pre-combustion chambers, turbocharging).

[D] Engine ID No. 7 included "operating map" testing in March 2006. Multiple operating conditions were run to map the engine from 47% to 99% load. This is the broadest load range tested for any of the 4SLB engines in the MACT floor and the highest CO emissions are associated with the low load test condition.

[E] Number of "tests" at unique conditions; not number of test runs. A multi-test run average (e.g., 3-run compliance test) is counted as 1 test.

[F] Load not available for all tests associated with quarterly portable analyzer tests.

3.1 Comparison with EPA 4SLB Data

INGAA discussed the EPA database emission data for 4SLB engines in its June 2009 comments. Those data are not presented in this report, but INGAA briefly reviewed the EPA data for comparison to the engines and CO emissions in Table 1. There are about 12 uncontrolled 4SLB engines in the EPA database with CO emission levels ranging from less than 100 ppmv to 420 ppmv. Two or three engines have "best performing" CO emissions commensurate with the MACT floor engines in Table 1. Nearly all of the tests are at relatively high load (80% or higher) and there are no engines with multiple tests that include low load (i.e. < 60 - 70%) data in the EPA data set. The EPA CSU engine was tested at loads as low as 59% of full load with CO emissions as high as 420 ppmv, but its lowest emission test was over 200 ppmv and thus it is not in the best performing 12% of the engine population.

If the EPA database engines are combined with the INGAA 4SLB data, the new total engine count would result in twelve or thirteen total engines in the MACT floor; these would include two or three engines from the EPA database (i.e., engine-specific identification is not clear in the EPA database and a "MACT floor" engine from the EPA database may be two similar engines or a single engine with multiple tests). These engines were tested at one point in time at high load and do not provide insight into variability. Thus, integrating the EPA and INGAA engines into a single data set should not significantly impact the determination of the MACT floor units shown in Table 1. In addition, that data integration should not significantly impact the variability analysis.

As discussed in Section 2, INGAA believes that the variability analysis needs to consider the range of emissions, and the related operating conditions for the emissions. The data in Table 1 and Appendix A document that nearly all the emission tests were conducted at higher load, typically 80% load or higher, and there are very few low load tests. The lack of low load data is not indicative of the typical operating profile for lean burn engines in common applications, but rather due to the preponderance of compliance tests emissions data, where high load is typically required for demonstrating compliance with NOx limits. Variability review should thus value tests on lean burn MACT floor engines that are completed over a range of operating conditions, such as load, because these tests provide more insight into emissions variability and operation under adverse conditions. This is consistent with the Court's conclusion, noted in Section 2, that data under more adverse conditions are more helpful in establishing the standard.

Based on the March 2010 RICE NESHAP, the emission standard will apply under all operating conditions other than startup. Thus, the operating conditions associated with CO emissions data for the MACT floor engines must be considered when assessing variability. This approach is warranted to achieve the directive of recent Court decisions that units must comply every day and under all operating conditions, and that it is reasonable to establish a standard that MACT floor units can meet if operating "under the most adverse circumstances which can reasonably be expected to recur." Lower load is a common and recurring condition for engines.

3.2 Variability and Factors that Influence 4SLB CO Emissions

For many gas transmission applications, it is commonly understood that a reciprocating engine is the preferred compressor driver (i.e., rather than a combustion turbine) because a reciprocating engine performs better at reduced load and increases operational flexibility. While higher load operation is generally preferable and inherent to pipeline system operating principles, gas transmission operations respond to pipeline demands, which require operational flexibility and lower load operation. Thus, reciprocating engines will continue to be an integral component of natural gas pipeline operational flexibility, and lower load operation is and will continue to be an inherent part of reciprocating engine operations in natural gas transmission. However, as discussed in Section 2, available emissions data are predominantly from high load compliance tests. The 4SLB data in the EPA database are also primarily high load data. With lower load significantly under-represented in the available data, special consideration of low load data is warranted when assessing emissions variability.

Thus, even though the INGAA data set includes many engines and test points, the population of test data is predominately from high load compliance tests, and the data do *not* adequately or uniformly encompass or capture emissions under more adverse conditions, such as operation at lower load operation or leaner air-to-fuel ratio where CO emissions will be higher. Since the MACT floor emission limit must be achievable at all times, proper consideration of emissions variability and the range of potential engine operating conditions is imperative to the analysis. "At all times" achievability should not be overlooked or dismissed when establishing the MACT floor, because failure to assess lower load operation and reasonable operating envelopes could result in technically questionable conclusions. This issue is discussed further below. Section 4.2 on 2SLB engines provides a hypothetical example of how data from more adverse operating conditions better inform the variability assessment. The example in Section 4.2 illustrates why it is reasonable to consider the relevance of data that better capture emissions over a range of operating conditions when assessing variability and that same rationale applies for 4SLB engines in this data set.

From Table 1, only one of the 4SLB MACT floor engines has data over an operating envelope that includes less than 50% load – the Ingersoll Rand 36 KVS-FT engine, the seventh engine listed in Table 1 with Unit Identification Number 7. The tested load range is well within normal operating scenarios and lower load operation (i.e., lower than 47% load) will recur in practice for gas transmission engines. This engine is rated at 1,000 hp and was purposefully tested over a range of common operating conditions in March 2006. This existing dataset is especially valuable because it provides better insight into adverse operating conditions and emissions variability across common operating conditions than other 4SLB engines in the INGAA data set. The test data for this engine are presented in Appendix A-1 and summarized in Table 2. The engine was tested over a range of common loads and speeds; but even for this more robust data set the minimum load was 47%, and lower operating loads occur in normal operation.

Table 2. CO Emissions Summary for Ingersoll Rand 36 KVS-FT.

Test No.	Load (hp)	Speed (rpm)	% load	$\%O_2$	CO (ppm, at 15% O_2)
1	573	270	57	12.4	230
2	472	270	**47**	13.4	**375**
3	990	330	99	11.8	137
4	926	300	93	12.2	202
5	853	270	85	12.1	182
6	725	270	73	11.9	207
7	795	300	80	11.0	200
8	872	330	87	11.0	175
9	752	330	75	11.2	213
10	675	300	68	10.9	178
11	571	270	57	11.2	182

The Ingersoll Rand 36 KVS-FT engine data demonstrate expected CO emission trends, with CO lowest at high load and increasing with lower loads. Although these data represent a more complete range of operating conditions and loads than other 4SLB MACT floor engines, the data do *not* capture the full range of expected operating conditions. For example, engine operation at lower than 47% of rated load will occur for gas transmission engines during normal operations. These March tests occurred at relatively cool ambient temperatures of 29 to 37^{o}F, but this range does not represent minimum temperatures for this site, and lower temperature can increase CO emissions.

Thus, while the test at 47% load represents the most adverse condition for this particular test program, it is not indicative of the most adverse condition likely to recur – i.e., lower load and/or cooler temperature are two parameters that will adversely effect CO emissions and would likely result in higher CO emissions over the course of annual operation. Those effects are not captured in this data set or other data that are available for this review, but support the assertion that 375 ppmv CO (at 15% O_2) for the low load (47%) test does not fully address the variability that is inherent to this MACT floor engine.

The data set for this MACT floor analysis is imperfect, and it is clear that the range of emissions (i.e., variability) for the MACT floor engines is limited by the fact that most tests were conducted at high load for compliance purposes, while the standard will require compliance under all operating conditions. Similarly, even the most robust test data within the MACT floor engines are limited by the testing completed. The 2006 test was not designed or conducted to evaluate emissions over the full range of operating conditions, but fortuitously included tests at lower load than other MACT floor units, as well as high load tests. Thus, when considering operating conditions and emissions variability that are likely to recur for MACT floor engines, it is reasonable to conclude that a 4SLB CO standard of at least 375 ppmv is warranted.

While INGAA understands that the regulatory criteria and standards differ, this emission level can be compared with other emission results and technology driven standards to provide context. For example, the spark ignition RICE New Source Performance Standard (NSPS) is based on "best demonstrated technology" for *new* engines and the NSPS does not require catalytic control – i.e., the technology basis is similar to the RICE NESHAP MACT floor. The NSPS CO standard is 540 ppmv (at 15% O_2) for new, modified and reconstructed engines, and decreases to 270 ppmv for new, non-emergency units manufactured after 2010 or 2011 (date depends on NSPS subcategory). Thus, the most adverse emission level shown in Table 2 is within the range of anticipated CO emissions for a new engine with best demonstrated technology. For another comparison, the EPA-sponsored 4SLB RICE MACT tests at CSU include testing over a reasonable operating envelope, but the minimum load was only about 59% of rated capacity. CO emissions for those tests ranged from 305 to 420 ppmv, with the highest emissions actually from a higher load test with marginally leaner operation (i.e., slightly higher excess O_2).

4.0 Data Summary and Discussion: Two-Stroke Cycle Lean Burn Engines

This section discusses the CO emissions data for 2-stroke lean burn engines, and focuses on emissions for the best performing 12% of engines. The majority of compressor drivers in the U.S. natural gas transmission sector are 2SLB integral engines. Because of this prevalence, there are many tests available; however, as discussed in Section 3 for 4SLB engines, the vast majority are high load compliance tests in response to NOx requirements. Data are available from 325 engines with over 3,000 test runs. Despite this wealth of data, there are still limitations due to the lack of low load tests. In addition, the 2SLB engine category could be more complicated due to technical differences inherent to engine design that could warrant the need for additional subcategories. Example technical differences include cylinder displacement (i.e., size), air supply (e.g., turbo-charged, piston scavenged), and air flow (e.g., "uniflow" versus loop scavenged designs).

