Aircraft Gas Turbine Smoke Measurement Uncertainty Using the SAE/EPA Method

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The advent of regulations limiting the emission of smoke from aircraft gas turbine engines has prompted increased emphasis on the development of smokeless or low-smoke combustors. As a result, increased demands are now being placed on the capability of the instrumentation which is utilized to measure the smoke level. The evaluation of the capability of smoke measurement instrumentation must include an assessment of measurement uncertainty. Without that assessment, it is difficult to distinguish between real and chance variation seen in test data. It is the main intent of this paper to report the results of an analysis aimed at evaluating the magnitude and effect of the various sources of instrument-related uncertainty on the measurement of smoke by the SAE/EPA procedure. This error analysis presents the bias and precision errors present in the clean and stained filter reflectance measurement, and in the gas volume, temperature, and pressure measurements. In addition, the derivation of a simpler and less costly smoke measurement procedure is presented. This alternate procedure is shown to have a precision error equivalent to the SAE/EPA procedure. Examples of the effectiveness of the new procedure are presented. The effect of ambient inlet air conditions on the generation of smoke was also investigated. Ambient temperature, but not ambient humidity was shown to affect significantly the smoke level of JT3D production engines.

Introduction

IN 1973 the Environmental Protection Agency (EPA) published regulations[1] establishing maximum smoke level limits for aircraft gas turbine engines. Those regulations also specified a measurement method to be used to assess the smoke level of gas turbines during compliance testing. That method, derived from an industry/government developed procedure published by the Society of Automotive Engineers (SAE),[2] has also become the basis for evaluating the effectiveness of "low-smoke" combustor designs in experimental test programs.

With the advent of the limiting regulations, the requirement for accurate, reliable smoke measurement has increased. This has focused attention on the capability and precision of the measurement instrumentation. Without an assessment of measurement uncertainty, it is difficult to decide whether changes observed in a test program are a result of hardware modification or merely a result of measurement variability. This paper reports the results of an analysis aimed at evaluating the magnitude and effect of the various sources of instrument-related uncertainty on the measurement of smoke by the SAE/EPA procedure.

The error analysis presented considers the precision errors present in the clean and stained filter reflectance measurement, and in the gas volume, temperature, and pressure measurements. In addition, there is a discussion of the bias error introduced by the specific curve form utilized to fit the smoke data so that the smoke level, at a specified sample flow, may be obtained for each power level.

Also reported is the derivation of a simpler, less costly, and often more accurate smoke measurement procedure. This alternate procedure is shown to have a precision error equivalent to the SAE/EPA procedure. Examples of the effectiveness of the new procedure are presented.

The effect of ambient inlet air conditions on the generation of smoke was investigated. Ambient temperature, but not ambient humidity, was shown to affect significantly the smoke level of JT3D production engines. This could seriously affect the capability of an engine to pass a certification test.

Error Components – Statistical Framework

Gas turbine emission measurement errors typically contain two components: bias and precision. The definition and effect of these errors has been detailed earlier.[3] It is sufficient here to be reminded that bias errors affect all repeat measurements of a variable the same amount. Bias errors offset the average of a group of measurements from the true value. Precision errors cause variability about the biased average.

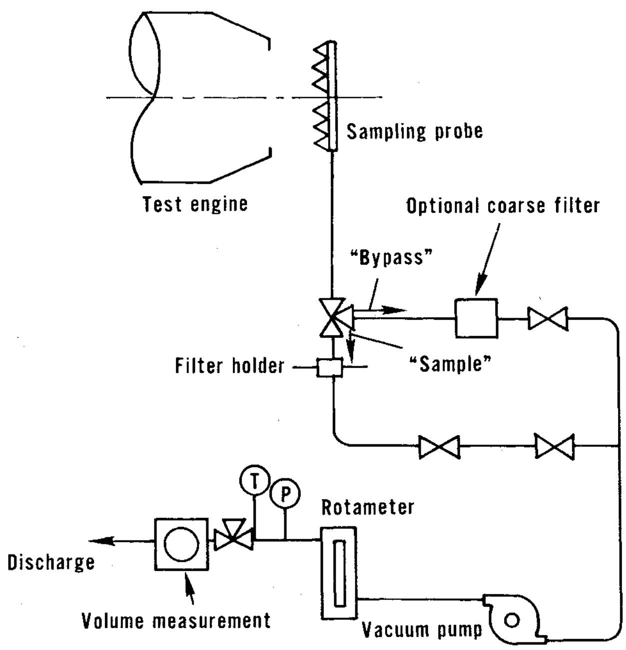

Fig. 1 Smoke sampling system.

