ABSTRACT
The American National Standards Institute (ANSI) required that the source testing Standard on Measurement of Exhaust Emissions from Stationary Gas Turbine Engines, B133.9, be brought up to date with today's regulatory requirements and best measurement technology. The criteria for the design of the Standard along with its content and format are discussed. The selection of measurement methods for gaseous components, smoke, and particulates emitted by present day emission controlled industrial gas turbine engines is presented.

INTRODUCTION
A competitive program was initiated by an ASME Research Task Force on Gas Turbine Emissions Standards to provide for the development of a new ANSI Standard for measuring, analyzing, and reporting exhaust emissions from stationary gas turbine engines. Applications were sought from individuals and organizations wishing to participate in a research project to clarify and document the best measurement procedures and standards that were either in use or being reduced to practice. Competitive bids were obtained and a contract issued for the project. This new source testing Standard, "Measurement of Exhaust Emissions from Stationary Gas Turbine Engines" was needed because:

- Procedures and techniques had continued to evolve since the publication of the last Standard(1).
- Measurement and reporting requirements were unclear, were obsolete, and varied from agency to agency.
- Method 20(2), the USEPA measurement procedure for gas turbines, was limited as it covered only oxides of nitrogen (NOx) and sulfur (SOx).

These obsolete and limited methods left many measurement and reporting problems unsolved or incorrectly solved. Significant funding and technical resources were being spent unnecessarily in conducting source testing for stationary gas turbines.

Note: The term "Standard" is used by ANSI to connote a practice or measurement method not the regulation of emission levels as is used by regulatory authorities in the United States.

DESIGN OF THE STANDARD
A program to develop the Standard was begun in February 1992. This work included research on measurement methods and emissions regulations as well as standards development. A coordinated final draft of the Standard was submitted to ANSI for approval on June 1, 1993.

Steering Committee
Representatives from ASME Research, the gas turbine industry, EPRI, and USEPA and the contractor formed a committee to provide technical direction and review progress during the development of the Standard. Meetings were held to monitor progress of the program and to review and comment on the criteria, the content of the Standard, technical findings of the research, and on the draft Standard. The membership of the Committee is listed at the end of this paper.

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Program Objectives

The Standard is written to provide guidelines for the emissions measurement of stationary gas turbine engines. It is designed to simplify, standardize, and reduce the cost of the measurement process wherever possible. The expected users are engineers and measurement technicians who require information on the measurement of emissions from gas turbines. The Standard also is written to inform project managers, contract and procurement staff, and engineers not directly involved with emissions of the measurement control and compliance of gas turbines.

Specific criteria for the Standard were established by the Steering Committee early in the program. These criteria were:

1. To standardize measurement techniques, analysis procedures, and reporting criteria.
2. To follow ANSI format and the ASME Guide to Writing Codes and Standards.
3. To be applicable to all industrial gas turbine engines operating on natural gas and distillate fuel oil.
4. To be applicable to engines with emission controls such as water injection and selected catalytic reduction (SCR).
5. To provide reference to other turbine regulations and measurement procedures.
6. To have general approval of industry and the USEPA.
7. To not set regulatory limits or control regulations.
8. To incorporate the International Standards Organization (ISO) gas turbine emissions measurement specification to the extent feasible.

Since there are many different sizes and applications of stationary gas turbines throughout the world, it was an objective of the program that these differences be considered in the development of the new Standard. Emissions measurement of turbines using heat recovery after firing and steam and water injection for NOx controls was included. The very low concentration of pollutants typical of turbines using dry low NOx combustion and SCR after treatment also was considered. Current measurement methods were researched to find the best methods, reduced to commercial practice, to include in the Standard. Where applicable, the measurement methods are referenced to EPA protocols. Since the development of measurement instrumentation is ongoing, future improvements will require periodic updating of the Standard.

