THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47 St., New York, N.Y. 10017

83-GT-72

INVESTIGATION OF FIXED-RAKE SAMPLING SYSTEM FOR THE ASSESSMENT OF EMISSION CHARACTERISTICS OF GAS TURBINE ENGINES

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ABSTRACT

The regulations proposed by the US Environmental Protection Agency to limit the quantity of pollutant gases emitted by aircraft engines allow the exhaust of engines submitted for compliance testing to be sampled by a fixed-multipoint rake. However, the onus is placed on the manufacturer to prove the representativeness of the samples taken in this relatively cheap fashion. To illustrate best possible accuracies, the exhaust of an M45H civil turbofan engine has been extensively sampled and a computer program has been used to select the optimum configuration of a cruciform rake. The program demanded excellent agreement between the sampling methods and this proved to be the case in actual tests. However, the program also indicates that the errors of a simply designed rake giving area-weighted samples would also be less than 10%. Sampling in the FAA diamond pattern would give rise to a 20% error in CO emissions.

NOMENCLATURE

CO	Carbon Monoxide
CO_2	Carbon Dioxide
EPA	Environmental Protection Agency
EPAP	Environmental Protection Agency Parameter
FAA	Federal Aviation Authority
ICAO	International Civil Aviation Organisation
LTO	Landing and Take-off
SAE	Society of Automotive Engineers

INTRODUCTION

The introduction of emission standards following the Clean Air Act of 1970 generated considerable activity in exhaust gas sampling, both in industry and in government establishments (1-4). A major problem identified was that of acquiring representative emission samples. JT3D and JT9D tests showed encouraging agreement between detailed traverse and area-weighted fixed-rake measurements for most emissions (2), but to obtain any degree of success for the mixed-fan JT8D it was found necessary to separate the two streams and sample solely from the hot core (1). The general conclusion from this early work was that accurate measurements could be accomplished only by detailed traversing (1).

More recently, the FAA investigated the problem and a statistical study of JT8D traverse emissions indicated that it was feasible to obtain representative samples using fixed probing techniques (5). However, the procedure employed was totally unrepresentative of EPA requirements in that the parameters optimised were not fuel flow and LTO cycle mode time weighted. Also, CO_2 was substituted for smoke and the test modes were not those of the EPA regulations. Using the same experimental data, the performance of several cruciform and diamond probe orientations was predicted (6). Excellent agreement was obtained for a number of area-weighted rakes, but when tested, their performance was significantly poorer than the predictions. Surprisingly, predictions for their recommended diamond probe configuration (7) revealed an 11% discrepancy at the idle condition. As in the earlier Pratt & Whitney Aircraft work the overall conclusion drawn was that detailed traverses were necessary to measure engine emissions accurately.

During Phase III of the Experimental Clean Combustor Programme, the performance of the FAA diamond probe was compared with the NASA/P&WA rake which has 24 sampling points located on eight radial arms at centres of equal area (8). Results showed good agreement for smoke and the gaseous emissions at high power settings, but a discrepancy of 10% in CO levels at the idle and approach conditions. Comparisons of diamond and cruciform sampling patterns have been carried out by the General Electric Company during tests on CF6-6 and CF6-50 engines (9). In this work only small differences in emission measurements were observed. Clearly, the problem has been far from completely resolved, despite the considerable effort devoted to it during the past decade.

The current investigation set out to demonstrate that a representative sample of all emissions over the area of the entire exhaust nozzle of a gas turbine engine can be obtained using a fixed cruciform rake designed to EPA specifications (10). The EPA allows the emissions to be characterised by ganged sampling of an engine exhaust. The regulations demand a minimum of 12 sampling points and specify various constraints on their disposition about the engine exhaust plane. It is required that the sampling points are to be placed so as to obtain a representative sample of the emissions over the entire area of the exhaust nozzle and to minimise errors due to pollutant stratification. To this end the exhaust plane of an M45H engine has been extensively investigated using a traversing rake at the four operating conditions specified by the EPA. These detailed measurements were first used to obtain accurate values of the emission parameters at the four running conditions. A computer program was then developed to use the spatial distributions of the pollutants to design an optimum fixed-cruciform rake. The program determined where the 12 sampling points on a fixed rake should be positioned in order to minimise the fractional error in measuring the masses of the four pollutants emitted during their dominant modes of the EPA landing and take-off cycle.

