CONTINUOUS MEASUREMENT
OF GAS COMPOSITION
FROM STATIONARY SOURCES

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by

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Prepared for

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ABSTRACT

The program objective was to develop and evaluate methods for the continuous measurement of gaseous emissions from stationary sources, specifically in large or complex ducts where total flow processing techniques are not practical. This report is concerned with the measurement of mean gas concentrations in rectangular ducts. Work consisted of a review of related programs, development of a computer program to assess stratification levels and evaluate sampling techniques, formulation and evaluation of point sampling methods for continuous monitoring, development of a multi-port continuous gas sampling probe, and field demonstration of hardware and techniques. Results showed that emissions can be accurately monitored using as few as one flow sensor and one sampling probe, even in the presence of significant velocity and compositional stratification, although stratification levels were too high for single point samples to be acceptable. It was shown for all data examined that good accuracy can be attained by taking a spatial concentration average -- flow proportional sampling is not required. The field demonstration verified the acceptability of the proposed methodology.

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SECTION I
CONCLUSIONS

- Single point gas sampling is considered unacceptable from an accuracy standpoint due to the high stratification levels and poor temporal repeatability of the cases examined.

- For gas sample traverses, spatial concentration averages are as accurate as flow proportional concentration averages in rectangular ducts for most engineering purposes. This justifies the development of continuous sampling systems which do not need to take local flow velocity into account.

- Measurement techniques developed during the program can be used to reliably measure total mass flow, gas species concentration, and gas species mass emission to accuracies of 5-10 percent, 2-6 percent, and 11-14 percent, respectively, in rectangular ducts on a continuous basis. This can be accomplished through the use of as few as one flow sensor and one sampling probe.

- The row average technique, developed originally for velocity measurement during the first phase of the program, is also acceptable for continuous gas sampling. Rows should be taken in the direction of maximum compositional stratification whenever possible.

- The stratification level of gases for the data examined varied from 8 percent to about 40 percent of the mean concentration value, and was generally in the 10-20 percent range.

- Poor correlation was observed for the CO_2 Tracer Method.

- Use of continuous gas analyzers is much more compatible with spatial gas sampling than with flow proportional sampling.

SECTION II
RECOMMENDATIONS

- The data base for comparison of spatial and flow proportional averages should be expanded to fully verify the adequacy of spatial sampling.

- Applicability of developed methods to sampling in circular ducts needs to be assessed.

- Development of multi-point continuous gas sampling probes should be pursued.

- Agreement between results of traverses involving as few as 24 sampling points and the expanded computer matrix of 525 points suggests that work should be done to determine a reasonable maximum number of sample points for traverses. Reducing the number of points would also reduce errors due to temporal variation during the traverse.

- Extensive work should be performed at a representative site, such as an EPA demonstration plant, to fully assess the extent of temporal concentration variations in a process stream and their effect on the accuracy of both manual traverses and continuous measurements.

- A standard quantitative definition of the term "stratification level" needs to be adopted. It is recommended that the 2σ designation used in the program be adopted for this purpose, where 2σ is twice the standard deviation of traverse points from the mean concentration.

SECTION III

INTRODUCTION

The objective of the program is to develop methods to measure total
gaseous mass emissions and individual gas species emissions from stationary
sources on a continuous basis. Continuous monitoring is important for
both process control and compliance with emission standards. The primary
methodological difficulty involved in continuous monitoring is due to
stratification of both velocity and composition in the stream. The
sampling methods developed during the program apply in general to any
stationary source.

The program is concerned with point sampling methods in large ducts,
that is ones where monitoring of the total flow is impractical. The first
phase of the program was concerned with the measurement of total mass
emission (total volumetric flow rate) in rectangular and circular ducts,
and a report (Reference 1) has been issued documenting the results. This
report is concerned with measurement of gas concentrations, which are
coupled with flow data to determine constituent gaseous emissions. Work
during this part of the program was concerned with measurements in rectangu-
lar ducts only due to shortage of data for circular ducts. It is felt
that measurements in rectangular ducts represent the more difficult problem,
and that the methods developed for that case can be easily adapted to
circular ducts. Examination of existing data showed single point monitor-
ing to be unacceptable. It was also recognized that continuous monitoring
systems using a large number of sampling points would be too expensive and
complex. The general approach used was to consider methods which extract
samples from a number of discrete points in the process stream, then mix
and analyze the samples. Emphasis was placed on minimizing the number of
sampling points and specifying optimum locations.

The program began in October 1972. The gas sampling phase started
in July 1974, and the technical effort was concluded in March 1975. The
task breakdown was as follows:

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Task I Data Review. The effort was begun with a review of an EPA program on stratified gas measurement conducted by Walden Research. Baseline work was then performed to determine a viable method for specification of stratification levels, and to determine desired system accuracies.

Task II Flow Analysis Program. A computer program was developed to evaluate stratification data and determine the applicability of proposed sampling techniques.

Task III Mapping Technique Evaluation. The analysis program developed in Task II was used to analyze sample traverse data obtained from the Walden Research report and from a stratification assessment program conducted by Exxon Research and Engineering Company. Results were used to select methods for field evaluation in Task V.

Task IV Sample Probe Development. A multi-port sampling probe was designed and prototype units were fabricated for field evaluation. The probe was designed to obtain samples for the Row Average sampling method, which was initially developed and successfully demonstrated for velocity measurement.

Task V Field Demonstrations. Assessment of stratification levels and demonstration of continuous sampling techniques were performed during two field demonstrations at the Nevada Power Company station at Moapa, Nevada.

The most important program results were the discovery that the average stratification level was on the order of 10-15%, which resulted in the conclusion that single point sampling is not generally acceptable, and the discovery that spatial average concentrations agreed with flow proportional average concentrations to within an average of 2% for all data considered in spite of the stratification levels. The latter result means that concentration and flow data can be taken independently and still be used to accurately determine species mass emissions. This greatly simplifies hardware for continuous monitoring systems. As a result of this discovery, emphasis was placed on development of spatial averaging techniques. A monitoring system employing a single flow probe and a single sampling probe showed accuracies on the order of 2-3% for total and constituent mass emissions during the second field demonstration.