It also was necessary to incorporate methods to measure each of the exhaust components controlled by the various regulatory agencies and emission regulations. Laws and rules were researched, and the results became one of the bases for the Standard.

Concurrently, the specification "Gas Turbines — Exhaust Gas Measurement" was being developed by ISO(3)(4). While this specification did not provide for use of USEPA protocols and was not acceptable for use in the United States, considerable effort by an international working group had been expended in its development. It was an objective of the program that the new Standard incorporate as much of the ISO document as was practical.

Other measurement specifications such as those used for aircraft gas turbines(5) and for reciprocating engines(6) were reviewed for methods and content. These specifications were found to be only indirectly applicable to the testing of stationary gas turbines in the United States.

CONTENT

The Standard contains information that will guide the user in the technologies of emissions compliance and control as well as measurement. During their review of requirements, the Steering Committee found that many agency staffs had little experience with most of the gas turbines used in the United States that are operated on clean fuels, natural gas, and distillate oil. Also, they found that agency personnel were unfamiliar with the practical aspects of engine operation, the formation, identity, and concentration of the various components in the exhaust of turbines, the measurement of these components, and methods of emission control. As a result, the Standard was designed to provide information and references on these subjects as well as to establish the best measurement practices. The subjects covered in the Standard are as follows:

Definitions. Terms most likely to be encountered in emissions measurement, compliance, and control.

Exhaust Components. Description of each of the chemical components in the gas turbine exhaust.

Responsibilities. Gas turbine manufacturer and user environmental responsibilities.

Operating and Test Conditions. Specification of system operating and test conditions.

Measurements. Recommended methods of measurement of gaseous components, smoke, particulates, and fuel. Definition of the measurement system, sampling, instrumentation, and quality provisions.


General References. Information on reference conditions, physical properties, air laws, regulations, air toxics, and emission control methods.

MEASUREMENT OF GASEOUS COMPONENTS

The Standard specifies the gaseous components in the exhaust and the methods to be used to measure them. These components are listed in Table 1. This listing was determined by the Steering Committee based on the regulatory requirements of the EPA, the state agencies, and the collective experience of the members. It is recognized that measurement technology is advancing rapidly, and this listing deserves regular updating.
Measurement System

The three basic elements of the measurement system are: (1) the sampling probe, (2) transfer and conditioning, and (3) analytical instruments and data acquisition. These elements are described in detail in the Standard and refer to EPA protocols. A schematic of the measurement system is shown in Figure 1.

With the exception of sulfur dioxide, sulfuric acid mist, and water vapor, the gaseous measurements are to be made by continuous flow sampling instruments. These instruments are combined into a measurement system.

Sampling

The approach taken to sampling gaseous components is designed to save test time and effort. It differs from the multipoint traverse usually required by the USEPA in Method 2(7), which requires at least eight and normally many more sampling locations in two planes.

The Standard recommends that the sample be proven to be representative using a carbon balance. Once that is done, sampling may be achieved using a three-holed sampling probe tube or a single probe located at 16.7, 50, and 83.3% of a measurement line taken through the centroid of the duct area. Ducts larger than 2.4 meters can be sampled at 0.4, 1.2, and 2.0 meters from the wall to reduce probe overhang. The use of three sampling points is based on the EPA Continuous Emission Monitoring Specification 2(8) and is illustrated in Figure 2.

The number of sampling points is reduced because, in the majority of industrial turbine installations, the exhaust gas stream is well mixed and the concentration of the individual components is, from a practical standpoint, uniform across the entire exhaust duct. This uniformity is due to the length of exhaust ducting, the changes in direction and cross section required for the installation of boilers and silencers, and the requirement for stack heights. As a result, the number of sample points required for sampling gas turbine gaseous components is far less than that required for most industrial plants. The EPA CEM Specification provides substantiation that a representative gas sample can be obtained with three sampling points.