The rake was manufactured and subsequent tests were carried out to verify the recommended design. Excellent agreement between the traverse and fixed-rake measurements was observed. The EPA parameters for unburned hydrocarbons, carbon monoxide and oxides of nitrogen calculated from the optimised fixed-rake data were 37.6, 144.9 and 32.2 respectively. These compare with values of 37.8, 143.7 and 37.2 derived in the detailed traverse exercise. A maximum SAE Smoke Number of 15.5 was measured by the fixed rake. This compares with a value of 12.8 obtained in the traverse tests.

When unarmed with the spatial distributions of the emissions and a suitable computer program, the standard fixed rakes employed are area-weighted cruciform or FAA diamond patterns. The emission profiles determined by traversing were used to predict the levels that would have been obtained from such configurations. Agreement for the cruciform rake appeared acceptable, but a particularly poor value for CO was predicted for the diamond rake.

TEST SYSTEM

Description of M45H Engine

The M45H engine is a two-spool turbofan which has a bypass ratio of approximately 3:1. Its assembly comprises a single-stage fan leading to a cold exit nozzle, a five-stage intermediate compressor which is driven by a three-stage turbine and a separate seven-stage high-pressure compressor driven by a single turbine.

For this exercise the production standard annular vaporising combustor was replaced by a low-emission combustor (Z-ring, double blown ring standard) to render it more representative of current technology. It must be stressed, however, that the emission levels of unburned hydrocarbons and carbon monoxide presented in this paper are significantly higher than those achievable with current annular vaporising combustors.

The jet efflux is taken through a hot nozzle at the rear of the engine. For this investigation a slave jet pipe was fitted (because of the protruding afterbody) to enable sampling close to the nozzle exit plane.

Traverse Probe Mechanism

The rake used in this work was a multipoint rake with each point individually piped to an external manifold system incorporating motorised switching valves which allowed selection of any one point for sampling. To comply with EPA regulations, the rake was made of stainless steel and the sampling points were designed so that the principal pressure drop through the probe assembly (greater than 80%) occurred at the orifice. Preliminary investigations however, revealed that the sample flows through the system were unacceptably low. To obtain suitable flows it was found necessary to open up the sampling heads from 0.040 in to 0.064 in, thus sacrificing pressure-drop achievements (55% at orifice).

The EPA specifies that sample transfer lines from the probe to the instrumentation system be maintained at a temperature of $150 \pm 5^{\circ}$C. To satisfy this requirement within the rake, the pipework was surrounded by a water jacket fed by a recirculating high-pressure hot water system.

This system, which incorporates a pressurising pump, a circulating pump and a heater, is capable of delivering water at temperatures up to 200°C and pressures up to 250 psig.

The rake was axially located as close to the exit plane of the nozzle as possible (5 inches) and within the half exit nozzle diameter as recommended by the SAE (11).

Control of the traverse gear was achieved by balancing the resistance of a potentiometer in the control unit against the resistance of a potentiometer driven by the drive-shaft of the gear, the voltage being balanced on a galvonometer on the control unit. Because of the different limits of traverse for each of the heads on the rake, detailed calibration of the control unit was required. It was found necessary for the rectangular frame supporting the rake to be strapped to the detuner to suppress the substantial vibration observed under engine loads.

Sample Transfer Lines

The individual delivery lines which transferred the samples from the rake bulkhead to the unit housing the external manifolds and switching valves met EPA specifications. Pressure tappings on each individual line upstream of the valve allowed use of the rake to obtain pressure profiles in addition to gas sampling. These were directly connected to the test bed data recording system.

The three-way ball valves (Type Hoke Selecto-Mite 316 SST) which were driven by electric 'stepper' motors allowed the following options:

1. A no-flow situation necessary for pressure measurements.
2. Connection of the individual sample lines (via a manifold) to a common delivery line to the instrumentation system.
3. Exhausting of individual samples.

The complete system was shown to be leak-proof both before and on completion of the test programme.

Pipework, valves and manifolds within the valve enclosure were heated by radiation and convection from passes of the hot water supply to the rake. Sample temperatures measured at the exit from this unit and at the inlet to the instrumentation system were in the range 100-110°C. Although this implies we were not satisfying the regulations, these sample temperatures were judged satisfactory for tests on AVTUR.

Specifications were met regarding sample line length but the modest gas flows caused sample system transport times greater than the maximum permitted two seconds. A residence time within the line of the order of three seconds was achieved.