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It should be noted that, throughout this paper, the convention of utilizing twice the standard deviation ($2S$) as an estimate of precision error has been employed. $2S$, in addition, is assumed to be the 95% confidence interval, i.e., for a set of measurements of the variable X, 95% of the individual measurements, X_i will fall within the interval $\bar{X} \pm 2S$ where $\bar{X}$ is the average of the set.

In smoke measurement, a "true" value is not defined. The SAE/EPA smoke measurement method is a relative comparison technique, not an absolute-level measurement. As such, there are no clearly discernable bias errors of any significance with the exception of those caused by ambient effects and the use of the semilog curve fit specified by the regulations. It may be argued that some bias error is present in the National Bureau of Standards traceable reflectance tiles to which unknown samples are compared. That error is considered insignificant, even when smoke measurements from different facilities are compared.

The instrument errors reported in this paper are precision errors. The error data, in addition, may be described by a Gaussian-normal distribution. When such precision error data are used in combination, it is usually appropriate to combine them in quadrature as detailed by Abernethy et al.[4]

Error Model for the SAE/EPA Smoke Measurement Procedure

The SAE/EPA Smoke Measurement Procedure

The Federal Register[1] defines, with sufficient detail, the method of smoke measurement which is utilized to measure aircraft gas turbine exhaust smoke levels. It is briefly, a method for staining clean Whatman #4 filters with smoke by passing a metered mass of air through the filters and measuring the reduction in reflection by an appropriate reflectometer. A schematic of the smoke sampling system is shown in Fig. 1.

The "smoke number" (SN) is calculated from Eq. (1):

$$\mathrm{SN} = 100\left[1 - \frac{R_s}{R_w}\right] \tag{1}$$

where

SN = smoke number
R_s' = stained filter (absolute reflectance)
R_w = clean filter (absolute reflectance)

At every engine power level tested, this smoke number (SN) is obtained for four specific weights of exhaust gas per unit filter area (W/A), two on each side of $W/A = 0.0230$ lb of air/in.^{2} of filter, henceforth referred to as just lb/in.^{2}. This approach avoids extrapolating a curve fit to a region outside the data set taken. The reported SN is then obtained from the least-squares straight line fit of $\ell n(W/A)$ vs SN by interrogating the fit at $W/A = 0.0230$. W/A is calculated from Eq. (2):

$$W/A = 1.326[PV/TA] \tag{2}$$

where

P = sample pressure, in. HgA
T = sample temperature, °R
V = sample volume, ft^3
A = filter area, in.^{2}

Uncertainty Analysis

The error sources in the measurement procedure considered in this analysis are 1) filter reflectance, both clean and stained, and 2) sample weight, a function of P, T, and V. Noninstrumentation error is also estimated. Filter area error is considered to be negligible. Throughout, the final errors reported are expressed in units of smoke number for easy application to the measurement itself.

Filter Reflectance Uncertainty

The error in a dependent variable which results from uncertainty in the measurement of one or more independent variables may be evaluated by expanding the defining equation in a Taylor Series, an error propagation procedure developed by Ku,[5] among others. Applying a Taylor Series expansion to Eq. (1) yields Eq. (3), an error propagation equation which relates smoke number error to uncertainty in both clean and stained filter reflectance measurements:

$$2S_R = \pm\left[(100 \cdot R_s/R_w^2)^2 (2S_{Rw})^2 + (100/R_w)^2 (2S_{Rs})^2\right]^{1/2} \tag{3}$$

where

$2S_{Rw}$ = precision error of the clean filter reflectance measurement
$2S_{Rs}$ = precision error of the stained filter reflectance measurement

1) *Clean-Filter Reflectance Uncertainty.* For clarity, the components of Eq. (3) will be dealt with separately. For the smoke number precision error resulting from clean filter reflectance measurement uncertainty the following equation is obtained:

$$2S_{\mathrm{SNC}} = \pm(100/Rw)(Rs/Rw)(2S_{Rw}) \tag{4}$$

where $2S_{\mathrm{SNC}}$ is the precision error of the smoke number due to clean filter reflectance measurement uncertainty.