These and other factors present technical differences that affect the engine "type" and characteristic emissions – and thus may warrant consideration for additional 2SLB subcategories. However, INGAA believes that with proper consideration of variability, the emission differences for different 2SLB engine types are minimized. Thus, despite these design differences, it may be feasible to avoid additional subcategorization if a MACT floor engine has test data over a broad enough range of operating conditions to encompass emissions variability indicative of performance for the MACT floor engines for different possible subcategories – i.e., variability exhibited across the operating envelope may reasonably capture the emission differences due to design and operational differences between 2SLB engine types. Or, expressed another way, while the lowest or best performing emissions for different possible subcategories may be significant and reflective of different engine types, emissions variability across the operating range for different engine types may suppress some of the differences seen at the "best performing" point (i.e., lowest emissions exhibited at high load and nominal speed and AFR). These issues are discussed further below, after the summary data for "MACT floor" engines are presented.

Two-stroke lean burn engines are typically large bore, slow speed integral units and the size of tested engines ranged from under 300 hp (Ajax engines) to more than 10,000 hp with most engines from 1,000 to 4,000 hp. The most prevalent 2SLB engine types (based on manufacturer) are Cooper Bessemer, Clark, Worthington, and Cooper Cameron (Ajax). Within the engine lines produced by these manufacturers, operated by INGAA members, and represented in the INGAA dataset, there are more 2SLB engine models in this report with unique design and technical attributes than 4SLB engine models with design and technical attributes that significantly impact CO emissions. These array of differences are due in part to different ways of "handling the air" to promote cylinder scavenging (i.e., sweep out the exhaust products for the two-stroke cycle).

In addition to the INGAA data, 2SLB Ajax engine test data is presented in this report from the Exterran, JW Power and CSI (EJC) Group that also recently submitted a test report to EPA for rich burn engines. The Ajax engine CO emissions tests completed during the EJC test program were limited in scope. The CO data were reviewed along with the INGAA data and CSU engine data (discussed below). None of the Ajax engines, including an Ajax engine operated by an INGAA member, exhibited CO emissions low enough for inclusion in the MACT floor. Thus, the data for these engines are shown in Appendix B-3 with units that comprise 88% of the 2SLB engine population that are not MACT floor engines.

In addition, INGAA members participated in EPA testing for the RICE MACT at CSU, and the CSU Cooper Bessemer GMV-4TF engine is included in this report, with a separate section discussing the engine and emission results. This engine is extremely important to the 2SLB engine dataset because:

- The Cooper GMV engine is the most prevalent engine model in natural gas transmission. There are several different primary designs mainly differentiated by air handling (e.g., piston scavenged, blower scavenged, turbo-charged);
- The CSU engine cylinder bore and stroke, parameters that impact emission performance, are characteristic of in-service engines. While the CSU engine has a lower full load rating than most field applications of Cooper GMV engines, this difference is due to the number of cylinders – i.e., four cylinders for the CSU engine where eight is the most standard GMV configuration. Despite this difference in maximum rating, the key "size" characteristics (cylinder bore and stroke) and engine systems that impact performance and emissions for the CSU GMV-4 are the same as GMV engines with more cylinders and higher rated capacities.
- The EPA-sponsored tests at CSU captured some operational variability. As discussed below, the "best performing" CO results from the CSU test matrix for the EPA-sponsored RICE MACT testing are just marginally higher than the threshold that defines the best performing 12%. Thus, the engine would not be a MACT floor unit based solely on the EPA tests. However, this engine has been used for numerous other studies and supplemental data are available from "standard" engine configurations (i.e., not "experimental" configurations associated with technology review or development projects at the CSU test bed) with a wider range of emissions. Additional supplemental data are further discussed below and presented in Appendix B-2. CO emissions from these supplemental tests include test points with marginally lower (and marginally higher) emissions than from the EPA tests. This results in the CSU engine being in the best performing 12%, and thus establishes the engine as a MACT floor unit.

- For 2SLB engines, the full range of emissions data from the CSU engine provides the best data set to assess variability for 2SLB engines. Although, like other engines, low load test data are limited. The lack of low load emissions data is due to the historical focus on NOx emissions; because NOx emissions decrease at lower load for 2SLB engines, minimal low load data have been collected. However, some emission data are available for engine operation at lower loads and marginally higher air-to-fuel ratios, and these data provide an indication of CO variability at operating conditions that recur in practice for 2SLB engines.

The emissions review and analysis, and data presentation in this section are consistent with the discussion in Section 2. When a single test included multiple tests runs (e.g., 3-run compliance test), the average of the three runs was used for engine-to-engine comparisons. This is consistent with the EPA diesel engines data presentation for the March 2010 RICE NESHAP amendments. When an engine has data for more than one test, the lowest (i.e., best performing) emissions level from the multiple tests was used for comparison with other engines. Based on this comparison, the engine population that comprises the best performing 12% was identified. 325 engines were evaluated, so thirty-nine engines comprise the best performing 12% if all 2SLB units are grouped in a single subcategory. (A section below discusses the possible need for additional subcategories but INGAA believes that additional subcategories may not be necessary if emissions variability is assessed as discussed in Sections 4.2 and 4.3.)

All of the 2SLB emission test data are presented in Appendix B, with the MACT floor engines in Appendix B-1, CSU engine data tabulated in Appendix B-2, and the balance of the 2SLB engine population in Appendix B-3. Each test run is shown in a single row in the data tables, and the average of multiple runs at a common operating condition is shown where appropriate.

Table 3 presents summary information for the best performing 12% of the 2SLB engines (i.e. the MACT floor units) from the INGAA data set, including the minimum CO emissions, maximum CO emissions, number of tests, and horsepower range for the tests. The CSU engine is included in the MACT floor. The engines are ranked based on the minimum emission level. In addition to the MACT floor units, the next three best performing engines are shown to indicate the next units that would be included in the MACT floor if the number of MACT floor units changes (e.g., other data are available that increases the number of MACT floor units). In addition, Table 3 indicates whether the engines are LEC-equipped for lower NOx emissions. LEC includes technology differences that could warrant separate subcategories.

Table 3. Summary of INGAA CO Emissions Data for 2SLB MACT Floor Units (39 units comprise the top 12%).[A]

Performance Rank	ID No.	Make	Model	CO (ppm, 15% O_2) Min	CO (ppm, 15% O_2) Max	# Tests[E]	Approximate Min. Load Tested (%)	hp Range Tested[B]	LEC[C]
1	2S-90	Cooper Bessemer	GMVA-10	33	104	11	84%	1,110 – 1,318	No
2	2S-137	Cooper Bessemer	GMW-6TF	40	198	13	53%	596 – 1,117	No
3	2S-57	Cooper Bessemer	GMV-10TF	43	43	1	>90%	982 – 1,235	No
4	2S-80	Cooper Bessemer	GMVA-10	50	56	2	95%	1,235 – 1,300	No
5	2S-86	Cooper Bessemer	GMVA-10	51	108	10	80%	982 – 1,235	No
6	2S-79	Cooper Bessemer	GMVA-10	52	52	1	>90%	1,300	No
7	2S-145	Cooper Bessemer	GMV-8TF	53	142	13	75%	1,397 – 1,856	No
8	2S-96	Cooper Bessemer	GMVC-10	53	53	1	>90%	1,790	No
9	2S-132	Cooper Bessemer	GMW-10	53	325	5	72%	1,863 – 2,582	Yes
10	2S-55	Cooper Bessemer	GMV-10TF	54	54	1	>90%	875	No
11	2S-78	Cooper Bessemer	GMVA-10	56	56	1	>90%	1,270	No
12	2S-141	Cooper Bessemer	GMW-6TF	56	127	10	67%	927 – 1,379	No
13	2S-78	Cooper Bessemer	GMVA-10	56	56	1	>90%	1,270	No
14	2S-91	Cooper Bessemer	GMVA-10	57	114	12	78%	977 – 1,260	No
15	CSU[A,D]	Cooper Bessemer	GMV-4TF	58	407	98	62%	273 – 441	Y / N
16	2S-85	Cooper Bessemer	GMVA-10	58	91	10	86%	1,131 – 1,320	No
17	2S-87	Cooper Bessemer	GMVA-10	58	190	10	86%	1,137 – 1,325	No
18	2S-97	Cooper Bessemer	GMVC-10	59	59	1	>90%	1,780	No
19	2S-144	Cooper Bessemer	GMW-8TF	59	301	14	64%	1,240 – 1,948	No
20	2S-140	Cooper Bessemer	GMW-6TF	59	238	14	77%	967 – 1,254	No
21	2S-124	Cooper Bessemer	GMVH-8	59	59	1	>90%	1,790	No
22	2S-88	Cooper Bessemer	GMVA-10	61	161	10	89%	1,110 – 1,250	No
23	2S-105	Cooper Bessemer	GMVH-12	61	64	2	90%	2,457 – 2,737	Yes
24	2S-89	Cooper Bessemer	GMVA-10	62	98	10	75%	959 – 1,275	No
25	2S-82	Cooper Bessemer	GMVA-10	62	146	9	>90%	1,110	No
26	2S-108	Cooper Bessemer	GMVH-12	63	125	15	91%	2,489 – 2,725	Yes