Instrumentation System

The exhaust gas analytical system was as specified by the EPA for all gaseous emissions (10). Smoke concentrations were measured using a Hartridge Smoke Meter in place of the EPA recommended filter paper method. All instruments were coupled to chart recorders.

Cruciform Rake

The fixed-cruciform rake, which was also water-cooled, was mounted on the same rectangular frame with its sampling heads (the EPA specified minimum of three per arm) in the same axial plane as the heads of the traversing rake. The probe pressure drop and sample transfer time specifications were met for this rake. The common sample transfer line was connected directly to the rake manifold. All adaptors were wrapped with trace heating tapes and well lagged. Sample temperatures were measured at the exit from the rake manifold and at entry to the instrumentation system.

TEST PROCEDURES

Engine Conditions and Measurements

A full-datum performance curve with the standard hot nozzle and a limited curve with the extended slave jet pipe were carried out prior to gas sampling tests to establish the engine running line.

Traversing was carried out at the four engine operating conditions specified by ICAO (12) and the EPA (with the exception of the fixed 7% idle rating).

Ground Idle	7%	Take-off Thrust
Take-off	100%	Take-off Thrust
Climb Out	85%	Take-off Thrust
Approach	30%	Take-off Thrust

To preclude engine surging, the anti-icing bleed was taken at the idle condition. The performance parameters recorded at each engine mode were:

Engine speed, N_H
Combustor inlet temperature, T3
Combustor inlet pressure, P3
Stator outlet temperature
Exhaust gas temperature
Fuel flow
Total engine airflow
Bypass ratio
Thrust

In addition, ambient temperature, pressure and humidity were measured during each test.

Gas Analysis Traverses

After allowing a settling time of ten minutes at each engine condition, continuous gas analysis traverses of the exhaust were carried out. This continuous-traversing technique (validity of which has previously been demonstrated even at the combustor exit plane) offers a considerable saving in engine running time, but of course precludes use of the filter paper method for measuring smoke. A suitable correlation is available for converting Hartridge Smoke Units to SAE Smoke Number. The rake was traversed in alternate directions (at a speed of approximately ten inches per minute) sampling in turn from each of the heads. Heads not being sampled were vented to atmosphere. To ensure that the entire traverse lay within the exhaust plane, the limits of each traverse were on a circle of 0.5 in smaller diameter than the jet pipe exit diameter.

Throughout the series of traverses the rake was cooled by water nominally at 150°C and 200 psig. Water temperatures varied in the range 150 - 190°C due to difficulty in controlling the system, particularly at the high engine power settings. The water was circulated at the operating temperature for approximately 90 minutes prior to engine light-up to achieve the maximum temperature of the sample transfer lines within the valve enclosure. Electrically heated lines were controlled to within the specified temperature range.

Pollutant species measured were:

Total unburned hydrocarbons (UHC)
Carbon monoxide (CO)
Carbon dioxide (CO_2)
Oxides of nitrogen (NO_x)
Smoke

Pressure Traverses

Total pressures were measured using the sampling rake as a pressure probe. The rake was positioned at each of ten stations spaced at 1.5 in intervals across the exhaust nozzle.

Ganged Sample Measurements

Upon completion of the traversing exercise, tests were carried out to establish the validity of the ganged sampling technique. With the rake stationary on the engine centreline, samples were taken from heads 8, 9 and 10 individually and then from all three ganged together. This was done at the approach condition for the gaseous emissions and repeated at the take-off condition for smoke analysis.

Cruciform Rake Tests

The exhaust gases were sampled at six engine speeds, the four specified by ICAO and an additional two (one either side of the 7% idle condition) to enable reliable comparisons of Emission Indices on a T3 basis. Water temperatures varied in the range 150-170°C and sample temperatures in the range 140-150°C were recorded at the rake exit and the inlet to the instrumentation system.

DATA ANALYSIS

Calculation of Corrected Emission Parameters

Values of the emission data, fuel/air ratios and combustion efficiencies at 110 discrete points across the exhaust area (depicted in Fig 1), together with total pressures at the grid points specified above, were fed into a computer for subsequent analysis.