From Eq. (4) it may be seen that smoke measurement uncertainty due to Rw errors is greatest for low smoke numbers and decreases with increasing smoke number. This result is similar to that obtained by Champagne.[6] As will be seen, clean filter reflectance error is the major source of instrument-related smoke measurement error and is a direct result of the use of an average reflectance for clean filters. The use of an average clean filter reflectance would have caused the reduction in data scatter with increased smoke number observed by Champagne.

Smoke measurement precision was of greatest concern near a regulation limit such as SN = 20 for a JT9D. Obtaining $2S_{\mathrm{SNC}}$ for a single filter smoke measurement required calculating Rs/Rw. At a smoke number of 20, $Rs/Rw = 0.8$.

Evaluating the effect of uncertainty in clean filter reflectance required evaluating filter variability prior to use. Average reflectance and two standard deviations, $2S_{Rw}$, were calculated for 442 filters for which clean filter reflectance was measured prior to use. These filters are representative of filters used by Pratt & Whitney Aircraft. The average reflectance was 75.6% and $2S_{Rw}$ was calculated to be ± 1.86% reflectance. If an average value of 75.6% were used in smoke number calculations, the reflectance of an individual filter would be known to be within the bounds 75.6% ± 1.86% with 95% confidence.

Substituting into Eq. (4) using an average value for Rw, $2S_{\mathrm{SNC}} = \pm(100/0.756)(0.8)(0.0186) = \pm 1.97$ SN. The use of an average value for Rw is permitted by the regulations and results in an error of ± 1.97 smoke numbers. That error, ± 1.97 *SN*, includes the precision of the reflectometer (estimated at ± 0.307%).

2) *Stained-Filter Reflectance Uncertainty.* For the second error component of Eq. (3), the contribution of stained filter reflectance measurement uncertainty to smoke number precision error, we obtain the error propagation equation:

$$2S_{\mathrm{SNS}} = \pm(100/Rw)2S_{Rs} \tag{5}$$

where $2S_{\mathrm{SNS}}$ is the precision error of the smoke number due to variation in Rs.

A maximum permissible value of the stained filter reflectance precision is not specified by the Federal Register. Current reflectance measured precision at Pratt & Whitney is estimated to be ± 0.307% reflectance. Substituting this value into the preceding relation gives $2S_{SNS} = \pm(100/0.756)(0.00307) = \pm 0.406$ SN.

The uncertainty in smoke measurement due to stained filter reflectance precision error is ± 0.406 smoke numbers.

Sample Weight Uncertainty

The error in sample weight resulting from temperature, pressure, and volume imprecision can be obtained by a Taylor series expansion of the defining relationship, Eq. (2). That expansion yields the following error propagation equation:

$$2S_{W_{abs}} = \pm[(1.326V/AT)^2(2S_P)^2 + (1.326PV/AT^2)^2(2S_T)^2 + (1.326P/AT)^2(2S_V)^2]^{1/2} \quad (6)$$

where

$2S_{W_{abs}}$ = precision of the calculated sample weight per unit area, lb/in.^{2}
$2S_P$ = precision of the pressure measurement, in. HgA
$2S_T$ = precision of the temperature measurement, °R
$2S_V$ = precision of the volume measurement, ft^3

The term relating error in filter area is omitted as the area is assumed known with negligible error. Manipulating this relation to obtain the precision error of W expressed in percent yields:

$$2S_W = \pm 100[(2S_T/_T)^2 + (2S_P/P)^2 + (2S_V/V)^2]^{1/2} \quad (7)$$

where $2S_W$ is the precision of W (percent).

The Federal Register [Ref. 1, Sec. 87.82(b)] requires temperature, pressure, and volume measurement accuracies of ±4°R±0.1 in. Hg and ±0.01 ft^3, respectively. The bounds described by these specifications are assumed to be confidence bounds for random errors. If the 95% confidence level is assumed for the current applications, two standard deviations for temperature measurement $2S_T$, pressure measurement $2S_P$, and volume measurement $2S_V$, are ±4°R, ±0.1 in. Hg, and ±0.01 ft^3, respectively.

The error in W due to temperature, pressure, and volume imprecision permitted by current regulations is then obtained by direct substitution into Eq. (7).

$$2S_W = \pm 100[(4/545)^2 + (0.1/29.92)^2 + (0.01/0.248)^2] = \pm 4.11\%$$

The values of $T = 545$°R, $P = 29.92$ in. Hg, and $V = 0.248$ ft^3 are representative of sample temperature, pressure, and volume observed in practice. Variations in T, P, and V over the limited range of operating conditions encountered would result in a negligible change in the estimate of $2S_W$. The error in sample weight, W, is limited by the SAE/EPA procedure to ±4.11%.