SECTION IV
TASK I - DATA REVIEW

The objective of this phase of the program was to determine suitable methods for continuous gas sampling, and to combine these methods with those developed under the first phase of the program for measurement of total volumetric flow. At the time Phase II of this program started, EPA program 68-02-1306, "Procedure for Measurement in Stratified Gases," performed by Walden Research Division of Abcor, Inc., had recently been completed. By design, the results of the Walden program served as the basis for Phase II gas sampling work. The first task was begun with analysis of the Walden report (Ref. 2, EPA Report EPA-650/2-74-086-a) and a review in their facility. This was followed by a survey of requirements and analytical techniques used in gas sampling. Results were used to determine the type and extent of work required for subsequent Phase II tasks.

4.1 REVIEW OF STRATIFIED GAS PROGRAM RESULTS

The following excerpts are from pages 1 and 2 of Reference 2:

CONCLUSIONS

Results from the literature and field surveys indicate that gas stratification exists, but it is likely to be less general and less severe than particulate stratification. For a given gas stream, it is necessary to make a preliminary gas concentration survey to determine the existance of spatial stratification.

Where stratification exists, we have concluded as a result of this program, that there are two methods of obtaining representative gas samples. Where conditions permit, we recommend a system of monitoring the ratio of pollutants such as SO_2, NO_x, etc. to CO_2 from a single location. Then from the measured fuel flow and

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chemistry of the process, the mass flow of CO_2 is the mass flow of the pollutant. Where conditions do not permit such a system, we recommend a schedule of manual surveys and installation of a multi-element proportional sampler and gas velocity array.

RECOMMENDATIONS

In the course of this project, areas requiring further development were identified. These are as follows:

A. A program is needed to develop an automatic instrumentation system for extracting continuous representative gas samples from stratified gas streams, for example, a multi-probe automatic proportional gas sampler which would be practical in terms of cost and adaptability to various process streams.

B. A program is needed to develop techniques for determining the total gas flow profile or velocity vector in process streams. It is likely that in practice a significant fraction of errors in emission measurements are attributable to errors in gas velocity/flow determination.

C. Further documentation of the extent and frequency of gas stratification in process streams together with statistical analyses of data would be helpful in refining sampling methodologies.

The first conclusion and third recommendation were given first consideration. It is clear that the extent of stratification present in a process stream is a major factor in determining required gas sampling techniques. In their field work, Walden found no evidence of significant gas stratification in tests in oil-fired power plants in Weymouth, Massachusetts and Boston (Boston Edison Mystic Station) or in a coal-fired power plant in Bow, New Hampshire. Typical maximum deviations from the mean concentration for CO_2 and SO_2 were $\pm 15\%$, with average deviations from the mean on the order of $\pm 4\%$.

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For a continuous monitoring system, it would seem reasonable that the number of sampling points required would increase with increasing compositional stratification. Hardware cost would in turn be proportional to the number of sampling points, which is clearly not the case for manual sampling. Assessment of stratification levels to be expected under normal circumstances is then very important in terms of eventual hardware costs and system complexity.

The review of the Walden report made it clear that the following work would need to be performed:

- Develop analysis techniques to determine stratification levels in a simple, uniform manner.

- Expand the data base for compositional stratification to determine the severity of the problem.

- Develop a methodology for continuous gas sampling and/or verify the acceptability of the Walden CO_2 tracer method.

4.2 ANALYTICAL CONSIDERATIONS

4.2.1 Proportional Sampling Requirements

The first step in formulating the required analytical techniques is to start with the basic flow equations. Consider the duct shown in Figure 1. The four sides and the entry and exit planes form a control volume. By definition, the sides are solid, so that all fluid must enter through the left plane and leave through the right plane. For simplicity (which does not compromise accuracy), assume that the flow rate into the control volume is always exactly the same as the flow rate out of the control volume. This relation becomes true as the size of the control volume approaches zero. The flow through the control volume may then be given as the flow through the exit plane of the control volume:

$$\dot{m} = \iint_A \rho \vec{u} \cdot \vec{n} \, dA = \overline{\rho u} \, A \tag{1}$$

where

$\dot{m}$ = mass flow rate, gm/sec

ρ = local fluid density, gm/cm^3 (gas phase only)

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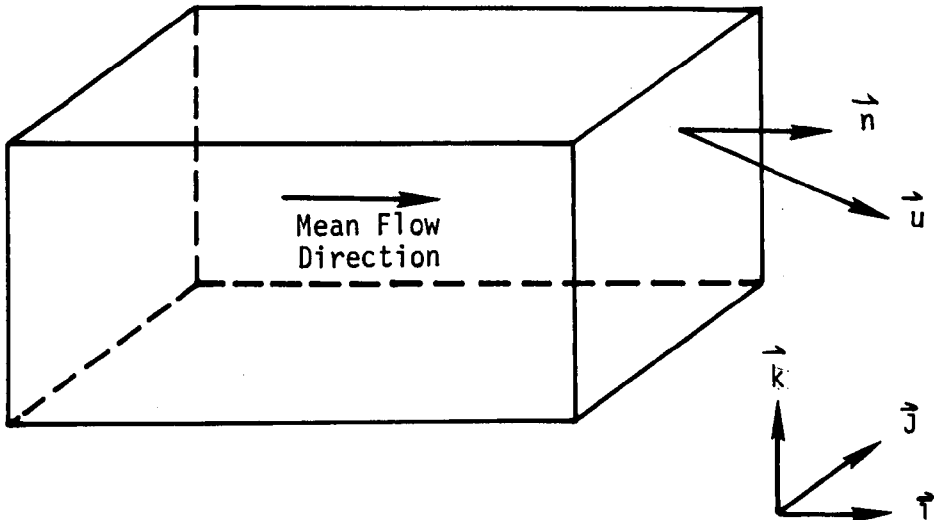
Flow enters from the left and exits
to the right.