Performance Rank	ID No.	Make	Model	CO (ppm, 15% O_2)		# Tests[E]	Approximate Min. Load Tested (%)	hp Range Tested[B]	LEC[C]
				Min	Max				
27	2S-115	Cooper Bessemer	GMVH-12	64	118	27	86%	2,418 – 2,824	Yes
28	2S-118	Cooper Bessemer	GMVH-12	64	117	27	87%	2,375 – 2,726	Yes
29	2S-134	Cooper Bessemer	GMW-6TF	65	135	13	55%	625 – 1,136	No
30	2S-119	Cooper Bessemer	GMVH-12	65	123	17	65%	1,775 – 2,739	Yes
31	2S-113	Cooper Bessemer	GMVH-12	67	122	27	73%	1,969 – 2,708	Yes
32	2S-95	Cooper Bessemer	GMVB-10	67	97	24	73%	1,026 – 1,400	Yes
33	2S-146	Cooper Bessemer	GMW-8TF	68	150	13	82%	1,467 – 1,800	No
34	2S-110	Cooper Bessemer	GMVH-12	68	128	27	80%	2,175 – 2,708	Yes
35	2S-83	Cooper Bessemer	GMVA-10	68	95	10	62%	811 – 1,303	No
36	2S-117	Cooper Bessemer	GMVH-12	69	122	27	84%	2,330 – 2,765	Yes
37	2S-112	Cooper Bessemer	GMVH-12	69	132	27	91%	2,541 – 2,787	Yes
38	2S-139	Cooper Bessemer	GMW-6TF	69	278	13	60%	749 – 1,253	No
39[A]	2S-84	Cooper Bessemer	GMVA-10	70	123	9	82%	1,010 – 1,235	No
40	2S-129	Cooper Bessemer	GMW-10	71	327	10	85%	2,021 – 2,374	No
41	2S-107	Cooper Bessemer	GMVH-12	71	117	16	89%	2,402 – 2,697	Yes

[A] The first 39 engines comprise the MACT floor from the INGAA data (plus CSU engine) and EJC Group data. The next two engines in the list are also shown.

[B] Maximum horsepower tested is at or near maximum rated load.

[C] Low (NOx) Emission Combustion configuration (e.g., enhanced ignition and/or mixing, pre-combustion chambers, turbocharging)

[D] The CSU engine is included in the MACT floor. Data are presented in Appendix B-2, and the data are discussed in Section 4.2.

[E] Number of "tests" at unique conditions; not number of test runs. Counts multi-test run average (e.g., 3-run compliance test) as one test.

4.1 Overview of MACT Floor Engines and 2SLB Engine Subcategories

INGAA discussed the EPA database emission data for 2SLB engines in its June 2009 comments. Those data are not presented in this report, with the exception of the CSU engine, as discussed below. There are about fifteen to twenty 2SLB engines in the EPA database, and several have emissions at or below the MACT threshold of 70 ppmv from Table 3. The integration of EPA engines with the data in this report would not have a significant impact on the analysis. However, in comparing CSU data, an apparent discrepancy was discovered. It appears that the EPA database recorded "as measured" CO values as "corrected to 15% O_2." The original CSU-EPA report was reviewed to confirm that the CSU CO emissions data presented in this document are correct and based on the original data in the report. (The report citation is provided in Section 4.3.)

The CSU engine is a Cooper Bessemer GMV-4TF engine and the MACT floor engines in Table 3 are all Cooper GMV and GMW engines. Other Cooper engine models, or Clark or Worthington engines are not represented in the MACT floor. This is likely due to two primary factors: Cooper engines are relatively "well-mixed" in comparison to Clarks and Worthingtons (e.g., Worthingtons use "uniflow" rather than "looped" air scavenging which significantly affects mixing), and the GMV and GMW series include many engines that are not turbo-charged. In addition, the GMV cylinders are smaller (smaller bore and stroke or swept cylinder volume) than nearly all other 2SLB engines in the INGAA dataset, with Ajax engines an exception. More recent vintage Cooper engines include turbochargers. Thus, a 2SLB floor comprised entirely of Cooper GMV and GMW engines could inappropriately represent other types of 2SLB engines, and additional subcategories may need to be considered to address different types of engines. However, if variability is appropriately considered, the need for additional subcategories may be mitigated.

INGAA understands that emission levels are not the basis for defining a subcategory. This decision must be based on unique size, type or class attributes according to the Clean Air Act. While detailed documentation is not provided in this report, there are distinct differences between different types of 2SLB engines, and those differences are reflected in the CO emissions data. Thus, for comparison to the summary emissions data provided in Table 3, Table 4 presents the best performing units for 2SLB engine types not represented in the MACT floor (i.e. engines other than Cooper GMVs and GMWs). In addition, detailed data in Appendix B show different characteristic emissions for different 2SLB engine types. There are inherent physical and operational characteristics within the 2SLB subcategory, and INGAA believes that additional subcategories based on different types of technology (or different size) could be justified and may be warranted. However, this would add complexity to rule development and implementation. Review of the emission ranges in Table 3 and Table 4 indicates that considering variability within the data set for GMVs – primarily based on more comprehensive data from CSU tests – offsets some of the CO emission differences evident at the lowest or best performing points. Thus, properly accounting for variability may in part reconcile emission differences that could otherwise compel INGAA to strongly support developing additional 2SLB subcategories.

Table 4. Summary of Best Performing 2SLB Engines Excluding Cooper GMV and GMW Engines.

Count	Make	Model	CO ppm (at 15% O_2)		LEC
			Min	Max	
1	Cooper	8V-250	73	80	yes
2	Clark	BA-5	83	194	no
3	Cooper	12V-250	84	87	no
4	Clark	BA-5	86	487	no
5	Clark	TLA-6	90	235	no
6	Cooper	12Q145HM	90	302	yes
7	Worthington	UTC-168	93	284	no
8	Worthington	UTC-168	94	94	no
9	Cooper	8W330	95	178	yes
10	Clark	BA-5	96	321	no
11	Cooper	12Q-145LM	98	300	yes
12	Clark	TCVD-10	101	277	yes
13	Worthington	UTC 168	103	143	yes
14	Cooper	16W330	104	216	yes
15	Cooper	8W330	104	181	yes
16	Worthington	UTC 168	108	256	yes
17	Clark	TLA-10	109	333	yes
18	Clark	BA-5	111	158	no
19	Worthington	UTC 168	112	115	yes
20	Clark	BA-5	116	645	no
21[A]	Clark	TLA-8	117	135	no
22	Worthington	UTC 168	118	131	yes
23	Clark	TLA-10	119	308	yes
24	Clark	TCVA-10	120	226	yes
25	Clark	TLA-6	122	217	no
26	Worthington	SUTC6	122	389	no
27	Clark	TCV-12	125	189	yes

[A] Clark, Worthington and Cooper Engines (excluding GMV and GMW) total 175 engines, thus 21 units comprise the best performing 12% for this engine group.

The lowest emissions (i.e., minimum CO) and cut point for the best performing 12 percent is higher for these engines than units in Table 3. In addition, some engines exhibit a significantly higher maximum. However, the upper end of the CO emissions range from the CSU data set (in Table 3) is similar in magnitude to some engines in Table 4. Appendix B data for all engines, including the 88% not in the MACT floor, indicate that many of the makes / models of engines in Table 4 have emissions significantly higher than the best performing units shown in Table 4.

Thus, the range of emissions (variability) in Tables 3 and 4 is not high enough to ensure that many of the engines in the INGAA data set can achieve those levels without additional action; that is, variability is not being assessed in this report as a convenient means to facilitate compliance, but rather as an imperative part of the standard setting process.

The range of emissions for the CSU engine provides a reasonable means to assess variability. If all 2SLB engines are grouped into one subcategory regardless of technical differences, then over thirty engines comprise the MACT floor and, as shown in Table 3, the CSU engine is included in the best performing 12 percent. However, if the engines in Table 3 are used to establish a standard without consideration of lower load and other common and more adverse operating conditions, then INGAA would recommend reviewing the need for additional subcategories. INGAA does not provide a detailed technical basis for subcategories in this report. However, if needed, that technical information can be provided so that the different 2SLB engine types can be better documented and subcategories can be supported.

4.2 Emissions Variability Assessment

As discussed in Section 3, reciprocating engines are preferentially used in gas transmission because of their operational flexibility and ability to perform reasonably well across a range of loads based on pipeline demand. INGAA believes that it is appropriate, technically justifiable, and consistent with D.C. Circuit Court directives to carefully consider the available emissions data that best captures the range of expected operations (i.e., adverse conditions that are reasonably likely to recur) when assessing variability. If an emissions dataset for variability analysis is homogeneous (i.e., all or most units tested under similar operating conditions that encompass the expected/normal range of engine operation), determining and considering which of the available emissions data best captures the range of expected operations is less of an issue. However, even though the INGAA data set includes many engines and test points, the population of test data is predominately from high load compliance tests and does *not* adequately encompass or capture emissions under more adverse conditions, such as lower load operation, where CO emissions will be higher. Since the MACT floor emission limit must be achievable at all times, proper consideration of emissions variability and the range of potential engine operating conditions is imperative to the analysis. "At all times" achievability should not be overlooked or dismissed when establishing the MACT floor, because failure to assess lower load operation and reasonable operating envelopes could result in technically questionable conclusions.