To determine the effect of temperature, pressure, and volume precision error on SN, any error in determining filter area, A, is considered negligible and $2S_{\% W/A} = 2S_W$, where $2S_{\% W/A}$ and $2S_W$ are expressed as percentages of W/A and W. The effect of variation in sample weight measurement on smoke measurement uncertainties can be determined using the Federal Register [Ref. 1, Sec. 87.88(c)] specified equation:

$$SN = C_0 + C_1 \ln(W/A) \quad (8)$$

where

C_0, C_1 = constants determined by the method of least squares
A = filter area, in.^{2}
W = sample weight, lb

Equation (8) relates smoke number to sample size, W/A. Expanding this relation, too, with a Taylor series expansion yields the following error propagation equation:

$$2S_{SNW} = \pm C_1(2S_{\% W/A})/100 \quad (9)$$

where

$2S_{SNW}$ = precision of the EPA smoke number due to variation in W/A
$2S_{\% W/A}$ = precision of the sample weight expressed as a percentage of W/A

To evaluate $2S_{SNW}$, a value for C_1 is required. Unique values of the constants C_0 and C_1 in Eq. (8) are associated with a particular smoke number at a specified sample size. To evaluate the constants, a series of 53 EPA smoke measurements was reviewed. Each measurement of smoke level resulted from a series of four filters using the EPA specified procedure. The measurements were obtained from JT8D and JT3D engines and included smoke numbers from 0 to 40 at 0.0230 lb/in^2. A least-squares polynomial $C_1 = 0.00940\ SN^2 + 0.802\ SN + 1.14$, fitted to the smoke measurement data described earlier, provided an excellent means of estimating C_1 for a given smoke number at 0.0230 lb/in^2. The value of C_1 calculated for an EPA smoke number of 20 at 0.0230 lb/in^2 was 13.44.

Estimates of C_1 and $2S_{\% W/A}$ have now been obtained and an estimate of smoke number error resulting from temperature, pressure, and volume measurement errors can be calculated from the relation $2S_{SNW} = \pm C_1(2S_{\% W/A})/100$, Eq. (9).

Maximum smoke number error will occur for high smoke numbers where C_1 is large. At a smoke number of 20, assuming pressures and temperature imprecision permitted under smoke regulations, $2S_{SNW} = \pm(13.44)(4.11)/100 = \pm 0.552$ EPA SN.

Noninstrumentation Sources of Uncertainty

The effect of remaining error sources which include variation in physical properties of Whatman No. 4 filter material, variation in the smoke source over time, and any unidentified errors can be estimated by experiment. Two standard deviations for 16 repeat measurements of a smoke source having a smoke number of approximately 20 at 0.0230 lb/in.^{2} was observed to be ±1.22 smoke numbers. Two standard deviations for the sample size calculated from P, V, and T measurements, was observed to be ±2.12%. The smoke measurement of clean filter and sample reflectances was previously reported to be ±0.325 and ±0.405 smoke numbers, respectively. Subtracting, by quadrature, smoke measurement imprecision attributable to sample size and reflectance measurements from the total uncertainty gives

$$2S_{remainder} = \pm[1.22^2 - 0.285^2 - 0.325^2 - 0.405^2]^{1/2} = \pm 1.07\text{SN}$$

Smoke measurement uncertainty contributed by noninstrumentation sources is estimated to be ±1.07 smoke numbers.

Error Due to Specified Curve Form

The EPA specified curve form of $SN = C_0 + C_1 \ln(W/A)$, to be used at each engine power level, introduces a bias error when an SN obtained by interpolation is compared to that obtained with a measurement made at $W/A = 0.0230$. In order to demonstrate this, smoke levels from a gas turbine engine were measured during four tests over a three month

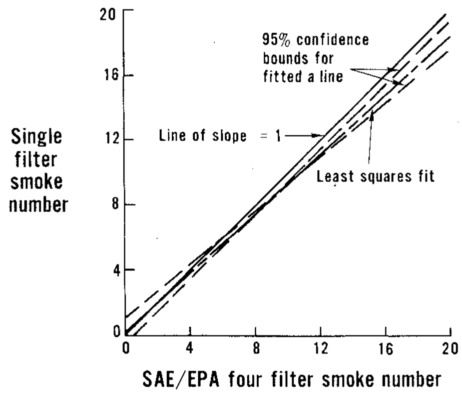

Fig. 2 Smoke number at 0.0230 lb/in.^{2}.