Initially, the emission parameters were calculated from the observed engine performance and chemical data. At each point on the chemical grid, pollutant concentrations were converted into local flow rates. The flow rate of pollutant, 'A', at x, y and at engine condition i,

$$q_A(x,y:i) = \frac{\rho V\ M_A}{100\ M_P}\left[\%\text{A by volume at } x,y:i\right]\ \text{kg/m}^2\text{s}$$

where ρ and V were the local density and axial fluid velocity,

M_A = molecular weight of pollutant A

and M_P = molecular weight of combustion products

Determination of these expressions required a knowledge of local temperatures and pressures. Temperatures were calculated from local fuel/air ratio and efficiency data and total pressures were obtained at the chemical grid points by linear interpolation between the measured values. Using these ρ

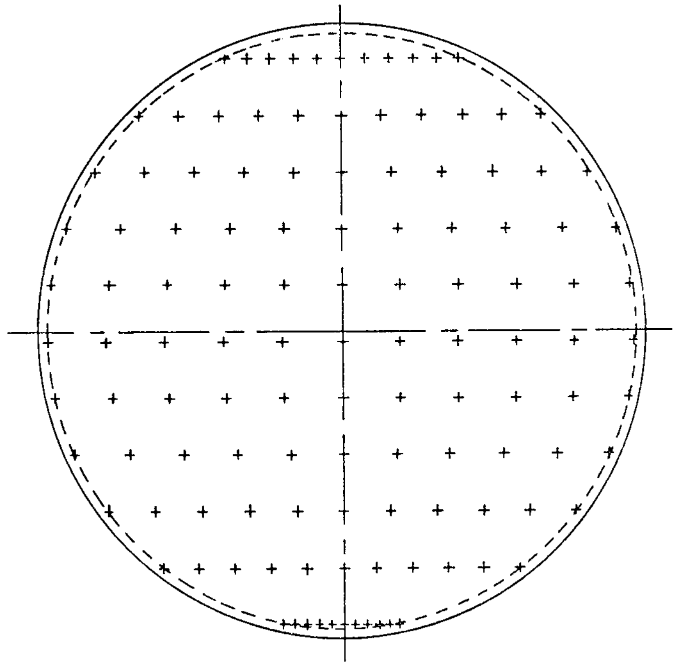

FIG 1 CHEMICAL GRID POINTS

and V data, continuity checks were carried out. Satisfactory agreement was obtained at each of the four conditions. Total emission rates at each engine condition (Q_A, kg/s) were derived by integrating over the entire sampling plane (using the trapezoidal rule).

These emission rates were then converted to Emission Indices and EPA parameters:

$$\text{Emission Index, } EI_A(i) = \frac{1000\ Q_A(i)}{W_F}$$
(grams A/kilogram fuel)

Where W_F = Fuel flow rate kg/s

$$EPAP_A = 1000\ \frac{\sum_{i=1}^{4} Q_A(i)\ \text{Time}(i)}{F_\infty}\ \text{g/kN}$$

Time (i) is the specified time in seconds at engine condition i in the EPA cycle (10) and F_∞ is the take-off thrust in kN. In a similar way a global smoke number was calculated from a numerical integration of the local mass weighted smoke numbers.

The next stage involved correction (to ISA day conditions) of these observed data in accordance with ICAO recommended procedure (12). Local concentrations were then scaled accordingly and fed back into the program together with the corrected performance data. Corrected Emission Indices, EPA parameters and Smoke Numbers were thus derived.

Cruciform Rake Design

A computer program was written to use the mass-weighted emission profiles to determine the optimum configuration of a cruciform rake. The task in hand was to find the radial positions of the twelve probes and the orientation of the rake that gave the smallest possible difference between the true pollutant level (as derived from the traverse exercise) and the pollutant level that would be determined by a ganged sample from the rake. The program first calculated what would be measured by just ganging together samples taken isokinetically at twelve points, (x_j,y_j) $j = 1,\ldots,12$, from the details of the distribution of the pollutants and their local mass fluxes over the sampling plane. The gas analysis data was not available for all values (x_j,y_j) and pollutant emissions for a general point in the sample plane were evaluated by linear interpolation between the data points. The interpolation was done in such a way as to ensure that the interpolated pollutant emissions were continuous over the sample plane.