To illustrate this point, consider an example case where the initial step of MACT review has been completed and there are two "units" in the MACT floor. Both units utilize the same technology. As is commonly observed for engines, this example assumes that it is understood and technically supported that emissions for these units will vary across the operating envelope. One of the two units (unit 1) has a single data point measured at optimal operating conditions (e.g., full load, warm ambient conditions, and nominal air to fuel ratio for a lean burn engine). Conversely, unit 2 has emissions data from multiple test conditions. One test condition for unit 2 is identical to the unit 1 data point (high load, and nominal settings) and results in similar emissions. The other data points for unit 2 cover the full operating envelope and include a range of operating conditions at different points in time; that is, the emission data encompass seasonal variation (cold versus warm weather) and include a range of process operations. Although data from unit 2 show similar emissions under the similar optimal operating condition, significant variability is exhibited in its more robust data set. In this instance, it is appropriate and technically superior to assess variability based on the data set from the second unit.

In addition, if the unit 2 data are combined or integrated with the single test from the first unit, different weighting should be applied to the datasets. If each unit is assigned similar weighting, the technical insight on *variability* from the more complete data set will be compromised, and proper consideration will not have been given to the range of observed operating conditions that are likely to recur as reflected in the unit 2 data.

INGAA believes that it is imperative that technical objectives for assessing variability consider the range of reasonable operating conditions. In this example, that would mean that the variability assessment would consider the range of emissions associated with the more robust data set from the second unit, and limitations associated with the single data point from the first unit would be recognized.

Thus, the breadth of operating conditions and associated CO emissions data from individual MACT floor engines should be considered when assessing variability. This approach is warranted to achieve the directive of recent Court decisions that units must comply every day and under all operating conditions, that data under adverse conditions may be more informative, and that it is reasonable to establish a standard that MACT floor units can meet if operating "under the most adverse circumstances which can reasonably be expected to recur." Lower load is a common and recurring condition for engines that will impact CO emissions for lean burn engines.

4.3 Discussion of CSU 2SLB Engine Data and NOx – CO Tradeoff

The CSU Engines & Energy Conversion Laboratory Cooper-Bessemer GMV-4TF has four cylinders with 14 inch diameter cylinder bore and 14-inch piston stroke. The nominal speed is 300 rpm and the nominal maximum load is 440 brake-horsepower. This engine is used to characterize emissions and evaluate the impacts of ignition and mixing enhancements on engine performance. It has been instrumental in supporting the development of technologies that are reducing emissions in the existing gas transmission fleet. During the course of these evaluations, the CSU engine is often operated and tested at standard, baseline configurations to provide a benchmark for the particular project. The standard configurations, typical of the 2SLB engine population, include an open combustion chamber (OCC) design and a pre-combustion chamber (PCC) design. Emission data from multiple test projects that include standard configuration tests provide a dataset to evaluate emission variability for a single engine. In addition to OCC and PCC, some open chamber tests used multi-strike spark plugs. The CSU data incorporate the impacts of time (e.g., different ambient conditions, time lapse since engine maintenance) and normal range operating parameters (e.g. load, air-to-fuel ratio, ignition timing). Thus, these emissions data represent operation at conditions that are reasonably expected to recur, and are common to the fleet of Cooper GMV and other gas transmission engines.

Table 5 presents emission measurement data, sorted from lowest to highest CO emissions, from test projects conducted on the CSU engine. These projects include the EPA sponsored testing[1] and an emissions tradeoff paper from a 1999 conference[2]. Additional data are provided from industry or manufacturer sponsored testing and those results are documented in Appendix B-2.

These data are for engine operation in standard, baseline configurations and do not include emission data from engine operation associated with evaluating developmental or experimental control technologies. CO emissions range from 58 to 407 ppmvd at 15% O_2. These data also demonstrate the tradeoff between CO and NOx emissions, with NOx ranging from 8 to 1,317 ppmvd at 15% O_2. These emissions are not indicative of long-term performance that is continuously achieved, but rather the range of emissions that can occur under operating conditions associated with variations in load and excess air.

Figure 1 plots the CO emission data as a function of NOx emissions. As expected, operations associated with higher NOx result in the lowest CO emissions. Thus, a too strident CO standard could compel operators to operate at conditions that result in higher NOx. The curve shows the familiar CO/NOx trade-off, illustrates the emissions variability, and demonstrates the overlap of the CO emissions data from different test projects at similar NOx emission levels. The data congruency supports the ability to consider emissions from these different points in time, and supplement the EPA program data already in the EPA database with additional test results. Additional data details are provided in Appendix B.

[1] CSU-EPA 2000 – "Final Report: Testing a 2-Stroke Lean Burn Gas-Fired Reciprocating Internal Combustion Engine to Determine the Effectiveness of an Oxidation Catalyst System for Reduction of Hazardous Air Pollutants," EPA/OAQPS, EPA-454/R-00-036a, July 2000.

[2] CSU GMC 1999 – "Carbon Pollutant Emissions and Engine Performance Trade-Offs vs NOx Emissions for Reciprocating Internal Combustion Engines Utilized in Gas Transmission Service." Gary Hutcherson, CSU; Chad Fletcher, Enginuity International, Inc.; Greg Beshouri, Advanced Engine Technologies Corporation (AETC). Presented at 1999 Gas Machinery Conference, Houston, October 6, 1999.

Table 5. CSU CB GMV-4TF Standard Configurations Emissions Data.

Project	Test #	Load	O2	CO	NOx
		%	% dry	ppmvd @ 15% O2	
CSU-GMC 1999	4A-1	112%	13.5%	58	740
CSU-GMC 1999	2A-6	100%	13.4%	59	1,018
CSU-GMC 1999	0.10	86%	11.9%	59	1,116
CSU-GMC 1999	2B-3	101%	13.2%	61	1,315
CSU-GMC 1999	3A-6	86%	12.2%	61	1,159
CSU-GMC 1999	0.20	101%	13.6%	61	862
CSU-GMC 1999	4A-2	112%	13.6%	65	456
CSU-GMC 1999	2A-7	86%	13.4%	65	786
CSU-GMC 1999	4B-8	86%	12.0%	65	1,317
CSU-GMC 1999	2A-5	100%	13.6%	66	648
CSU-GMC 1999	0.40	112%	13.3%	66	797
CSU-GMC 1999	3B-1	112%	13.0%	67	1,154
CSU-GMC 1999	2A-4	101%	13.7%	68	560
CSU-GMC 1999	2A-8	100%	13.8%	69	585
CSU-GMC 1999	4A-3	112%	13.9%	71	275
CSU-GMC 1999	2B-2	100%	13.6%	72	750
CSU-GMC 1999	0.02	100%	13.9%	73	482
CSU-EPA	PAH-1	85%	14.6%	73	304
CSU-EPA	6	100%	14.3%	75	202
CSU-EPA	4	86%	14.7%	75	306
CSU-GMC 1999	3B-2	112%	13.4%	75	826
CSU-GMC 1999	0.04	112%	13.4%	76	471
CSU-EPA	9A	100%	14.5%	78	123
CSU-GMC 1999	2A-3	100%	13.8%	78	331
CSU-EPA	10	100%	14.6%	78	145
CSU-EPA	13	100%	14.6%	81	88
CSU-GMC 1999	3A-1	86%	14.3%	81	248
CSU-GMC 1999	0.00	100%	14.0%	83	236
CSU-EPA	1	100%	14.6%	83	101
CSU-GMC 1999	0.00	112%	13.6%	84	283
CSU-GMC 1999	4A-4	112%	14.4%	85	117
CSU-GMC 1999	2A-2	101%	14.0%	85	184
CSU-GMC 1999	0.01	86%	14.5%	86	177
CSU-GMC 1999	3A-2	86%	14.4%	87	151
CSU-EPA	16	100%	14.6%	88	152
CSU-GMC 1999	3B-3	112%	13.7%	88	402
CSU-GMC 1999	2A-12	100%	13.8%	89	129
CSU-GMC 1999	1B-1	100%	14.0%	89	438
CSU-GMC 1999	2B-1	100%	14.0%	89	388
CSU-GMC 1999	4B-7	86%	14.4%	89	243
CSU-GMC 1999	0.00	100%	14.1%	91	141
CSU-EPA	15	100%	14.7%	92	133
CSU-GMC 1999	0.00	101%	13.8%	92	49
CSU-GMC 1999	4A-5	112%	14.5%	93	110
CSU-EPA	14	100%	14.6%	95	82

Table 5. CSU CB GMV-4TF Standard Configurations Emissions Data. (continued)