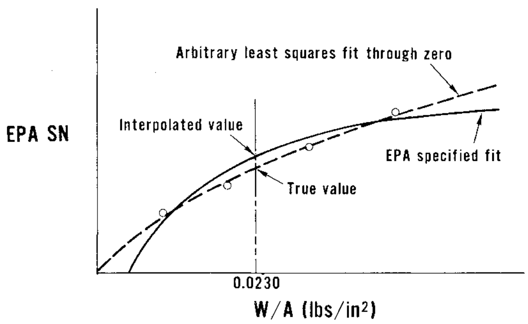

Fig. 3 EPA smoke number.

period. Thirty-one power levels were tested using a series of five smoke measurements at each power level. Four of the five samples were at approximately .012, .020, .035, and .048 lb/in.^{2}, which are the usual sample sizes selected for a four-sample determination as required by SAE/EPA. A fifth measurement near .0230 was included in each series to provide a direct comparison between one- and four-sample measurements. A plot of the single-filter vs four-filter EPA smoke numbers is given in Fig. 2. The 95% confidence bounds about the least-squares fit line do not include a substantial portion of the line of equivalence between the single- and four-filter smoke samples. Figure 3 demonstrates the source of this basis for a typical data set. The two curves in Fig. 3 demonstrate difference between the actual SN at $W/A = 0.0230$ and that obtained by interpolation of the specified curve fit. The data are plotted on rectilinear rather than semilog coordinates for clarity. In summary, the four-filter sample procedure yields biased smoke data, as illustrated in Fig. 3, due to the particular curve fit and sample sizes selected.

Summary of SAE/EPA Smoke Measurement Procedure Errors

Table 1 summarizes the errors reviewed in the preceding sections for a smoke level of 20.

The total error for one filter results from the quadrature sum of the individual precision errors. The precision error of the line at the point of interpolation is obtained by dividing the single-filter precision by the square root of the number of data points used, $\sqrt{4}$. This approximates the precision of the line at $WHA = 0.0230$ lb/in.^{2} in the same manner that the precision of an average is obtained by dividing the precision of the data by the square root of the number of data points. The precision of the SAE/EPA smoke measurement procedure is, therefore, estimated at $\pm 2.34/\sqrt{4}$, or ± 1.17 SN.

Error Model for an Alternate Procedure

Alternate Procedure

It may be observed from Table 1 that the major source of error in the SAE/EPA procedure is the clean-filter reflectance

Table 1 SAE/EPA procedure smoke measurement error in smoke number (at a smoke level of 20)

Error source	Permitted by SAE/EPA procedure
Pressure, temperature, and volume	± 0.552
Clean-filter reflectance	± 1.97
Stained-filter reflectance	± 0.406
Noninstrumentation	± 1.07
Total for one filter	± 2.34
Precision of curve at interpolation point (total for one filter/$\sqrt{4}$)	± 1.17

uncertainty permitted by the use of an average value for clean-filter reflectance. Partially as a result of this observation, an alternate, simpler procedure has been investigated which yields smoke data of equivalent precision to the SAE/EPA procedure but at reduced cost. This procedure has three main points: 1) it requires measuring the clean reflectance of each filter; 2) it permits the use of less precise pressure and temperature instrumentation; and 3) it requires measuring the smoke level at a W/A of 0.0230 lb/in.^{2} with a single filter rather than interpolating a four-filter line fit at that point.

Uncertainty Analysis

Measuring the Clean Reflectance of Each Filter

Equation (4) may be utilized to evaluate clean-filter reflectance error when each filter's clean reflectance is measured. For that case, $2S_{Rw}$ drops from $\pm 1.86\%$ reflectance to the precision of the reflectometer itself, $\pm 0.307\%$. Rs/Rw remains at 0.8 and the average clean filter reflectance remains 75.6%. If, therefore, instead of using an average value for clean filter reflectance, the reflectance of each clean filter is measured, the ± 1.97 SN error calculated by Eq. (4) drops to $\pm(100/0.756)\times(0.8)\ (0.00307) = \pm 0.325$ SN. At a smoke number of 20, measuring clean reflectance of each filter prior to sampling reduces the smoke measurement error contributed by clean reflectance error from ± 1.97 SN to ± 0.325 SN.