The estimated emission rates for the pollutants, the estimated EPAPs and the estimated smoke number were all functions of the twelve sampling positions (x_j,y_j) $j = 1,\ldots,12$, or equivalently, since the rake had a cruciform shape, functions of $(r_1,\ldots,r_{12},\Theta)$, the radial positions of the twelve probes and the orientation of the rake. The program then proceeded to find the values of $(r_1,\ldots,r_{12},\Theta)$ that made the difference between the true and estimated values of the pollutant level (allowing for relative fuel flow and mode times) as small as possible. The way chosen to quantify this difference was to minimise f:

$$f(r_1,\ldots,r_{12},\Theta) = \sum_A \sum_{i=1}^{4} \left[\frac{\text{EEM } A_i - \text{EM } A_i}{\text{MAX (EM } A_i)}\right]^2$$

Where (a) EEM A_i and EM A_i are the estimated and true emissions of A at condition i and MAX (EM A_i) is the maximum emission of A for the four ratings, and (b), A is summed over the pollutants UHC, CO, NO_x and smoke. This ensured that the smallest fractional error was made in the estimate of the emission of each species at the engine rating where its largest emission occurred. The function of thirteen variables, f, was minimised subject to EPA constraints of probe positions by using Box's method (13). Box's method of minimising a function f ($\underline{z}$) subject to constraints may be used whenever the constraints define a convex region. The EPA insists that the distance between any pair of probes be greater than one-tenth of the jet pipe radius. This condition imposed constraints on the values of $\underline{z} = (r_1,\ldots,r_{12},\Theta)$. Although most of these constraints describe a convex region, four do not. However, we made the allowed region convex by changing two of the constraints and imposing slightly stronger conditions than the EPA. The effect of these stronger conditions was to reduce the possible range of the values of r_4 and r_{10} (the radial distance of the probes nearest to the jet axis on arms 2 and 4) from .365D to .35D, where D is the jet diameter. This is not a serious restraint and any error it might introduce is negligible in comparison with other errors, for example those introduced by only having the experimental data at discrete points.

In Box's method the constraints are handled by the use of a flexible figure, or complex with $k \geq n + 1$ vertices, where n is the dimension of the variable $\underline{z}$ (for 12 probes $n = 13$). The complex can expand or contract in any direction and it can extend round 'corners' in its search for the minimum. All the vertices of the complex must satisfy the constraints. The method first requires the generation of a suitable starting complex of random vertices (probe positions). It then calculates the emission parameters consistent with a ganged sample taken from these positions in the exhaust plane, and evaluates $f(\underline{z})$ for each vertex. In the minimisation procedure laid down by Box the vertex yielding the largest value of the objective function is rejected and replaced by a point which is located a distance α ($\alpha = 1.3$ was used) times as far from the centroid of the remaining points as the distance of this rejected vertex but on the other side of the centroid. If this new point is within the boundaries, and satisfies the constraints the function is evaluated there. If the new point does not lie within the boundaries, it is reset a small distance inside the appropriate boundary. If on the other hand a constraint is violated the vertex is moved half-way in toward the centroid. This is repeated until a suitable point is obtained. Since the region is convex this procedure will eventually lead to a point which lies within the boundaries and satisfies all the constraints. The function f is then evaluated there. The EPA constraints have a particularly simple form, and it was possible to treat some of these constraints in the same way that boundaries are treated in Box's method. When a new guess did not satisfy the constraint it was usually obvious how the point could be put back within the allowed region, in a way that only affects the co-ordinates actually on the constraint. Thus the overall size of the complex was not reduced, it merely spread out along the constraint. On the few occasions when it was not easy to see where the point should be replaced in order to satisfy all the constraints, we fell back on Box's suggestion of moving the point half-way towards the centroid. If the new point has the worst value in the set of vertices, its location was moved half-way in towards the previous centroid.

In this way the complex changed shape, expanding as it searched through the region for a minimum. It spread out along boundaries, reduced in size on constraints and finally, when the minimum had been located, shrunk down to the centroid. The method ceased when the 'size' of the complex was less than the specified convergence criterion. This convergence criterion was tightened until what was regarded as an engineering solution to the problem was obtained.

Box's algorithm has several advantages which make it a convenient way of minimising the function f. This function was complicated and fortunately in this method only one function evaluation was necessary at each step. Secondly the function was obtained by interpolation between experimental data points and so it is convenient that this method did not involve the differentiation of f.

Optimum Configuration

It was discovered that a number of satisfactory solutions could be obtained by slightly altering the tolerance between the true and fixed-rake predicted data. All solutions demanded a similar orientation of the rake (7^o range) with radial positions of probes on the arms varying by less than 0.5 in. In order to reveal the factors which were dictating the rake orientation, the mass-weighted emission profiles were derived using a contour plotting program (14).

FIG 2 THE DISTRIBUTION OF UHC AT IDLE

At high power conditions the profiles were generally flat and gave little indication as to why such arrangements were chosen. However, the contour plots of UHC (Fig 2) and CO at idle showed two regions (diametrically opposite) of high concentrations. These were determining the rake alignment. Primer jet fuel flows are considered responsible for these effects.