Sample Transfer and Conditioning

Long lines are often unavoidable in the measurement of large turbine systems; however, the sample transfer time should be kept as short as possible. It is important to avoid condensation of the various constituents, particularly water vapor, hydrocarbons, and sulfates. It is recommended that the entire sample line be heated above the condensation temperature of each constituent, considering its concentration. The sample is to be conditioned in a manner compatible with the various analyzers.

Instrumentation

Descriptions, general requirements, and performance specifications are given for each of the instruments and measurement methods that are recommended. These are listed in Table 1. For additional detailed information, specific USEPA methods and ISO standards are given as references.

Each of these measurement methods listed in Table 1 will not be covered in this summary paper. Some of the findings and recommendations on measurement methods that were formulated during the development of the Standard are discussed below.

Hydrocarbons and VOC. In most instances in the United States, a measurement of the volatile organic compounds (VOC) emitted by the engine is required. VOC are usually defined as the total of all hydrocarbons (HC) emitted minus the methane and ethane components. In many instances the term non methane hydrocarbons (NMHC) is used synonymously with VOC. In modern engines, emissions of VOC are often at a very low concentration, less than 1 to 10 ppmC (methane equivalent). Their measurement requires the accurate determination of concentrations of both the total and methane exhaust components. This determination is accomplished by measuring total HC and subtracting measured methane.

It is recommended that the measurement of total hydrocarbons be made using a flame ionization analyzer and volatile organic compounds by gas chromatograph (GC). Direct analyzers combine the features of both these instruments to obtain VOC concentrations. Separate analyzers can also be used to obtain VOC emissions. To improve accuracy, it is recommended that the ratio of VOC to total HC be obtained using the GC, and this ratio be applied to the total HC obtained by FID to obtain the concentration of VOC in the exhaust.

Ammonia. Ammonia in the exhaust of a turbine resulting from NOx emission control equipment, such as SCR, must be controlled to low concentration level, typically 10 ppm. The chemiluminescence difference method was listed as the best method then available. However, none of the methods commercially available was considered accurate enough. It was recognized that considerable research on ammonia measurement is in progress, and the Standard will require subsequent updating.

<table>
<thead>
<tr>
<th>Component</th>
<th>Recommended Method</th>
</tr>
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<tbody>
<tr>
<td>Oxides of nitrogen (NOx)</td>
<td>Chemiluminescence</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>Nondispersive infrared</td>
</tr>
<tr>
<td>Carbon dioxide (CO2)</td>
<td>Nondispersive infrared</td>
</tr>
<tr>
<td>Sulfur dioxide (SO2)</td>
<td>Fuel analysis</td>
</tr>
<tr>
<td>Sulfuric acid mist (H2SO4)</td>
<td>Impinger train</td>
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<tr>
<td>Total hydrocarbons</td>
<td></td>
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<tr>
<td>NMHC and VOC</td>
<td></td>
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<tr>
<td>Ammonia (NH3)</td>
<td>Flame ionization detector</td>
</tr>
<tr>
<td>Oxygen (O2)</td>
<td>Gas chromatograph</td>
</tr>
<tr>
<td>Water vapor (H2O)</td>
<td>Chemiluminescence difference</td>
</tr>
<tr>
<td></td>
<td>Electrochemical or permanent magnetic</td>
</tr>
</tbody>
</table>
Water Vapor. The exhaust from a gas turbine can contain varying quantities of water vapor, approximately 2 to 15% by volume. The absolute amount depends on the products of combustion that are fuel related, the absolute humidity of the air ingested into the engine, and the amount of water injected into the engine for emission control or power augmentation. Water entering the engine from evaporative inlet coolers and water fuel emulsions also must be considered.

The water vapor content of the exhaust is used in making emission calculations, and determining this value accurately is important. The quantity of water in the exhaust can be determined either by direct measurement or by measurement and summation of all sources. In the case where direct measurement is required, the reference method cited in EPA Method 4(9) is recommended.