Using Less Precise Pressure and Temperature Instrumentation

Less expensive and less accurate instrumentation than that required by the Federal Register may be utilized and still cause only a negligible change in SN error. If, for instance, the temperature and pressure accuracy requirements were permitted to deteriorate to $\pm 8°$F and ± 0.3 in. Hg, respectively, the error then permitted, according to Eq. (7), would be

$$\pm 100[(8/545)^2 + (0.3/29.92)^2 + (0.01/0.258)^2]^{1/2}$$

$$= \pm 4.26\%$$

Substituting $\pm 4.26\%$ into Eq. (9) yields an error of ± 0.574 SN. An error of ± 0.574 SN is not considered significantly worse than ± 0.552 SN, of the SAE/EPA procedure, suggesting that the use of less accurate temperature and pressure instrumentation as specified would not adversely affect compliance testing.

Single-Filter Smoke Measurements by Setting W/A = 0.0230 lb/in.^{2}

It may be shown that a single-filter smoke measurement procedure which requires setting W/A at 0.0230 lb/in.^{2} and measuring smoke at that precise W/A will yield a precision error equivalent to that of the SAE/EPA method of using four filter sets and interpolating the SN at $W/A = 0.0230$ lb/in.^{2}. Measuring smoke at $W/A = 0.0230$ lb/in.^{2} will also provide less biased smoke data.

Figure 3 illustrates why the single-filter method is less biased than the SAE/EPA four-filter method. To demonstrate that the single-filter method yields a precision error equivalent to that of the SAE/EPA method requires

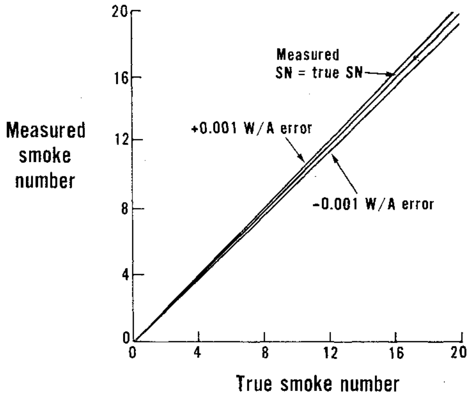

Fig. 4 Effect of sample size bias error.

evaluating an additional precision error – How well can $W/A = 0.0230$ be set? To investigate this, a test was run at a Pratt & Whitney facility during which 60 W/A measurements were within 0.0230 ± 0.002. The personnel conducting the test did not possess extensive smoke testing experience. For similar testing when the smoke measurement was conducted by personnel more familiar with smoke measurement, the procedure typically resulted in a W/A variation of approximately ± 0.001. It may be expected that less experienced personnel will improve their W/A setting precision as they gain experience but it is difficult to determine how much better they will get. It is presumed here, for the purposes of this analysis, that they will approach the lower error of the personnel more familiar with the smoke measurement procedures as experience is gained.

If that error, ± 0.001, is considered to be a 95% confidence estimate, it represents a $\pm 4.35\%$ error in W/A. Figure 4 shows 95% confidence bounds for SAE/EPA SN error caused by a $\pm 4.35\%$ W/A error as a function of EPA SN. At a smoke level of 20 SN, this error is ± 0.6 SN and is due to errors in P, T, and V. It must be combined, as summarized later, with the other errors associated with the alternate procedure to obtain an overall precision error estimate.

Summary of Alternate Procedure Errors

The alternate procedure errors are summarized in Table 2. That table reports the errors due to: clean-filter reflectance measurement uncertainty, where each filter's clean reflectance is measured; stained-filter reflectance uncertainty, which remains the same as in the SAE/EPA procedure; the noninstrumentation uncertainty, which also is identical to that in the SAE/EPA procedure; and W/A setting error. The overall precision error attributable to the alternate procedure is ± 1.33 SN at a smoke level of 20 SN.

Comparison of SAE/EPA and Alternate Procedure Errors

Table 3 summarizes the previously detailed error sources for both the SAE/EPA required instrument accuracies and for a system which requires individual clean-filter reflectance measurement but relaxed instrumentation accuracy for several smoke levels. Note that the SAE/EPA error decreased with increasing smoke level while the alternate procedure error increases. It is apparent from Table 3 that the alternate procedure yields a precision equivalent to the SAE/EPA procedure. While being less restrictive on the accuracy of the instrumentation utilized, the alternate procedure does require measuring the clean-reflectance of each filter.

A single-point filter taken at a W/A of 0.0230 lb/in.^{2} is equivalent in precision to the usual SAE/EPA specified four-filter method. Since the single-filter method does not exhibit the curve interpolation bias error of the four-filter method, the single-filter method is preferred. The single-filter method, in addition, is a less expensive procedure which, conserves fuel because of the shorter engine running times required.