The particular solution chosen for manufacture (Fig 3) permitted the radial positions of a number of probes to vary within .040 in without sacrificing the representativeness of the sample. The program requested a probe at the centre of the rake, a possibility not catered for in the rake design. This probe (probe 1, arm 1) was positioned as close to the centre as permitted and the overall effect on the predicted emission measurements was shown to be insignificant.

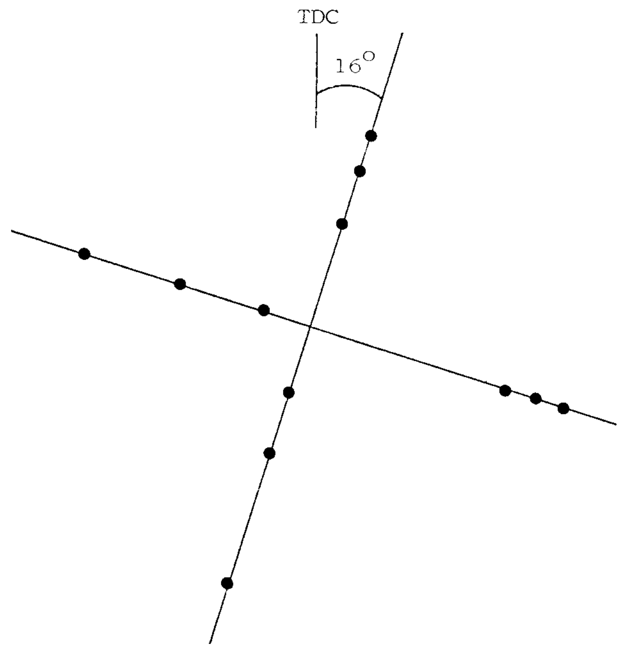

FIG 3 THE FIXED-RAKE GEOMETRY

Area-weighted Rake and Diamond Rake Predictions

When unarmed with the spatial distributions of the emissions, the standard fixed rakes employed are area-weighted cruciform or FAA diamond patterns (9). The detailed knowledge of the emission profiles was used to predict the pollutant levels that would be measured by a ganged sample from such probes for comparison with the performance of the optimum probe.