Velocity at a point in the exit plane is given
by

$$\vec{u} = u\,\vec{i} + v\,\vec{j} + w\,\vec{k}$$

where

$\vec{i}, \vec{j}, \vec{k}$ are unit vectors in the directions
shown, forming an orthogonal coordinate system

and

u, v, w are the scalar components of $\vec{u}$ in

the $\vec{i}, \vec{j}$ and $\vec{k}$ directions, respectively

The vector $\vec{n}$ is the unit vector normal to the
exit plane, so that

$$\vec{n} \equiv \vec{i}$$

and the net flow component out of the duct at the point
shown is

$$\vec{u} \cdot \vec{n} = u$$

Figure 1. Flow measurement control volume

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$\vec{u}$ = local velocity (vector), m/sec

$\vec{n}$ = unit vector normal to exit plane, dimensionless

A = exit plane area, m^2

$u = \vec{u} \cdot \vec{n}$, scalar velocity component normal to exit plane, m/sec

This equation represents the total instantaneous gas flow through the control volume. In gas sampling work, it is desirable to know the instantaneous mass flow of a specific constituent, such as O_2 or SO_2, for control and/or regulatory purposes. For this case, we have

$$\dot{m}_i = \iint \rho i \ \vec{u} \cdot \vec{n} \ dA \tag{2}$$

where

$(\ )_i$ denotes the property relative to species i, e.g.

$\dot{m}_i$ = mass flow of species i, gm/sec

ρi = mass density of species i, gm/cm^3

This can be put in terms of normally measured parameters as follows:

$$\rho_i = c_i M_i = c \mu_i M_i \tag{3}$$

where

c = global concentration, $moles/cm^3$

c_i = concentration of species i, moles of i/cm^3

M_i = molecular weight of species i, grams of i/ mole of i

μ_i = mole fraction of species i, moles of i/mole

$$c = \frac{RT}{p} \tag{4}$$

where

R = universal gas constant, $\dfrac{gm \cdot m^2}{mole \cdot sec^2 \cdot {}^\circ K}$

T = absolute temperature, ${}^\circ K$

p = absolute pressure, torr

Substituting in equation (2), we get

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$$\dot{m}_i = \iint \frac{RT}{p} \, \mu_i M_i \, \vec{u} \cdot \vec{n} \, dA \qquad (5)$$

or

$$\dot{m}_i = R \, M_i A \, \frac{\overline{T\mu_i u}}{p} \qquad (6)$$

where the average is defined by correct evaluation of the integral in equation (5). Equation (6) is now in terms of the basic engineering parameters commonly measured in a gas flow. The mole fraction μ_i is commonly given in units of parts per million for gases such as SO_x and NO_x, and in mole percent for N_2, O_2, H_2O, and CO_2.

It is common practice to evaluate equation (5) by means of a gas sample traverse. The integration is then approximated by the summation

$$\dot{m}_i \doteq RM_i \sum_{n=1}^{N} \frac{T_n}{p_n} \, (\mu_i)_n \, u_n \Delta A_n \qquad (7)$$

for N area segments. Usually the segments are of equal area, so that

$$\dot{m}_i \doteq \frac{A}{N} RM_i \sum_{n=1}^{N} \frac{T_n}{p_n} \, (\mu_i)_n u_n \qquad (8)$$

This is the practical form of equation (5). It shows that for accurate gas sampling measurements, the local velocity component normal to the sampling plane and the local static pressure and temperature must be measured as well as the local concentration (Note: from this point on, the term μ_i will be referred to as "concentration" rather than "mole fraction" in accordance with common practice). Temperature and pressure effects are most easily handled through introduction of the concept of "velocity at standard conditions." This is illustrated in Figure 2. For this control volume, the gas enters at arbitrary pressure and temperature. It then undergoes whatever changes are required in order to emerge uniformly with a static temperature of 20°C and at an absolute static pressure of 760 torr, which have been defined as standard conditions for this program. Also by definition, the gas is considered to be chemically frozen and there are no phase changes. This is important from a practical measurement standpoint. It means that the mass flow rate being considered is that of
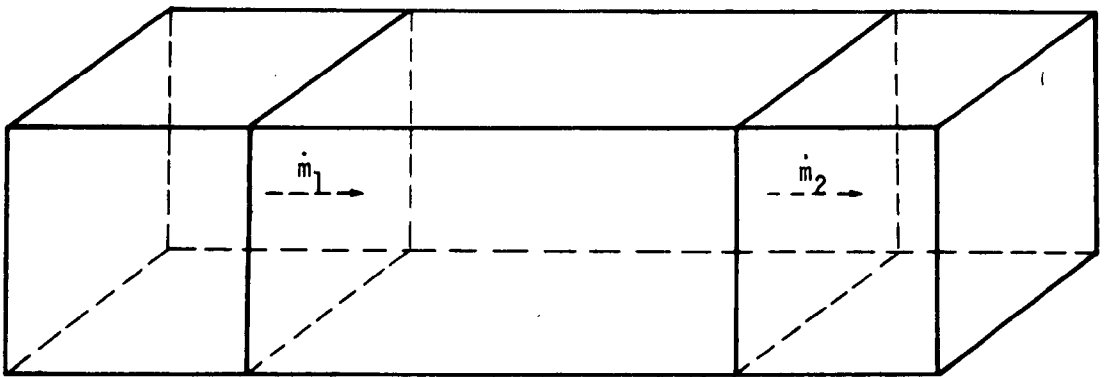
STATION 1 (TEST)

STATION 2 (STANDARD)