Table 2 Alternate procedure smoke measurement error in smoke number (at a smoke level of 20)

Error source	Single-filter alternate procedure
Pressure, volume, and temperature	–
Clean-filter reflectance	± 0.325
Stained-filter reflectance	± 0.405
Noninstrumentation	± 1.07
Setting $W/A = 0.0230$	± 0.6
Total for one filter	± 1.33

Table 3 Comparison of SAE/EPA and alternate procedures

Smoke level	SAE/EPA error in SN[a]	Single-filter procedure errors in SN
10	± 1.3	± 1.3
20	± 1.2	± 1.3
30	± 1.1	± 1.4
40	± 1.0	± 1.4

[a] Error in four-filter average reported equals the single-filter error $\div \sqrt{4}$.

Effects of Ambient Conditions on Smoke Production

During the course of the development of the error analysis of smoke measurement systems, it became clear that a substantial quantity of the current test data exhibited smoke level variability in excess of that expected from the instrumentation alone. In an effort to determine whether or not ambient temperature and/or humidity effect gas turbine smoke production and increase the variability observed, a special test program was devised and carried out.

Test Program

Smoke measurements were made on 18 production engines during routine production final acceptance testing. Tests were conducted over a range of ambient conditions from 5 to 83°F inlet temperature, from 0.001 to 0.014 lb of H_2O/lb of dry air specific humidity, and from 29.8 to 30.6 in. H_gA barometric pressure. Three identical smoke meters were used for the measurements and either JP5 or Jet A was used as fuel.

The determination of smoke number was accomplished by taking a series of exhaust gas measurements using a sampling rake mounted behind the engine in a plane 10-in. aft of the nozzle and perpendicular to the axis of the engine. The rake had a cruciform shape with three nozzles on each arm located on centers of equal area for the tailpipe. These 12 nozzles were manifolded to a central plenum chamber from which a single sample was extracted. This rake conformed to the EPA probe specifications in the Federal Register.

The smoke measurements were made in accordance with the specified SAE/EPA procedures (i.e. at each power level, run four filters, then interpolate SN from a curve of the form $SN = C_0 + C_1 (\ln W/A)$ at a W/A of 0.0230). The data resulting from this test are shown in Fig. 5 where smoke number is plotted against corrected thrust.

Analysis of Ambient Effects

A statistical anaysis was performed on the data to determine the effects of ambient test conditions, and fuel type. The purpose of the analysis was to distinguish major effects from minor effects and to derive correction factors for major effects if possible. After observing, through graphical presentation of the data, that the effects of ambient temperature and humidity might be present, a regression analysis was performed. For the purposes of this analysis, the effects of both ambient temperature and humidity were assumed to be linear.

For the data set at the highest power setting, the analysis selected the inlet temperature as the most significant in-

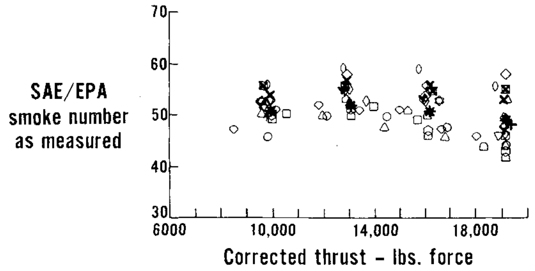

Fig. 5 JT3D smoke-as-measured.

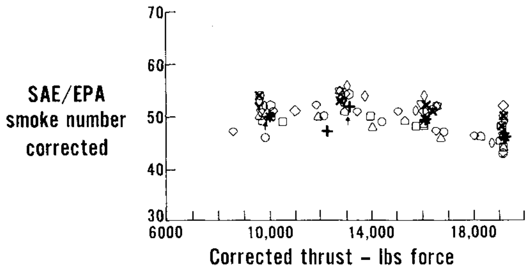

Fig. 6 JT3D smoke-corrected.

dependent variable, explaining 76% of the SN variation. When the analysis was repeated to include humidity, the remaining variation was reduced by less than ± 1%. It was concluded, therefore, that the major variable effecting smoke production was ambient temperature.