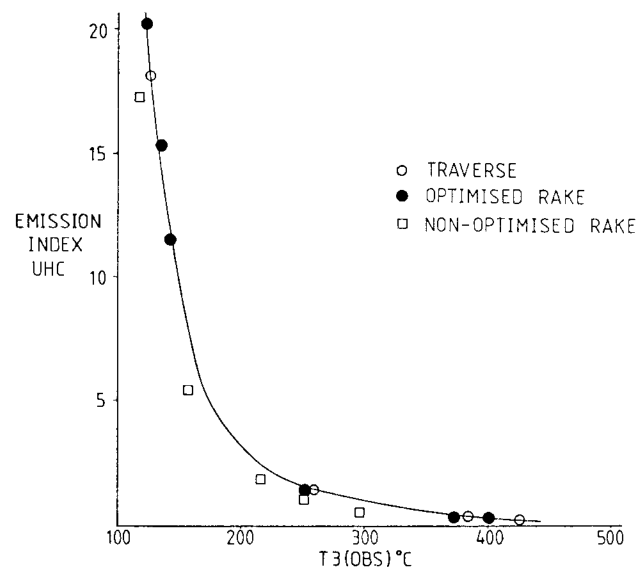

FIG 4 EMISSION INDEX UHC VERSUS T3

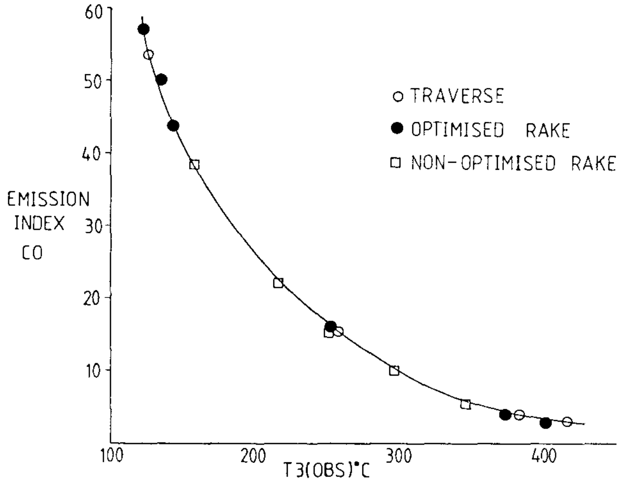

FIG 5 EMISSION INDEX CO VERSUS T3

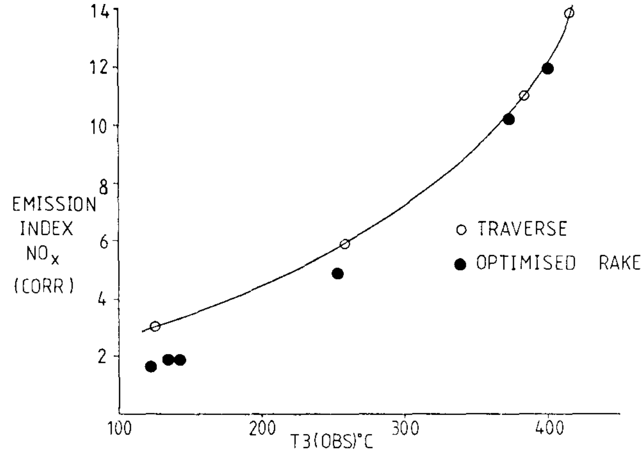

FIG 6 EMISSION INDEX NO_x VERSUS T3

RESULTS AND DISCUSSION

Traverse and Optimised Rake Emission Measurements

Observed emissions of unburned hydrocarbons and carbon monoxide are shown in Figures 4 and 5. Additional measurements (previously derived in tests on this engine employing a non-optimised fixed rake) were also plotted to assist curve definition. Oxides of nitrogen emissions, corrected for humidity and combustor inlet pressure are given in Fig 6. In general the gaseous emissions measured by the optimised rake agree very well with the traverse results. There is some discrepancy at low power settings between the NO_x emissions. This is not unexpected since the concentrations detected at these conditions are of the order of the measurement error involved.

ISA day corrected Emission Indices and EPA parameters obtained from the traverse and the optimised rake are listed in Tables 1 and 2. The emission profiles were used to predict the levels that would be measured from an optimum rake, an area-weighted rake

TABLE 1 COMPARISON OF EMISSION INDICES

EMISSION	ENGINE CONDITION	TRAVERSE MEASURED (ISA DAY CORRECTED)	OPTIMISED RAKE PREDICTED	OPTIMISED RAKE MEASURED	AREA WEIGHTED RAKE PREDICTED	FAA DIAMOND RAKE PREDICTED
UHC	IDLE	13.56	13.55	13.56	12.25	12.15
UHC	TAKE/OFF	0.26	0.26	0.26	0.25	.28
UHC	CLIMB	0.39	0.35	0.35	0.38	.42
UHC	APPROACH	1.45	1.44	1.38	1.46	1.45
CO	IDLE	45.96	45.95	46.90	44.09	35.47
CO	TAKE/OFF	2.86	2.63	2.40	2.75	3.03
CO	CLIMB	4.06	3.71	3.70	3.94	4.20
CO	APPROACH	14.29	14.51	14.00	14.50	12.15
NO_x	IDLE	3.04	3.03	1.60	2.93	2.45
NO_x	TAKE/OFF *	12.20	11.95	11.82	11.99	11.74
NO_x	CLIMB	10.98	10.82	10.75	10.74	10.35
NO_x	APPROACH	5.93	6.14	5.05	6.08	4.72

* EIs compared at T3 of fixed rake tests

TABLE 2 COMPARISON OF EPA PARAMETERS

EMISSION	TRAVERSE MEASURED	OPTIMISED RAKE PREDICTED	OPTIMISED RAKE MEASURED	AREA WEIGHTED RAKE PREDICTED	FAA DIAMOND RAKE PREDICTED
UHC	37.8	37.7	37.6	34.4	34.2
CO	143.7	143.2	144.9	138.8	114.2
NO_x	37.2	37.1	32.2	36.6	36.4

TABLE 3 COMPARISON OF SMOKE NUMBERS

ENGINE CONDITION	TRAVERSE MEASURED	OPTIMISED RAKE PREDICTED	OPTIMISED RAKE MEASURED	AREA WEIGHTED RAKE PREDICTED	FAA DIAMOND RAKE PREDICTED
IDLE	0.40	0.36	1.50	0.34	.27
TAKE/OFF	12.77	12.52	15.50	12.31	12.60
CLIMB	9.09	8.98	10.40	8.81	8.76
APPROACH	3.79	3.89	3.50	3.79	1.71

and a diamond rake. These results are also presented for comparison. The optimised rake gives good overall agreement with the traverse results. Unfortunately, the large percentage discrepancy between the values of NO_x at the idle condition observed in Fig 6 is reflected unfavourably in the EPA parameter.