TEMPERATURE	T_1	T_s
PRESSURE	p_1	p_s
DENSITY	ρ_1	ρ_s
VELOCITY	u_1	u_s
AREA	A	A

FROM CONSERVATION OF MASS,

$$\dot{m}_1 = \dot{m}_2$$

SO

$$\rho_1 \, u_1 \, A = \rho_s \, u_s \, A$$

AND

$$u_s = \frac{\rho_1}{\rho_s} u_1$$

Figure 2. Duct analogy for transformation of test velocity to standard velocity

the gaseous components only, since common velocity sensors for operation in a gas stream respond to gas flow, and not to liquids or solids which may be entrained in the flow. Therefore defining a gas flow in terms of standard rather than actual conditions implies changes in pressure and temperature only -- not composition and phase. Thus for any one area segment where the velocity and density are considered to be uniform,

$$\frac{T}{p} u = \frac{T_s}{p_s} u_s \tag{9}$$

where

$$(\ )_s = \text{value at standard atmospheric conditions}$$

so that

$$\dot{m}_i = \frac{AT_s}{Np_s} RM_i \sum_{n=1}^{N} (\mu_i)_n (u_s)_n \tag{10}$$

or

$$\dot{m}_i = \frac{AT_s}{Np_s} RM_i \overline{\mu_i u_s} \tag{11}$$

Thus for the term "proportional sampling" to be truly correct, it should be interpreted as "sampling in proportion to the local velocity at standard conditions" so that temperature and pressure effects are not ignored.

The proportional gas sampling requirement inherent in equation (11) is the source of significant practical difficulties in the field, since the sampling rate must be changed for each point when standard wet chemistry methods are used. Common use of continuous gas analyzers may be expected to change this approach. For that technique, it is easier to monitor the local value of μ_i with the analyzer, then multiply by the local velocity to obtain the local mass flow rate. This was the approach taken for all field work during the program, and is also the approach one would expect to take in designing a continuous multi-point sampling system. The alternative is somewhat less attractice -- it would require obtaining a volume of sample from each point, where the volume is proportional to the local velocity. These samples would then have to be mixed thoroughly in some type of mixing chamber and delivered to the analyzer. It is felt

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that the hardware requirements for this approach would be more expensive
and difficult to maintain than the software requirements for the first
method.

There is a third alternative which became apparent as a result of
the fairly low stratification levels reported by Walden: simple spatial
sampling rather than proportional sampling. Proportional sampling is
represented by the term $\overline{\mu_i u_s}$ in equation (11), which denotes that the
true constituent mass flow rate is given by the average of the products
of local concentration and local velocity. This is mathematically different
from the product of the average concentration and the average velocity,
i.e. in general,

$$\mu_i u_s \neq \overline{\mu_i} \cdot \overline{u_s} \tag{12}$$

The only times actual equivalence is guaranteed is if either concentration
or velocity is constant in the sampling plane. If gas stratification
levels are sufficiently low, and there is no direct correlation between
regions of high and low concentration and high and low velocity, then for
the accuracies desired, we may have

$$\overline{\mu_i} \cdot \overline{u_s} \approx \overline{\mu_i u_s} \tag{13}$$

If this approximation were generally valid, large savings on systems
hardware requirements would be realized. It would mean that proportional
sampling would not be required, which would allow for a simple constant
flow rate sampling network. Further it would mean that gas sampling and
volumetric flow, as designated by u_s, could be determined independently.
Since Phase I results (Reference 1) showed that volumetric flow can be
determined in complex ducts with as few as one velocity sensor, independent
determination offers even greater advantages. As will be shown in subse-
quent sections of this report, the approximation represented by equation
(13) proved to be very good for the data examined.

4.2.2 Stratification Assessment

In order to determine stratification levels from various sources in
a consistent manner, a uniform method to determine measures of data spread

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is required. Perhaps the most common and easy to work with measure of
spread is the standard deviation for a normal distribution. The potential
problem with using standard deviation as a measure of spread is that it
is normally applied to a number of measurements of the same parameter, such
as repeated measurements of the length of a table top, or repeated measure-
ments of gas composition in a fixed volume with no chemical reaction. For
the present case, we wish to apply it to a number of individual measurements
of concentration at separate points in a non-uniform gas stream. For this
case, there is no a priori reason to believe that the readings can all be
considered to belong to a normal distribution. Gas traverse data obtained
during the Phase I field test (Section VIII) were examined to see if they
approximated a normal distribution. Data consisted of 49 point traverses
for O_2, CO_2, and NO_x in a coal fired power plant. Actual data are pre-
sented in Section VIII. For each traverse, the mean value and standard
deviation of the gas concentration was determined as follows:

$$\mu_i = \frac{1}{N} \sum_{n=1}^{N} (\mu_i)_n \tag{14}$$

where for the case $N = 49$.

$$\sigma_{\mu_i} = \sqrt{\frac{\sum_{n=1}^{} [(\mu_i)_n - \overline{\mu_i}]^2}{N}} \tag{15}$$

where

$$\sigma_{\mu_i} = \text{standard deviation of } \mu_i$$

It is common, particularly for small values of N, to use (N-1) instead of
N in the denominator of equation (15). For the purposes of this program,
one or at most two significant figures are desired for σ, so that use of
N instead of (N-1) has no significant effect on desired accuracy. Results
of the calculations are shown in Table I. Results for all three cases are
very close to what would be expected for a normal distribution. This is
further illustrated in Figure 3 for the NO_x traverse. Figure 3 shows a
histogram of deviations from the mean NO_x value. Superimposed on this is

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Table 1. COMPARISON OF DEVIATIONS FOR ACTUAL AND
NORMAL DISTRIBUTIONS

DEVIATION	NORMAL DISTRIBUTION	ACTUAL DISTRIBUTIONS		
		NO_X	CO_2	O_2
σ	68.3	65.3	61.2	71.4
2σ	95.4	100	100	89.8
3σ	99.7	100	100	100

Data for actual distributions taken from TRW field test.
See Section VI.