Project	Test #	Load	O2	CO	NOx
		%	% dry	ppmvd @ 15% O2	
CSU-GMC 1999	0.00	86%	14.6%	95	87
CSU-GMC 1999	2A-1	101%	13.8%	96	134
CSU-GMC 1999	2A-9	101%	14.3%	98	133
CSU-GMC 1999	3A-3	86%	14.6%	99	120
CSU-GMC 1999	0.00	112%	14.2%	102	73
CSU-GMC 1999	2A-10	100%	14.2%	102	124
CSU-GMC 1999	0.00	100%	14.1%	102	88
CSU-GMC 1999	1B-2	101%	14.2%	105	223
CSU-GMC 1999	3A-4	86%	14.7%	109	99
CSU-GMC 1999	0.00	100%	14.2%	111	56
CSU-GMC 1999	4B-6	86%	14.7%	114	105
CSU-GMC 1999	1B-6	101%	14.3%	115	81
CSU-EPA	5	100%	15.1%	116	41
CSU-GMC 1999	0.00	112%	14.5%	116	51
CSU-GMC 1999	0.00	86%	14.7%	116	61
CSU-GMC 1999	2A-11	100%	13.8%	116	117
CSU-EPA	12	86%	15.3%	120	32
CSU-EPA	PAH-3	85%	15.3%	121	30
CSU-GMC 1999	3A-5	86%	14.8%	122	94
CSU-EPA	11	86%	15.2%	123	29
CSU-GMC 1999	3B-4	112%	14.7%	124	68
CSU-EPA	PAH-2	85%	15.4%	127	29
CSU-GMC 1999	0.00	112%	14.6%	130	51
CSU-GMC 1999	0.00	86%	14.7%	131	50
CSU-EPA	8	86%	15.6%	134	33
CSU-GMC 1999	0.00	100%	14.6%	136	46
PRCI PCC Eval	FE_BL_BM2	100%	14.3%	141	88
CSU-GMC 1999	1B-5	100%	14.7%	142	32
CSU-GMC 1999	0.00	101%	14.8%	151	41
CSU-GMC 1999	4B-5	86%	15.0%	152	46
CSU-GMC 1999	0.00	86%	14.8%	152	46
CSU-GMC 1999	3B-5	112%	15.0%	158	29
CSU-GMC 1999	0.00	86%	15.0%	174	43
CSU-GMC 1999	1B-3	101%	15.0%	187	21
CSU-GMC 1999	4B-4	86%	15.1%	188	26
PRCI PCC Eval	FE_BL_FS1	100%	14.5%	192	40
PRCI PCC Eval	FE_BL_FS5	101%	14.5%	195	49
PRCI PCC Eval	FE_BL_FS2	100%	14.6%	200	39
PRCI PCC Eval	FE_BL_FS4	100%	14.5%	201	43
PRCI PCC Eval	FE_BL_FS3	100%	14.5%	202	40
CSU-GMC 1999	3B-6	112%	15.1%	202	22
PRCI PCC Eval	FE_BL_BM1	100%	14.6%	208	39
CSU-GMC 1999	4B-1	101%	15.2%	216	26
CSU-EPA	3	62%	16.1%	246	9
CSU-GMC 1999	4B-3	86%	15.2%	249	18

Table 5. CSU CB GMV-4TF Standard Configurations Emissions Data. (continued)

Project	Test #	Load	O2	CO	NOx
		%	% dry	ppmvd @ 15% O2	
CSU-EPA	2-7	69%	15.8%	259	8
PRCI PCC Eval	FE_BL_BM6	100%	14.8%	263	19
PRCI PCC Eval	FE_BL_BM3	100%	14.8%	277	21
PRCI PCC Eval	FE_BL_BM4	100%	14.8%	280	21
PRCI PCC Eval	FE_BL_BM5	100%	14.8%	282	21
CSU-GMC 1999	1B-4	101%	15.5%	343	10
PRCI PCC Eval	FE_BL_BM7	100%	14.9%	369	15
CSU-GMC 1999	4B-2	86%	15.8%	407	11

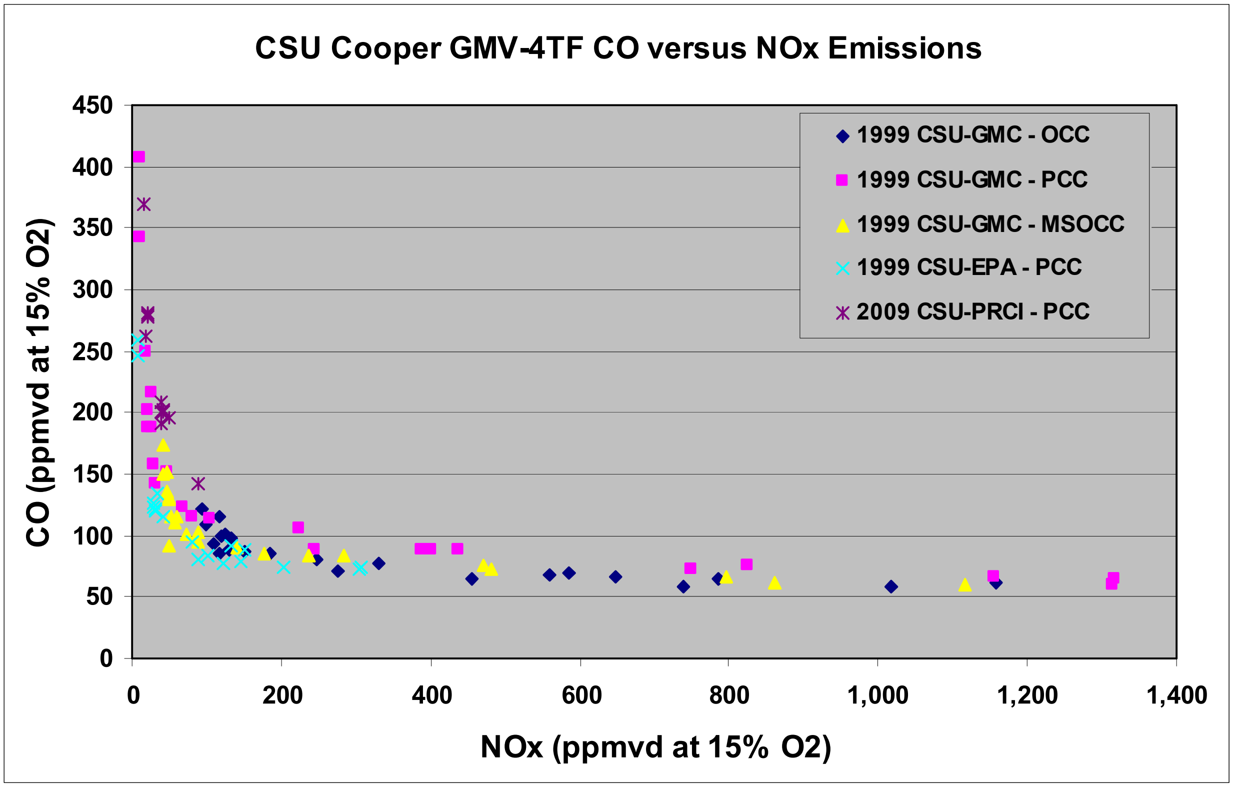

Figure 1. CSU engine standard configurations emission data; CO vs. NOx emissions.

For context, the NOx emission levels in Figure 1 can be compared to published emission factors for 2SLB engines. For example, in the NOx SIP Call Phase 2 Rule, EPA determined that a NOx emission factor of 16.8 g/bhp-hr is representative of uncontrolled gas transmission reciprocating engines. This equates to approximately 1,100 to 1,200 ppmv NOx (at 15% O_2) for typical 2SLB engine efficiency. The EPA AP-42 document presents uncontrolled NOx emission factors for load above 90% and a separate factor for load less than 90%. At the higher load, the AP-42 NOx emission factor (presented in lb/MMBtu) is approximately 850 ppmv and at lower load the emission factor is approximately 500 ppm. The CO emission factors are approximately 170 and 155 ppmv, respectively. This indicates that higher NOx levels introduced by supplementing data from the EPA sponsored CSU tests with additional CSU test data are well within expected ranges. In addition, as one might expect, the CO emissions from the CSU engine, a "best performing" MACT floor unit, are lower than the AP-42 emission factors for comparable NOx levels.

In addition, when only considering the CO data from the EPA-sponsored tests, the lowest CO point was 73 ppmv (at 15% O_2). CO data from other tests as low as 58 ppmv are marginally lower, which firmly establishes the CSU engine in the MACT floor. As shown in Table 3, the MACT floor cut point is 69 ppmv or only slightly lower than the lowest CO from the EPA tests. Considering measurement accuracy, the MACT floor cut point and 73 ppmv measured during the EPA tests are essentially the same; this agreement indicates that the CSU engine is effectively a "MACT floor" unit based solely on the EPA results. However, the additional test data further support the range of emissions and emissions variability for the CSU Cooper GMV-4TF engine.

As shown in Table 5 and Figure 1, CO emissions are as high as 407 ppmv, with several tests in the range of 240 to 407 ppmv. For EPA sponsored tests in this range (Test Points 3 and 2-7), these are lower load operation tests with commensurate lower peak combustion temperatures resulting in low NOx and higher CO. For other tests with higher CO, the engine was configured with the standard pre-combustion chamber technology and air flow was marginally leaner at the highest emitting point, but within common PCC operations. The engine configuration and operation were consistent with a unit complying with a low NOx emission limit.

While higher load operation is generally preferable and inherent to pipeline systems operating principles, response to pipeline demands requires operational flexibility and lower load operation. Thus, reciprocating engines have historically operated and will continue to operate across the load range under standard operating scenarios. With lower load and variations in other conditions such as excess air (or "turbo boost") significantly under-represented in the available data, special consideration of test results associated with those typical conditions is warranted when assessing emissions variability. In addition, the CSU data shows that lower load results in higher CO emissions, and the lowest load available from CSU test data is well over 50% - i.e., higher than loads that recur in normal operation. Based on the available data for MACT floor engines, the test data from the CSU engine best captures the range of operating conditions that are likely to recur, and those emission bounds should be a primary consideration for the variability assessment. Similar to 4SLB engines, the data from 2SLB engines support a standard of approximately 400 ppm or higher.

5.0 Conclusions and Recommendations

This report provides historical CO emissions data collected by INGAA. In general, test requirements for existing reciprocating engines have been driven by NOx concerns; thus, the operating conditions for the INGAA CO data are predominantly high load. Since CO tends to increase at lower load for existing lean burn engines, this limitation in the dataset (i.e. under-representation of low load emission data) is an important consideration when assessing variability.