**Instrument Calibration Gases**

The calibration of instruments through the use of calibrating gases is described in the Standard. These gases, introduced at the sampling probe, are to have certificates of compliance per ISO standards or USEPA protocols. Accuracy requirements for a number of calibration gases, including zero gas, are recommended in the Standard.
SMOKE MEASUREMENT

Smoke emitted from gas turbines is measured in two general ways: (1) visible plume opacity, and (2) smoke density that measures soot in the exhaust. Smoke measurements are made of engines operating on liquid fuels. Engines operating on natural gas will normally have no visible exhaust plume.

Visual Opacity
Currently, visual determination using USEPA Method 9(10) is the only accepted and practical method of determining the visual opacity of the exhaust plume of a gas turbine. However, this method does not produce results of acceptable accuracy.

Other methods were examined and found deficient. LIDAR measurements(11) were found to be too expensive for routine source testing. Transmissometers(12) measure the light obscuration caused by smoke in the exhaust duct but do not take into account plume behavior or plume illumination.

Method 9 requires that a trained observer, holding a valid USEPA certificate, make and record one or more sets of observations. The positive error of Method 9 for black plumes is cited as less than 5%. Evaluations of Method 9 during certification training(13) show that at the opacity values of 10% and 20%, which are the usual compliance levels for gas turbines, the standard deviation of measurement was 3.16% and 5.25% opacity, respectively.

When the standard deviation is as high as 25 to 33% of the measured value, compliance difficulties can be expected, particularly in cases where compliance is marginal. When this deviation occurs, referee measurements of smoke density are recommended. These measurements would be made using a smokemeter or in-stack transmissometer that was correlated with visual opacity tests made during source testing. In order to be effective, this procedure must be agreed to by the cognizant regulatory agency so that when questioned by an inspector, compliance during routine operation of the engine can be demonstrated using the referee method.

Smoke Density
In the United States regulations do not require smokemeter readings. Since these readings are required in Europe and other regions, smoke density measurement was included in the Standard.

Two different methodologies are available: smoke spot and optical. In the smoke spot procedure, a metered quantity of exhaust is passed through a filter paper and the density of the smoke stain on the paper is graded optically. In the optical procedure, a continuous flow of exhaust is extracted, metered, and passed through a cell that measures its light obscuration.

Three of the most common methods of measuring smoke from gas turbines were evaluated for inclusion in the Standard. These are described below.

ICAO/SAE Aircraft Method. The SAE Aircraft Method is a spot filtration procedure that is designed and used to measure the smoke density of aircraft gas turbine exhaust. In this method, the mass of exhaust collected and the optical grading of the stain are closely controlled. This method is specified by the International Civil Aviation Organization (ICAO) and aviation agencies throughout the world(14).

Bacharach/ASTM. Bacharach is the spot filtration method specified by ISO(3) and used throughout Europe to measure both turbine and diesel engines. It is not as precise as the aircraft method and employs a different scale for smoke density. The method, also identified as ASTM D2156, was designed for use with oil heating equipment(15).

Rolls-Royce Optical Smokemeter. The Rolls-Royce optical smokemeter was designed to measure smoke from gas turbines and component rigs on a continuous basis. It provides a measurement of the carbon density based on a standard cell that can be calibrated in units of carbon mass (milligrams per cubic meter) or in terms of Bacharach or SAE Smoke Numbers(16).

Comparison of Methods
These methods were compared for accuracy in the range of low smoke density typical of modern gas turbine engines. This evaluation, based on the accuracy stated in the description of each method, was to determine if a difference in accuracy that could be easily discernible and lead to a recommended method existed.

Figure 3 shows the results of the accuracy evaluation. In order to obtain a direct comparison between the methods, the smoke number values from the SAE and Bacharach methods were converted to carbon mass per unit of exhaust gas using published conversion data.
Recommendations

In reviewing the commercially available methods of measuring smoke, the Steering Committee decided not to recommend a specific method at this time. While the optical smokemeter is the most accurate, it could not be recommended for use in the Standard because there were no commercially developed competitive methods.