Tabular values are percentage of data points which differ
from the mean value by less than the specified deviation.
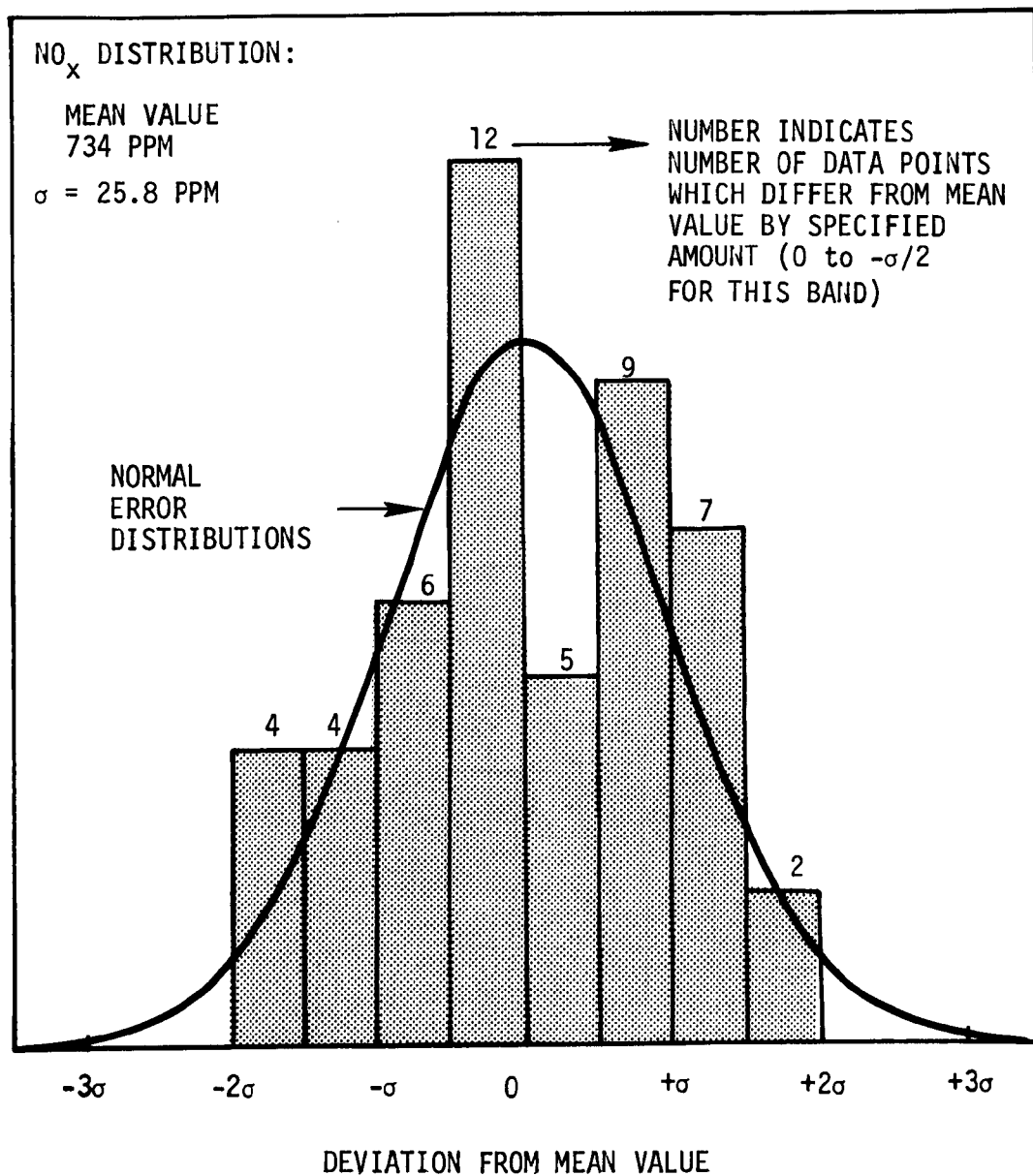
Figure 3. Histogram of deviations from mean value for NO$_x$ traverse

the normal distribution curve. The conclusion reached from Table I and Figure 3 is that the standard deviation used is a reasonably accurate reflection of the actual data distribution.

Given the validity of the standard deviation as a measure of spread, we can now define a parameter to indicate the degree of stratification in a stream. For most engineering applications, a 95% level of certainty with regard to the accuracy of a measurement is acceptable. This corresponds to a band of $\pm 2\sigma$ about the mean value. Consider the NO_x traverse as an example. The mean concentration was 734 ppm with a standard deviation of ± 26 ppm, or 3.5%. By definition, then, we will say that the stratification level was $\pm 7\%$ (i.e. 2σ) from the mean, which means that the probability is 95.4% that a point measurement taken anywhere in the sample plane will deviate from the mean concentration by less than $\pm 7\%$. Stratification level is being defined as $\pm 2\sigma$ from the mean concentration value in the sampling plane.