MACT floor engines and associated data are discussed in Sections 3 and 4, and the test data are tabulated in the Appendices. INGAA review of MACT floor implications are based on the principles discussed in Section 2. After the best performing units are identified, limitations in the dataset should be recognized when assessing variability. For both the 4SLB and 2SLB engine subcategories, low load data are limited. However, for each subcategory, there is a MACT floor engine that provides data over a broader range of conditions than the majority of the units that have either limited tests or multiple tests at higher load.

The D.C. Circuit Court has indicated that variability among MACT floor units can be considered when establishing the emission standard, because the units must meet NESHAP standards at all times and under adverse operating conditions. Thus, it is reasonable to consider emissions associated with adverse operating conditions that are likely to recur. That variability is likely under-estimated in the INGAA data set because the emissions data are not based on a project or testing designed to characterize variability, and common operating conditions associated with parameters such as reduced load or marginally higher excess air are not adequately represented by the data. Because of the data limitations, the emissions data from some MACT floor engines may provide more insight than others when considering variability.

For both the 4SLB and 2SLB engine subcategories, a specific engine with data available from broader test conditions is discussed in the report. Data from both of these engines indicate that emissions variability warrants CO standards over 370 ppmv (at 15% O_2) for both 4SLB and 2SLB engines. For context, comparing this level to the "best demonstrated technology" basis for lean burn engines under the NSPS, indicates that these existing engines would have a CO standard similar to or more stringent than a new, NSPS affected engine.

In addition, while the body of the report focuses on MACT floor engines, the complete data sets in Appendix A and Appendix B indicate that many engines will not readily achieve this standard, and action will be required. This could introduce new complexities. Add-on control technology (an oxidation catalyst) is challenged by the relatively low exhaust temperature for 2SLB engines, and low load and low NOx conditions most conducive to higher CO are also the conditions with the lowest exhaust temperatures. These implications should also be considered when establishing the standard and ensuring that variability is adequately addressed.

Finally, if variability is properly accounted for, then subcategories may not be necessary and added complexity could be avoided. If INGAA recommendations to properly consider CO emissions data associated with tests under more adverse operating conditions are not adopted in the EPA analysis, and EPA concludes that lower standards properly assess variability, then INGAA recommends that additional subcategories be considered. There are different types of engines within both the 4SLB and 2SLB subcategories due to design and technology differences such as engine cylinder displacement (which EPA has used in other engine rules), NOx control configuration, air handling, and scavenging design for 2SLB engines. This report introduces some of these issues but detailed documentation is not provided on additional subcategories. If needed, INGAA can provide additional background documentation on the technical basis that establishes different engine types for developing more refined subcategories.

APPENDICES

Appendix A: Four-Stroke Lean Burn Engine CO Emissions Test Data

Appendix A-1: 4SLB Engine CO Emissions Data for MACT Floor Engines

Appendix A-2: 4SLB Engine CO Emissions Data for Engines not in the MACT Floor

Appendix B: Two-Stroke Lean Burn Engine CO Emissions Test Data

Appendix B-1: 2SLB Engine CO Emissions Data for INGAA MACT Floor Engines

Appendix B-2: 2SLB Engine Emissions Data Summary for CSU GMV-4TF Engine

Appendix B-3: 2SLB Engine CO Emissions Data for Engines not in the MACT Floor

APPENDIX A-1: 4SLB Engine CO Emissions Data for MACT Floor Engines

Engine ID No.	Engine Make	Model	Rated Load (hp)	Test No.	Run No.	Test Date	Test Load (hp)	$\%O_2$	CO (ppmv at 15% O_2)	Avg CO[1]
4S-1	Ingersoll-Rand	512 KVS	2,500	5	1	10/31/1999	2442	10.1	115	114
4S-1	Ingersoll-Rand	512 KVS	2,500	5	2	10/31/1999	2420	10.0	114	
4S-1	Ingersoll-Rand	512 KVS	2,500	5	3	10/31/1999	2413	10.0	113	
4S-1	Ingersoll-Rand	512 KVS	2,500	7	1	10/2/2000	2374	10.7	126	126
4S-1	Ingersoll-Rand	512 KVS	2,500	7	2	10/2/2000	2375	10.7	126	
4S-1	Ingersoll-Rand	512 KVS	2,500	7	3	10/2/2000	2392	10.7	125	
4S-1	Ingersoll-Rand	512 KVS	2,500	3	1	11/4/1998	2423	11.0	139	131
4S-1	Ingersoll-Rand	512 KVS	2,500	3	2	11/4/1998	2457	11.1	125	
4S-1	Ingersoll-Rand	512 KVS	2,500	3	3	11/4/1998	2470	11.2	129	
4S-1	Ingersoll-Rand	512 KVS	2,500	1	1	10/22/1997	2357	11.1	148	139
4S-1	Ingersoll-Rand	512 KVS	2,500	1	2	10/22/1997	2397	11.4	134	
4S-1	Ingersoll-Rand	512 KVS	2,500	1	3	10/22/1997	2455	11.4	134	
4S-1	Ingersoll-Rand	512 KVS	2,500	8	1	5/31/2001	2501	10.3	146	146
4S-1	Ingersoll-Rand	512 KVS	2,500	8	2	5/31/2001	2490	10.3	146	
4S-1	Ingersoll-Rand	512 KVS	2,500	4	1	4/28/1999	2396	10.9	151	153
4S-1	Ingersoll-Rand	512 KVS	2,500	4	2	4/28/1999	2390	10.9	152	
4S-1	Ingersoll-Rand	512 KVS	2,500	4	3	4/28/1999	2384	11.0	155	
4S-1	Ingersoll-Rand	512 KVS	2,500	6	1	4/4/2000	2087	11.2	165	163
4S-1	Ingersoll-Rand	512 KVS	2,500	6	2	4/4/2000	2087	11.2	162	
4S-1	Ingersoll-Rand	512 KVS	2,500	6	3	4/4/2000	2088	11.2	162	
4S-1	Ingersoll-Rand	512 KVS	2,500	16	1	9/14/2009	2470	11.6	178	178
4S-1	Ingersoll-Rand	512 KVS	2,500	16	2	9/14/2009	2472	11.6	179	
4S-1	Ingersoll-Rand	512 KVS	2,500	14	1	9/3/2008	2441	11.1	185	185
4S-1	Ingersoll-Rand	512 KVS	2,500	14	2	9/3/2008	2443	11.1	186	
4S-1	Ingersoll-Rand	512 KVS	2,500	13	1	10/2/2007	2428	11.5	187	186
4S-1	Ingersoll-Rand	512 KVS	2,500	13	2	10/2/2007	2433	11.5	186	
4S-1	Ingersoll-Rand	512 KVS	2,500	15	1	5/14/2009	2205	11.6	191	192
4S-1	Ingersoll-Rand	512 KVS	2,500	15	2	5/14/2009	2201	11.6	193	
4S-1	Ingersoll-Rand	512 KVS	2,500	9	1	3/30/2005	1959	12.2	201	201
4S-1	Ingersoll-Rand	512 KVS	2,500	9	2	3/30/2005	2019	12.2	202	
4S-1	Ingersoll-Rand	512 KVS	2,500	10	1	9/21/2005	2428	11.3	203	204
4S-1	Ingersoll-Rand	512 KVS	2,500	10	2	9/21/2005	2477	11.3	205	
4S-1	Ingersoll-Rand	512 KVS	2,500	2	1	4/23/1998	2350	12.4	285	208
4S-1	Ingersoll-Rand	512 KVS	2,500	2	2	4/23/1998	2311	11.1	168	
4S-1	Ingersoll-Rand	512 KVS	2,500	2	3	4/23/1998	2275	11.1	171	
4S-1	Ingersoll-Rand	512 KVS	2,500	12	1	4/18/2007	1989	12.1	214	212
4S-1	Ingersoll-Rand	512 KVS	2,500	12	2	4/18/2007	2000	12.1	209	
4S-1	Ingersoll-Rand	512 KVS	2,500	11	1	4/12/2006	2497	11.4	216	214