The spot filtration methods were found to be of insufficient accuracy in the low smoke density ranges required by industrial gas turbines. The Steering Committee determined that no method would be recommended in the Standard, but that the most commonly used methods would be described for the convenience of the user.

PARTICULATE MEASUREMENT

The measurement of particulate material (PM) is frequently required in the United States by state and local agencies if the gas turbine is run on liquid fuel. In some instances PM measurement has been directed by local agencies even when the engine is run on natural gas.

Present Method 5

The method of measurement mandated by these agencies is USEPA Method 5(17), a method that uses filtration and collection of the particulates in the exhaust by traversing the exhaust duct over a large number of specified sampling points. It requires long sampling times because of low mass loading of particulates in the exhaust stream. It also requires the determination of the velocity profile of the exhaust at these same points using a pitotstatic probe. From this profile, the mass flow rate of the engine exhaust is computed. While this method may be acceptable for use in measuring various industrial sources such as cement kilns and coal fired boilers, it is misapplied to gas turbine engines. This application is expensive and time consuming and has high variability resulting in inaccurate data.

Alternate Methods

Because of these difficulties an alternate method was sought to determine PM emissions from turbines. Various procedures were examined, including correlation of particulate mass with the optical density of the exhaust(18) and the use of full sized and miniature dilution tunnels similar to the diesel testing(19). It was found that while research was continuing on optical correlation, this method had not yet been brought to commercial practice. Dilution tunnels, commonly used in automotive testing, would extend, not shorten, the sampling times and would not give real time test results.

Recommended Modifications to Method 5

The possibility of modification of Method 5 was examined to see if it could be simplified and made more practical and less costly. It was determined that a number of changes should be made when Method 5 is used to measure gas turbine PM. These changes, described below, were incorporated in the Standard.

Eliminate Isokinetic Sampling. The particulate material in the exhaust of a gas turbine operating on distillate fuel is composed primarily of submicronic carbon particles and condensable hydrocarbons and sulfates. With low sulfur distillate fuels all of the particles present in the exhaust are submicronic and will follow stream lines. Isokinetic sampling, to assure that the velocity into the probe and the stream velocity are equal, is unnecessary.

Increase Sample Flow. With the elimination of isokinetic sampling the sample flow rate may be increased, reducing collection times to obtain the required sample mass of 20 mg.

Reduce The Number of Sampling Points. As was previously discussed, the gas stream exiting from an industrial gas turbine is well mixed. The number of sampling points was reduced to the same three recommended for gas sampling. Verification that the gas sample is representative serves to determine that particulate sampling will also be representative.

Eliminate Velocity Profiling. The determination of mass flow from a gas turbine using the velocity profile measured in the exhaust duct is not recommended due to inaccuracy in measuring the true average flow velocity. Instead, the flow through the system should be determined using fuel flow measurements and a carbon balance. This determination should be verified by the computed exhaust flow using the engine manufacturer's engine performance model (performance deck) corrected to the source test conditions.

Eliminate PM Measurement From Gas Fired Engines. The Standard states that the measurement of particulates from natural gas fuels engines is not recommended. The level of material in the exhaust resulting from the combustion of natural gas is extremely low and is below the practical threshold of
measurement using Method 5. In some instances, agencies have required sampling times as long as 24 hours in order to obtain a viable sample.

AIR TOXICS
As a result of the 1990 Clean Air Act Amendments, numerous compounds have been listed as air toxics (20). The emission of these compounds is regulated at the levels of 10 tons per year, or 25 tons in combination.