4.3 DESIRED SYSTEM ACCURACY

The proposed relation which we wish to consider for determing mass flow rates of gaseous constituents is

$$\dot{m}_i \approx \frac{AT_s}{Np_s} \; RM_i \; (\overline{\mu_i}) \; (\overline{u_s}) \tag{16}$$

The uncertainty in the measurement may be given by (see Reference 3 and/or Appendix A of Reference 1):

$$\sigma^2_{m_i} = \left(\frac{\partial \dot{m}_i}{\partial A}\right)^2 \sigma^2_A + \left(\frac{\partial m_i}{\partial \overline{\mu}_i}\right)^2 \sigma^2_{\overline{\mu}_i} + \left(\frac{\partial m_i}{\partial \overline{u}_s}\right)^2 \sigma^2_{\overline{u}_s} \tag{17}$$

where

$$\sigma_x = \text{standard deviation of parameter } x.$$

The terms N, T_s, p_s, R, and M_i are considered to be known constants and as such are not error sources. Since each of the three variables is to be determined independently of the others, equation (17) can be written

$$\frac{\sigma^2_{m_i}}{m_i^2} = \frac{\sigma_A^2}{A^2} + \frac{\sigma^2_{\overline{\mu}_i}}{\overline{\mu}_i^2} + \frac{\sigma^2_{\overline{u}_s}}{\overline{u}_s^2} \tag{18}$$

The following assumptions may be made for normal field measurements:

$$\cdot \text{ Area: } \sigma_A = .01A$$

This is based on the assumption of a 2σ uncertainty of 1% in the duct linear dimensions.

$$\cdot \text{ Velocity: } \sigma_{\bar{u}_s} = .04\,\bar{u}_s$$

This is based on an assumed 2σ uncertainty of 8% for the average velocity as determined by techniques developed during Phase I of the program, using currently available hardware. Substituting, we get

$$\frac{\sigma^2{}_{\dot{m}_i}}{\dot{m}^2{}_i} = .0017 + \frac{\sigma^2{}_{\bar{\mu}_i}}{\bar{\mu}^2{}_i} \tag{19}$$

There are two main contributions to $\sigma\bar{\mu}_i$: The sampling method error and the error associated with the sampling hardware itself. Typical continuous gas analyzers have published accuracies of about $\pm 1\%$ of full scale. If we arbitrarily assume that averages readings will occur at about 50% of full scale, then the 2σ uncertainty for the instrument would be $\pm 2\%$ of the reading. If we can obtain a 2σ uncertainty of $\pm 5\%$ for the sampling method error, we would then have

$$\frac{\sigma^2{}_{m_i}}{\dot{m}_i{}^2} = .0017 + [(.01)^2 + (.025)^2] = .002425 \tag{20}$$

so that

$$\frac{\sigma\dot{m}_i}{\dot{m}_i} = \pm.049 \tag{21}$$

and

$$2\sigma_{\dot{m}_i} = .098\ \dot{m}_i \tag{22}$$

which gives about a $\pm 10\%$ uncertainty in the constituent mass flow rate. It must be noted that this uncertainty does not include errors due to the non-proportional sampling assumption underlying equation (16). If the

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2σ error due to this assumption is $\pm 3\%$, then we get a $\pm 10.3\%$ uncertainty for the measurement of $\dot{m}_i$; if the 2σ error is $\pm 6\%$, then we get a $\pm 11.5\%$ uncertainty for $\dot{m}_i$.

The conclusion is that the greatest uncertainty lies in the measurement of the average velocity. While the $\pm 8\%$ uncertainty for this measurement can be reduced through careful selection of sampling locations (if a good one exists in the stream of interest), extensive in-place calibration, and/or very expensive equipment, the quoted figure represents a valid achievable level at reasonable cost. Preliminary determination of stratification levels suggests that it is reasonable to expect 2σ accuracies on the order of $\pm 6\%$ or better for the measurement of average concentration. This combines with the velocity uncertainty to give a basic constituent mass flow rate uncertainty of $\pm 10\%$. An additional uncertainty due to non-proportional sampling errors would perhaps raise the emission uncertainty to between $\pm 10.3\%$ and $\pm 11.5\%$. This accuracy level would appear to be reasonable for a continuous monitoring system. One additional point should be made, and that is that the accuracy of the total gas emission rate* $\dot{m}$, will be better than the constituent mass flow rate $\dot{m}_i$ since the uncertainty in $\dot{m}$ is only slightly larger than that for $\bar{u}_s$. This is discussed in Reference 1. If $2\sigma_{\bar{u}_s} = \pm 8\%$ of $\bar{u}_s$, then we would expect $2\sigma_{\dot{m}} = \pm 8.4\%$ of $\dot{m}$.

$$* \quad \dot{m} = \sum_{i=1}^{I} \dot{m}_i$$

SECTION V
TASK II FLOW ANALYSIS PROGRAM

The purpose of this task was to formulate a computer program to evaluate stratification data and determine the applicability of various sampling techniques. Expected program inputs would be arrays of gas concentration and velocity data. In Task I, the desirability of using the average spatial concentration as opposed to the proportional sampling average concentration was discussed, so it would be desirable for the program to investigate this area. Since Phase I work for velocity determination resulted in development of the Row Average technique, it was decided that the program should assess the applicability of this technique to gas sampling. The finalized program performed the desired analyses by using the basic input data to predict the local velocity and concentration at any desired point in the sampling plane.

5.1 PROGRAM DEVELOPMENT

When the program was conceptualized, there was little certainty regarding the best sampling techniques to be evaluated. Possible approaches included:

a. Walden's CO_2 tracer method

b. Multi-point proportional sampling

c. Multi-point spatial sampling

d. Single point sampling

e. Row Average sampling

f. Use of sampling data to predict a better sampling site further downstream.

It was decided that the basic program should at a minimum compute proportional and spatial sampling mean values, and have the capability to determine local values at any point in the sampling plane. This eventually resulted in the capacity to evaluate approaches b-e. The CO_2 trace method was evaluated separately, and is discussed in Section VI. Approach f

would involve mixing calculations to predict lower stratification levels at a given distance downstream. The extent of stratification in the data examined was low enough that this approach was not felt to be justified.

The final program configuration incorporates the following features:

- Expansion of input data matrix into a 525 point (21 x 25) matrix

- Calculation of average velocity, average spatial concentration, and proportional average concentration

- Calculation of 21 row averages across the duct

- Computation of profiles of constant concentration in intervals of 5% of the mean value

The program as it exists could easily be modified to evaluate the performance of any proposed sampling array for either spatial or proportional sampling. Due to the acceptability of the results for the Row Average technique, other methods have not been investigated during the program.