4S-1	Ingersoll-Rand	512 KVS	2,500	11	2	4/12/2006	2499	11.5	213	
4S-2	Cooper-Bessemer	LSV-16SG	4,400	1	1	2/25/2010	4,205	15.3	113	123
4S-2	Cooper-Bessemer	LSV-16SG	4,400	1	2	2/25/2010	4,278	15.0	132	
4S-2	Cooper-Bessemer	LSV-16SG	4,400	1	3	2/25/2010	3,716	15.5	134	134
4S-2	Cooper-Bessemer	LSV-16SG	4,400	1	4	2/25/2010	3,347	13.2	140	140
4S-3	Ingersoll-Rand	36 KVS	1,000	2	1	4/23/1998	963	10.9	124	124
4S-3	Ingersoll-Rand	36 KVS	1,000	2	2	4/23/1998	964	10.9	126	
4S-3	Ingersoll-Rand	36 KVS	1,000	2	3	4/23/1998	963	10.8	122	
4S-3	Ingersoll-Rand	36 KVS	1,000	6	1	4/4/2000	843	10.9	128	126
4S-3	Ingersoll-Rand	36 KVS	1,000	6	2	4/4/2000	846	10.8	126	
4S-3	Ingersoll-Rand	36 KVS	1,000	6	3	4/4/2000	846	10.8	125	
4S-3	Ingersoll-Rand	36 KVS	1,000	5	1	10/31/1999	1044	10.7	127	127
4S-3	Ingersoll-Rand	36 KVS	1,000	5	2	10/31/1999	1041	10.7	127	
4S-3	Ingersoll-Rand	36 KVS	1,000	5	3	10/31/1999	1037	10.7	128	
4S-3	Ingersoll-Rand	36 KVS	1,000	7	1	10/2/2000	1003	11.4	141	140
4S-3	Ingersoll-Rand	36 KVS	1,000	7	2	10/2/2000	1002	11.4	139	
4S-3	Ingersoll-Rand	36 KVS	1,000	7	3	10/2/2000	1003	11.3	139	
4S-3	Ingersoll-Rand	36 KVS	1,000	16	1	8/25/2009	936	10.8	142	144
4S-3	Ingersoll-Rand	36 KVS	1,000	16	2	8/25/2009	933	10.8	146	
4S-3	Ingersoll-Rand	36 KVS	1,000	14	1	9/3/2008	966	11.0	153	153
4S-3	Ingersoll-Rand	36 KVS	1,000	14	2	9/3/2008	964	11.0	153	
4S-3	Ingersoll-Rand	36 KVS	1,000	1	1	10/22/1997	993	11.2	155	157
4S-3	Ingersoll-Rand	36 KVS	1,000	1	2	10/22/1997	974	11.2	155	
4S-3	Ingersoll-Rand	36 KVS	1,000	1	3	10/22/1997	967	11.3	161	
4S-3	Ingersoll-Rand	36 KVS	1,000	10	1	9/21/2005	970	11.5	163	163
4S-3	Ingersoll-Rand	36 KVS	1,000	10	2	9/21/2005	998	11.5	163	
4S-3	Ingersoll-Rand	36 KVS	1,000	11	1	4/12/2006	906	11.7	168	166
4S-3	Ingersoll-Rand	36 KVS	1,000	11	2	4/12/2006	907	11.7	164	
4S-3	Ingersoll-Rand	36 KVS	1,000	3	1	11/3/1998	950	11.3	165	169
4S-3	Ingersoll-Rand	36 KVS	1,000	3	2	11/3/1998	926	11.4	166	
4S-3	Ingersoll-Rand	36 KVS	1,000	3	3	11/3/1998	910	11.5	176	
4S-3	Ingersoll-Rand	36 KVS	1,000	8	1	5/30/2001	987	11.8	170	170
4S-3	Ingersoll-Rand	36 KVS	1,000	8	2	5/30/2001	980	11.8	170	
4S-3	Ingersoll-Rand	36 KVS	1,000	9	1	3/30/2005	798	11.3	169	172
4S-3	Ingersoll-Rand	36 KVS	1,000	9	2	3/30/2005	799	11.4	176	
4S-3	Ingersoll-Rand	36 KVS	1,000	13	1	10/2/2007	951	11.4	180	179
4S-3	Ingersoll-Rand	36 KVS	1,000	13	2	10/2/2007	955	11.4	179	
4S-3	Ingersoll-Rand	36 KVS	1,000	15	1	5/14/2009	860	11.5	203	204
4S-3	Ingersoll-Rand	36 KVS	1,000	15	2	5/14/2009	862	11.5	205	
4S-3	Ingersoll-Rand	36 KVS	1,000	4	1	4/27/1999	960	11.5	224	233
4S-3	Ingersoll-Rand	36 KVS	1,000	4	2	4/27/1999	954	11.6	233	
4S-3	Ingersoll-Rand	36 KVS	1,000	4	3	4/27/1999	952	11.6	241	

4S-3	Ingersoll-Rand	36 KVS	1,000	12	1	4/18/2007	799	11.8	274	270
4S-3	Ingersoll-Rand	36 KVS	1,000	12	2	4/18/2007	799	11.8	267	
4S-4	Ingersoll-Rand	KVH-616	4,200	13	1	8/4/1999	3489	9.87	128	128
4S-4	Ingersoll-Rand	KVH-616	4,200	10	1	8/4/1999	3175	9.89	128	128
4S-4	Ingersoll-Rand	KVH-616	4,200	9	1	8/4/1999	2958	9.94	131	131
4S-4	Ingersoll-Rand	KVH-616	4,200	12	1	8/4/1999	3169	10.19	152	152
4S-4	Ingersoll-Rand	KVH-616	4,200	3	1	8/22/1995	3243	10.27	152	152
4S-4	Ingersoll-Rand	KVH-616	4,200	6	1	8/22/1995	3801	10.29	160	160
4S-4	Ingersoll-Rand	KVH-616	4,200	1	1	8/22/1995	4209	10.29	160	160
4S-4	Ingersoll-Rand	KVH-616	4,200	11	1	8/4/1999	2881	10.49	162	162
4S-4	Ingersoll-Rand	KVH-616	4,200	4	1	8/22/1995	2950	11.10	205	205
4S-4	Ingersoll-Rand	KVH-616	4,200	5	1	8/22/1995	2777	11.10	205	205
4S-4	Ingersoll-Rand	KVH-616	4,200	8	1	8/4/1999	2393	11.11	223	223
4S-4	Ingersoll-Rand	KVH-616	4,200	7	1	8/22/1995	4007	11.12	240	240
4S-4	Ingersoll-Rand	KVH-616	4,200	2	1	8/22/1995	3229	11.12	240	240
4S-5	Ingersoll-Rand	512 KVS	2,000	3	1	11/4/1998	1967	11.6	127	131
4S-5	Ingersoll-Rand	512 KVS	2,000	3	2	11/4/1998	1939	11.6	130	
4S-5	Ingersoll-Rand	512 KVS	2,000	3	3	11/4/1998	1917	11.7	136	
4S-5	Ingersoll-Rand	512 KVS	2,000	5	1	10/30/1999	1949	11.5	155	154
4S-5	Ingersoll-Rand	512 KVS	2,000	5	2	10/30/1999	1957	11.5	155	
4S-5	Ingersoll-Rand	512 KVS	2,000	5	3	10/30/1999	1962	11.4	153	
4S-5	Ingersoll-Rand	512 KVS	2,000	4	1	4/28/1999	1910	11.5	152	156
4S-5	Ingersoll-Rand	512 KVS	2,000	4	2	4/28/1999	1904	11.5	158	
4S-5	Ingersoll-Rand	512 KVS	2,000	4	3	4/28/1999	1901	11.6	158	
4S-5	Ingersoll-Rand	512 KVS	2,000	15	1	5/14/2009	1820	11.8	157	157
4S-5	Ingersoll-Rand	512 KVS	2,000	15	2	5/14/2009	1813	11.9	158	
4S-5	Ingersoll-Rand	512 KVS	2,000	1	1	10/22/1997	1922	11.6	164	161
4S-5	Ingersoll-Rand	512 KVS	2,000	1	2	10/22/1997	1961	11.6	164	
4S-5	Ingersoll-Rand	512 KVS	2,000	1	3	10/22/1997	1998	11.6	154	
4S-5	Ingersoll-Rand	512 KVS	2,000	14	1	9/3/2008	1903	11.9	166	165
4S-5	Ingersoll-Rand	512 KVS	2,000	14	2	9/3/2008	1902	11.9	164	
4S-5	Ingersoll-Rand	512 KVS	2,000	10	1	9/21/2005	1942	11.6	172	168
4S-5	Ingersoll-Rand	512 KVS	2,000	10	2	9/21/2005	1953	11.5	165	
4S-5	Ingersoll-Rand	512 KVS	2,000	12	1	4/18/2007	1672	12.2	169	170
4S-5	Ingersoll-Rand	512 KVS	2,000	12	2	4/18/2007	1667	12.2	170	
4S-5	Ingersoll-Rand	512 KVS	2,000	13	1	10/2/2007	1962	11.8	170	170
4S-5	Ingersoll-Rand	512 KVS	2,000	13	2	10/2/2007	1958	11.8	169	
4S-5	Ingersoll-Rand	512 KVS	2,000	16	1	8/25/2009	2015	11.5	177	177
4S-5	Ingersoll-Rand	512 KVS	2,000	16	2	8/25/2009	2003	11.5	177	
4S-5	Ingersoll-Rand	512 KVS	2,000	9	1	3/30/2005	1674	11.8	186	185
4S-5	Ingersoll-Rand	512 KVS	2,000	9	2	3/30/2005	1660	11.8	183	
4S-5	Ingersoll-Rand	512 KVS	2,000	11	1	4/12/2006	2040	11.4	185	185