Occurrence in Gas Turbine Exhaust
At these regulated levels, the emission of these quantities of air toxic compounds from gas turbine engines operating on natural gas and high quality distillate fuels is unlikely due to the cleanliness of the fuels and the design and installation characteristics of industrial turbine engines. Some air toxic compounds cannot be generated by gas turbines. More specific reasons are as follows:

1. High fuel quality is required to extend engine endurance life and maintain performance. The level of contaminants in the fuel must be closely controlled in order to prevent erosion and corrosion of the engine gas path. ASTM specifications require that trace metal concentrations of vanadium, sodium and potassium (in combination), calcium, and lead be held to 0.5 ppm by weight (21).

2. High combustion efficiency and large dilution ratios are design characteristics of stationary gas turbine engines. Typical combustion efficiencies are 99.99% and air-to-fuel ratios are approximately 50. In combination, these characteristics along with careful design control of combustors have resulted in total HC emission levels in the exhaust gas of 1 to 10 ppm, measured as methane. As a result, only minute fractions (ppb or less) of unburned fuel components will be present in the exhaust.

3. Good fuel filtration is required in order to prevent finely divided solids containing earth compounds and metals from entering the fuel system and fouling and eroding control orifices and fuel injectors.

4. High quality inlet air filtration is used to prevent airborne particles from entering the engine and causing deterioration of engine performance and life. These particles also are prevented from subsequently being oxidized and reinjected into the atmosphere.

5. Close specification control of other fluids such as water, steam, and lubricating oil used in gas turbines is maintained. These fluids have specifications that stipulate allowable levels of contaminants to prevent deposition, corrosion, and erosion in the engine. Particularly rigid control is required to minimize the induction of halogen compounds to prevent them from entering the gas path. This class of compounds is particularly corrosive and greatly reduces engine life.

Determination of Air Toxic Compounds
Air toxic compounds emitted by the engine must come from the fluids introduced into the engine during its operation. These fluids are fuel, air, lubricating oil, water, steam, and engine washing compounds. Each installation should be considered as specific. If determinations of the presence and quantity of emissions of air toxic compounds must be obtained, it is recommended that an analysis of each of the fluids used by the engine be made to determine the presence and expected concentrations of compounds that can form air toxic compounds.

Because of very low concentrations, direct measurement of these compounds in the exhaust is not recommended. If exhaust measurement is mandated, the prior identification of each air toxic compound, its source, and probability of occurrence is recommended.

SUMMARY AND CONCLUSIONS
B133.9 New Standard
The revised ANSI Standard B133.9 has been completed and is available from the American National Standards Institute. Its use will provide the following:

1. The guidance and criteria for the measurement of exhaust emissions from stationary gas turbines.

2. Standardized measurement techniques, analysis, and reporting in the United States and internationally.

3. Reduced labor and cost of source testing by simplified sampling, exhaust flow measurement, and measurement of particulates.

4. Improved understanding of the character and measurement of gas turbine emissions by industry and government staff involved in the permitting process.

Contract Vs Committee Methods
In the past most standards, including ANSI B133 Gas Turbine Procurement Standards, have been written by volunteer committee members whose membership and time were sponsored by their various employers. Because this committee activity was secondary to their main work, standards development was a slow and limited process. Recent reductions in technical staffs have made voluntary committee work even less productive.

Changing this procedure to one in which research, development, and drafting of the standard are performed by a contractor under the technical direction of a steering committee has proven to be advantageous to the sponsoring groups. Our experience in writing the new B133 Exhaust Emissions Standard has shown the following advantages of using the committee method:

- Defined scope. The specific work requirements are defined by contract that can be monitored and administered.
• Reduced manpower. The technical man-hours and involvement required of the sponsors' technical staff are greatly reduced.
• Shortened time. The time to complete the Standard is shortened to less than half the usual development time.
• Cost and time are controlled. The cost and time required of each sponsor are known at the onset of the contract and can be budgeted.
• Defined responsibility. It is the responsibility of the contractor to produce a superior specification.

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(19) "Subpart N -- Emission Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines; Gaseous and Particulate Exhaust Test Procedures," US Federal Register, Title 40, Part 86 Subpart N.