5.2 PROGRAM DESCRIPTION

The program itself is presented in Appendix A. The following is a description of the program and how it performs. Major steps in the program are:

1. Data Input - Arrays of velocity and concentration data are entered.

2. Array Expansion - The input arrays are expanded to 25 x 21 arrays using a TRW developed subprogram to interpolate between input points and determine values for the larger arrays. The subroutine is TRW BVIC (Bivariate Interpolation Subroutine), which uses polynomial interpolation to calculate the local values from the input values. The program assumes that the concentrations and velocities can be described by continuous single valued functions everywhere in the plane, which is physically realistic. For the input

arrays, there were no data taken at the duct walls, so
no boundary conditions (i.e. conditions at the wall)
were input. It is of course recognized that the velocity
must always be zero at the wall. It has also be recog-
nized that for the data considered, the flows were very
non-developed, and consequently thin boundary layers
would be present since there was no opportunity for
them to become significantly large. It is felt that
ignoring boundary layer development (other than that
which showed up in the input data itself) by not speci-
fying a no-slip condition at the wall leads to smaller
errors than would be obtained with that boundary
condition. It is believed that imposition of a no-slip
condition would lead to inaccurately low predicted
velocities near the wall.

3. Calculation of Averages - Using the 25 x 21 arrays, the
    program calculates three sets of 21 row averages:
    velocity, flow proportional concentration, and spatial
    concentration. In each case, the 25 points along each
    line are averaged using Simpson's rule. The 21 row
    averages are then averaged in the same way to produce
    the three mean values.

4. Calculation of Profiles - The program takes the mean
    flow proportional concentration and velocity and calcu-
    lates values in 5% intervals on either side of the mean.
    It then uses the BVIC subroutine described above to
    calculate the points in the sampling plane corresponding
    to the locus of each specified interval. The purpose
    of this is to provide data which can be presented in
    the form of a concentration map, showing profiles in 5%
    increments from the mean. This allows for quick visual
    inspection of the sampling data, including stratification
    level, distribution of concentrations in the duct, and
    comparisons of data for various constituents and temporal
    variations of any one gas.

5.3 TYPICAL PROGRAM RESULTS

Results for CO_2 sampling by an Exxon team are shown in Table 2 and Figures 4 and 5. The test is discussed in more detail in Section VI. The duct measured 3.182m x 8.269m, and a 6 x 8 sampling array was used. The first part of Table 2 shows results of calculations based on the 48 sampling points. The CO_2 stratification level, defined by 2σ, was $\pm 11\%$ of the mean CO_2 value. The second part of the table shows results from the computer program. As would be expected, the computer results agreed very closely with the sample point results. Of particular note is the fact that the spatial mean values agreed with the flow proportional mean values to within 1%. Profiles for the run are plotted in Figure 5. The maximum deviations from the mean are about +15% and -25% of the mean value. Row averages, where a row is being defined as a line parallel to the short sides of the duct (vertical in Figure 5) are shown in Figure 4. The plot shows that row averages taken between 5% and 85% of the distance from the left wall deviate from the mean flow proportional concentration by 3% or less. All row averages plotted are spatial averages.

Table 2. TYPICAL ANALYSIS PROGRAM RESULTS

Exxon Run 1 - CO_2 Data

Direct calculations from field measurements:
48 point array (6 x 8)

SPATIAL CO_2 MEAN VALUE	13.83% of dry gas
STRATIFICATION LEVEL, 2σ	$\pm$11% of mean value
FLOW PROPORTIONAL AVERAGE	13.71% of dry gas

Computer Calculations:
273 point array (13 x 21)

SPATIAL CO_2 MEAN VALUE	13.82% of dry gas
FLOW PROPORTIONAL AVERAGE	13.69% of dry gas