The high correlation between the predicted and measured pollutant levels for the optimum rake leads one to believe that the predicted results for the area-weighted and diamond rakes are meaningful. For the area-weighted rake a 10% error in the unburned hydrocarbons at the idle condition generates a similar error in the EPAP. Otherwise agreement appears to be acceptable (errors less than 4%). The reason for the poor area-weighted prediction for unburned hydrocarbons at idle is that this particular rake orientation (vertical/horizontal) does not sample from the areas of high concentration (Fig 2) which appear to have determined the optimum probe alignment. The performance of the diamond rake would appear similar to that of the area-weighted rake for UHC, NO_x and smoke, but significantly poorer for CO. A 20% discrepancy is observed between the traverse and the prediction for this rake.

In Table 1, all Emission Indices of NO_x at the take-off condition are compared at the combustor inlet temperature measured during fixed-rake sampling (not the ISA day T3). This was done to preclude unreliable extrapolation beyond the fixed-rake points.

The measured and predicted Smoke Numbers are listed in Table 3. At high power conditions the optimised rake appears to measure 20% higher smoke levels but the discrepancy may be explained by the experimental errors involved in measuring such small concentrations.

Although the optimisation procedure took no account of CO_2 profiles, the ICAO 'carbon balance' criterion (12) was satisfied at all engine speeds (Table 4). This criterion requires that 'the air/fuel ratio as estimated from the integrated sample total carbon concentration exclusive of smoke agree with the estimate based on engine air/fuel ratio within ± 15 percent for the taxi/ground idle mode, and within 10 percent for all other modes'.

TABLE 4 CARBON BALANCE CHECK

		AFR	
FUEL	T3	ENGINE	GAS ANALYSIS
AVTUR	401	56.7	52.0
	373	60.9	56.2
	253	90.9	83.0
	143	108.7	107.3
	135	105.4	107.5
	123	103.0	107.8

Ganged Sample Measurements

The results of the tests described in the earlier section are presented in Table 5. The validity of this ganged sampling technique was thus established for the gaseous emissions. The result for Smoke Numbers is less conclusive. The Smoke Number of the ganged sample is higher than that taken from the heads individually, although the discrepancy could be explained by experimental error (eg non-isokinetic sampling effects). The effect of ganging could account for the difference between the Smoke Numbers measured by the traverse and optimum rake. Further investigation is required to clarify this point.

TABLE 5 THE EFFECT OF GANGED SAMPLING

	APPROACH			TAKE/OFF
VALVE SELECTION	CO	UHC	NO_x	SMOKE
8, 9, 10 (GANGED)	212	45	32	14.0
8	199	39	32	12.5
9	205	38	34	12.7
10	231	62	33	12.7
MASS WEIGHTED MEAN OF 8, 9, 10	212	46	33	12.6

CONCLUSIONS

The representativeness of the optimum fixed rake is thus adequately demonstrated for all gaseous emissions over the complete landing and take-off cycle. The result for Smoke Numbers is less conclusive.

Unfortunately, the non-availability of engines of this standard meant that it was not possible to optimise rake design based upon data derived from more than one engine (as was originally intended), nor was it possible to sample the exhaust of an 'untraversed' engine using the optimised rake.

The EPA regulations make no quantitative reference to the representativeness of a fixed-rake sample and it must be possible to satisfy the ICAO carbon balance check, which specifically omits smoke without guaranteeing the same level of accuracy for the carbon-containing pollutants (and vice versa) as these by necessity will only account for a very small fraction of the exhaust total carbon. It is therefore concluded that the regulations as currently written do not call for the representativeness of pollutant sample achievable with an optimised rake design. However, if, in the future, the authorities clarify what is meant by a representative sample and call for the manufacturers to demonstrate specified levels of accuracy in pollutant species measurement, fixed-rake optimisation may then be found essential. Until such time, standard area-weighted rakes may be used with confidence for sampling the exhausts of engines equipped with annular vaporising combustors.

Based upon the data derived from this one engine, the FAA diamond configuration optimised for the mixed-fan JT8D would appear unsuitable for sampling such exhausts.

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