The correlation factors at each of the four power levels were expressed as a linear function of thrust using a least-squares fit. The resulting smoke number correction equation may be written:

$$SN_{std} = SN_{meas} - [\,(1.55 \times 10^{-5} Fn + 0.103)\,(T_2 - 59.0)\,] \quad (10)$$

where

SN_{std} = smoke number corrected to standard temperature (59°F)
SN_{meas} = measured smoke number
Fn = corrected thrust, lbf
T_2 = inlet temperature when measurement was made, °F

When the corrections for T_2 were applied to data, the scatter in smoke data was reduced significantly. Figure 6 shows the SN data after corrections.

Table 4 demonstrates, quantitatively, the improvement in the precision of the smoke data, at various power levels, as a result of the correction for ambient temperature.

The variability remaining is similar at all thrust levels, permitting individual values to be combined. The combined error for JT3D smoke measurement corrected to standard temperature was ± 4.4 EPA smoke numbers. Smoke meter precision error was estimated to contribute approximately ± 2 smoke numbers for this test program. Subtracting ± 2.0 from ± 4.4 by quadrature results in a remaining variation of ± 3.9 smoke numbers. This remaining variability results from engine-to-engine variation, sampling errors, and possible uncorrected effects of ambient conditions.

Effect of JP-5 and Jet A Fuel on Smoke Production

The data were then examined to determine if remaining variability could be explained by differences in fuels used during the series of tests. Corrected smoke measurements were ordered from least to greatest. The fuel type was indicated next to each measurement. If one fuel type contributed to a lower smoke number, it should appear more frequently with low smoke numbers. This comparison is shown in Table 5. Testing the distribution of the two fuel types using the t statistic indicated that the incidence of a fuel type with a particular level of smoke measurement was random. The use of either JP-5 or Jet A fuel does not affect the level of JT3D smoke.

Table 4 Reduction in precision error due to correction of smoke data for the effect of ambient temperature

	Precision	
Power setting	Uncorrected	Corrected
55%	± 4.9 SN	± 4.2 SN
70%	± 6.1 SN	± 4.4 SN
85%	± 7.3 SN	± 4.3 SN
100%	± 9.3 SN	± 4.6 SN

Table 5 EPA SN vs fuel type

Fn(obs) = 12,000 lb		Fn(obs) = 17,500 lb	
EPA SN	Fuel	EPA SN	Fuel
48.1	JP5	42.9	Jet A
49.1	JP5	43.0	JP5
49.5	JP5	44.2	JP5
50.1	JP5	44.2	JP5
50.6	Jet A	44.5	Jet A
51.1	Jet A	45.1	Jet A
51.3	Jet A	45.4	JP5
51.5	Jet A	45.4	JP5
51.6	JP5	45.8	Jet A
53.4	JP5	46.2	Jet A
53.4	Jet A	46.2	Jet A
53.4	Jet A	46.3	JP5
53.6	JP5	47.2	JP5
54.4	JP5	47.7	Jet A
54.5	JP5	48.1	JP5
54.6	Jet A	48.2	Jet A
54.8	JP5	49.0	JP5
55.6	Jet A	51.7	JP5

Conclusions

1) The major instrument-related source of error in SAE/EPA smoke measurement is clean-filter reflectance precision. It is a direct result of the variability in filter reflectance about the average value used.

2) Smoke measurement uncertainty, due to error in clean-filter reflectance, decreases with increasing smoke number.

3) The regulation-specified curve fit introduces a bias error into the smoke level reported by interpolation of that curve at $W/A = 0.0230$ lb/in.^{2}.

4) An alternate single-filter procedure, which requires measuring the clean reflectance of each filter, yields a precision error equivalent to the SAE/EPA four-filter procedure.

5) For both the SAE/EPA and the alternate smoke measurement procedures, pressure and temperatures measurement precision may be permitted to deteriorate from ± 4°F and ± 0.1 in. Hg to ± 8°F and ± 0.3 in. Hg, respectively, without significantly deteriorating the smoke measurement precision.

6) Ambient temperature is a significant factor affecting JT3D smoke production.

7) The use of either JP5 or Jet A fuel does not affect the level of JT3D smoke.

Further Effort

Other error sources not specifically considered in this work include operator effects, filtering mechanics, engine setting precision, engine stability, and statistical sample error resulting from utilizing a finite number of samples from a tailpipe exhibiting a gradient in smoke level. (D. L. Champagne touched on both sample error and engine stability in his work in 1971.) Future efforts should include a detailed evaluation of the magnitude and effect of these sources of uncertainty, particularly sample error, which for gaseous emission measurement of gas turbine engines has been shown to be the major error source.[3]

References

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