4S-5	Ingersoll-Rand	512 KVS	2,000	11	2	4/12/2006	2035	11.4	184	
4S-5	Ingersoll-Rand	512 KVS	2,000	8	1	5/31/2001	1969	11.3	190	194
4S-5	Ingersoll-Rand	512 KVS	2,000	8	2	5/31/2001	1972	11.3	197	
4S-5	Ingersoll-Rand	512 KVS	2,000	7	1	10/2/2000	2037	11.6	211	212
4S-5	Ingersoll-Rand	512 KVS	2,000	7	2	10/2/2000	2035	11.5	212	
4S-5	Ingersoll-Rand	512 KVS	2,000	7	3	10/2/2000	2028	11.5	212	
4S-5	Ingersoll-Rand	512 KVS	2,000	6	1	4/4/2000	1626	11.8	218	214
4S-5	Ingersoll-Rand	512 KVS	2,000	6	2	4/4/2000	1628	11.8	214	
4S-5	Ingersoll-Rand	512 KVS	2,000	6	3	4/4/2000	1628	11.8	211	
4S-5	Ingersoll-Rand	512 KVS	2,000	2	1	4/28/1998	1714	12.3	207	226
4S-5	Ingersoll-Rand	512 KVS	2,000	2	2	4/28/1998	1691	12.6	229	
4S-5	Ingersoll-Rand	512 KVS	2,000	2	3	4/28/1998	1666	12.6	243	
4S-6	Cooper-Bessemer	LSV-16SG	4,400	2	3	2/26/2010	4,323	9.6	135	135
4S-6	Cooper-Bessemer	LSV-16SG	4,400	2	1	2/26/2010	3,550	10.3	137	137
4S-6	Cooper-Bessemer	LSV-16SG	4,400	2	2	2/26/2010	3,975	9.9	144	144
4S-7	Ingersoll-Rand	36 KVS-FT	1,000	3	1	3/23/2006	990	11.8	137	137
4S-7	Ingersoll-Rand	36 KVS-FT	1,000	8	1	3/23/2006	872	11.0	175	175
4S-7	Ingersoll-Rand	36 KVS-FT	1,000	10	1	3/23/2006	675	10.9	178	178
4S-7	Ingersoll-Rand	36 KVS-FT	1,000	5	1	3/23/2006	853	12.1	182	182
4S-7	Ingersoll-Rand	36 KVS-FT	1,000	11	1	3/23/2006	571	11.2	182	182
4S-7	Ingersoll-Rand	36 KVS-FT	1,000	7	1	3/23/2006	796	11.0	200	200
4S-7	Ingersoll-Rand	36 KVS-FT	1,000	4	1	3/23/2006	926	12.2	202	202
4S-7	Ingersoll-Rand	36 KVS-FT	1,000	6	1	3/23/2006	725	11.9	207	207
4S-7	Ingersoll-Rand	36 KVS-FT	1,000	9	1	3/23/2006	752	11.2	213	213
4S-7	Ingersoll-Rand	36 KVS-FT	1,000	1	1	3/22/2006	573	12.4	230	230
4S-7	Ingersoll-Rand	36 KVS-FT	1,000	2	1	3/22/2006	472	13.4	375	375
4S-8	Ingersoll-Rand	36 KVS	1,000	5	1	10/31/1999	983	10.4	136	139
4S-8	Ingersoll-Rand	36 KVS	1,000	5	2	10/31/1999	981	10.4	140	
4S-8	Ingersoll-Rand	36 KVS	1,000	5	3	10/31/1999	976	10.5	140	
4S-8	Ingersoll-Rand	36 KVS	1,000	7	1	10/2/2000	986	11.2	166	166
4S-8	Ingersoll-Rand	36 KVS	1,000	7	2	10/2/2000	986	11.3	166	
4S-8	Ingersoll-Rand	36 KVS	1,000	7	3	10/2/2000	987	11.2	166	
4S-8	Ingersoll-Rand	36 KVS	1,000	14	1	9/3/2008	965	11.4	170	170
4S-8	Ingersoll-Rand	36 KVS	1,000	14	2	9/3/2008	968	11.4	170	
4S-8	Ingersoll-Rand	36 KVS	1,000	11	1	4/12/2006	911	11.7	172	172
4S-8	Ingersoll-Rand	36 KVS	1,000	11	2	4/12/2006	908	11.6	172	
4S-8	Ingersoll-Rand	36 KVS	1,000	13	1	10/2/2007	977	11.6	173	172
4S-8	Ingersoll-Rand	36 KVS	1,000	13	2	10/2/2007	977	11.6	171	
4S-8	Ingersoll-Rand	36 KVS	1,000	16	1	8/25/2009	938	11.5	168	172
4S-8	Ingersoll-Rand	36 KVS	1,000	16	2	8/25/2009	936	11.5	176	
4S-8	Ingersoll-Rand	36 KVS	1,000	10	1	9/21/2005	955	11.5	178	178
4S-8	Ingersoll-Rand	36 KVS	1,000	10	2	9/21/2005	950	11.5	178	

4S-8	Ingersoll-Rand	36 KVS	1,000	2	1	4/28/1998	705	10.6	186	180
4S-8	Ingersoll-Rand	36 KVS	1,000	2	2	4/28/1998	706	10.6	188	
4S-8	Ingersoll-Rand	36 KVS	1,000	2	3	4/28/1998	706	10.3	166	
4S-8	Ingersoll-Rand	36 KVS	1,000	8	1	5/30/2001	984	11.7	181	183
4S-8	Ingersoll-Rand	36 KVS	1,000	8	2	5/30/2001	981	11.8	185	
4S-8	Ingersoll-Rand	36 KVS	1,000	6	1	4/4/2000	802	11.2	185	186
4S-8	Ingersoll-Rand	36 KVS	1,000	6	2	4/4/2000	799	11.2	186	
4S-8	Ingersoll-Rand	36 KVS	1,000	6	3	4/4/2000	798	11.3	186	
4S-8	Ingersoll-Rand	36 KVS	1,000	9	1	3/30/2005	763	12.1	196	192
4S-8	Ingersoll-Rand	36 KVS	1,000	9	2	3/30/2005	761	12.1	189	
4S-8	Ingersoll-Rand	36 KVS	1,000	1	1	10/22/1997	936	11.3	195	195
4S-8	Ingersoll-Rand	36 KVS	1,000	1	2	10/22/1997	904	11.3	195	
4S-8	Ingersoll-Rand	36 KVS	1,000	1	3	10/22/1997	900	11.3	195	
4S-8	Ingersoll-Rand	36 KVS	1,000	3	1	11/3/1998	822	11.5	197	195
4S-8	Ingersoll-Rand	36 KVS	1,000	3	2	11/3/1998	816	11.5	197	
4S-8	Ingersoll-Rand	36 KVS	1,000	3	3	11/3/1998	816	11.5	191	
4S-8	Ingersoll-Rand	36 KVS	1,000	15	1	5/14/2009	859	11.7	205	204
4S-8	Ingersoll-Rand	36 KVS	1,000	15	2	5/14/2009	856	11.7	203	
4S-8	Ingersoll-Rand	36 KVS	1,000	12	1	4/18/2007	795	12.0	211	214
4S-8	Ingersoll-Rand	36 KVS	1,000	12	2	4/18/2007	790	12.1	217	
4S-8	Ingersoll-Rand	36 KVS	1,000	4	1	4/27/1999	901	12.0	301	298
4S-8	Ingersoll-Rand	36 KVS	1,000	4	2	4/27/1999	902	11.9	298	
4S-8	Ingersoll-Rand	36 KVS	1,000	4	3	4/27/1999	901	11.8	295	
4S-9	Caterpillar	G3516	880	3	1	10/15/2002	785	8.80	142	141
4S-9	Caterpillar	G3516	880	3	2	10/15/2002	785	8.80	141	
4S-9	Caterpillar	G3516	880	3	3	10/15/2002	785	8.80	139	
4S-9	Caterpillar	G3516	880	5	1	2/20/2003	747	8.50	157	156
4S-9	Caterpillar	G3516	880	5	2	2/20/2003	747	8.50	156	
4S-9	Caterpillar	G3516	880	5	3	2/20/2003	747	8.50	156	
4S-9	Caterpillar	G3516	880	4	1	12/12/2002	806	9.00	160	161
4S-9	Caterpillar	G3516	880	4	2	12/12/2002	806	9.00	162	
4S-9	Caterpillar	G3516	880	4	3	12/12/2002	806	9.00	161	
4S-9	Caterpillar	G3516	880	2	1	6/27/2002	861	8.59	190	190
4S-9	Caterpillar	G3516	880	2	2	6/27/2002	861	8.59	191	
4S-9	Caterpillar	G3516	880	2	3	6/27/2002	861	8.61	189	
4S-9	Caterpillar	G3516	880	1	1	4/12/2002	659	8.39	183	196
4S-9	Caterpillar	G3516	880	1	2	4/12/2002	659	8.37	198	
4S-9	Caterpillar	G3516	880	1	3	4/12/2002	659	8.33	206	
4S-10	Ingersoll-Rand	KVT-512	3,000	1	1	10/25/1995	2712	10.23	149	149
4S-10	Ingersoll-Rand	KVT-512	3,000	6	1	12/27/2006	2823	11.50	183	183
4S-10	Ingersoll-Rand	KVT-512	3,000	6	2	12/27/2006	2812	11.50	180	
4S-10	Ingersoll-Rand	KVT-512	3,000	6	3	12/27/2006	2833	11.50	187	

4S-10	Ingersoll-Rand	KVT-512	3,000	4	1	10/25/1995	2024	11.26	201	201
4S-10	Ingersoll-Rand	KVT-512	3,000	3	1	10/25/1995	2902	10.61	202	202
4S-10	Ingersoll-Rand	KVT-512	3,000	5	1	4/26/2001	2921	11.97	220	220
4S-10	Ingersoll-Rand	KVT-512	3,000	2	1	10/25/1995	2253	10.62	226	226
4S-11	Ingersoll Rand	KVS-412	~2,050	1	1	9/13/1995	2,044	12.7	156	153
4S-11	Ingersoll Rand	KVS-412	~2,050	1	2	9/13/1995	2,007	12.8	156	
4S-11	Ingersoll Rand	KVS-412	~2,050	1	3	9/13/1995	1,793	12.7	146	
4S-11	Ingersoll Rand	KVS-412	~2,050	2	1	3/22/2006	1,962	15.0	219	223
4S-11	Ingersoll Rand	KVS-412	~2,050	2	2	3/22/2006	1,943	15.0	224	
4S-11	Ingersoll Rand	KVS-412	~2,050	2	3	3/22/2006	1,946	14.8	225	

NOTE 1: ppmvd @ 15% O_2; Values in column are either multi-run average or value of a single test (i.e., a one run test)