RATIO OF ROW AVERAGE CONCENTRATION
TO PROPORTIONAL AVERAGE CONCENTRATION

DISTANCE FROM DUCT WALL TO ROW
LOCATION, PERCENT OF DUCT WIDTH
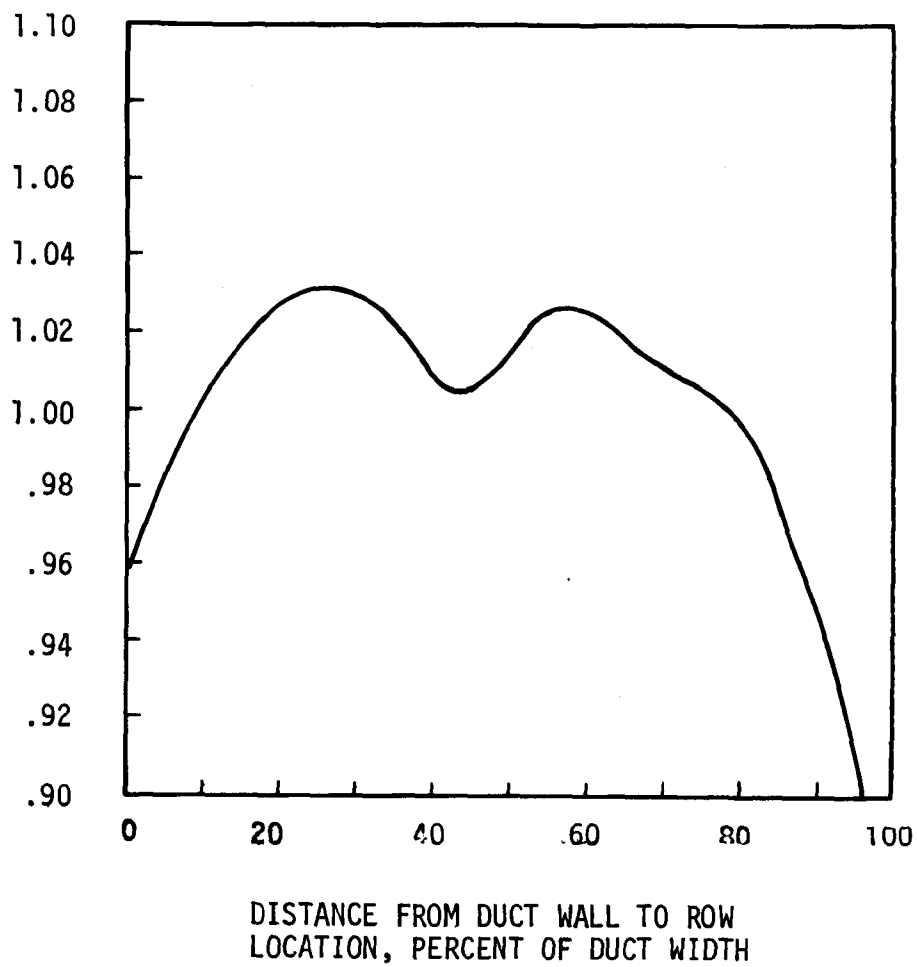
Figure 4.   Row Average analysis for CO_2
concentration map--Exxon run 1
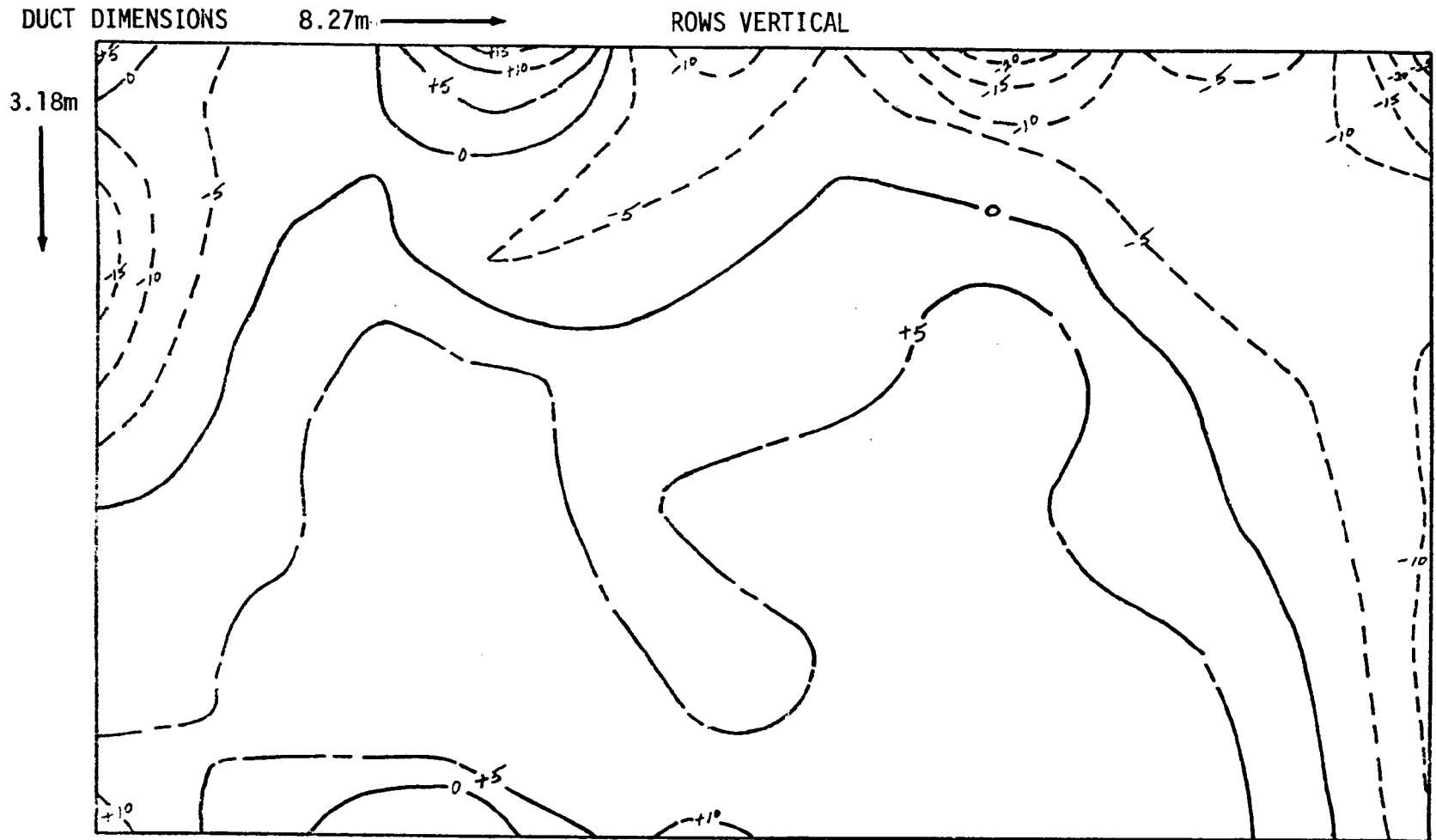
DUCT DIMENSIONS   8.27m ⟶   ROWS VERTICAL

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 13.69% (DRY GAS)

Figure 5. Normalized CO_2 concentration distribution--Exxon run 1

SECTION VI
TASK III MAPPING TECHNIQUE EVALUATION

This task involved analytical evaluation of continuous gas sampling techniques. Two separate groups of data were involved: one was obtained through the courtesy of Mr. Michael Gregory of Exxon Research and Engineering Company and Dr. Mike Barnes of EPA. The data were obtained at TVA's Widows Creek Unit No. 7, under EPA Contract No. 68-02-1722, which is concerned with stratification assessment in fossil fueled power plants. The examined data consisted of two traverses for velocity and for CO_2, SO_2, NO, and O_2 concentrations. The data are hereafter referred to as the Exxon data. The second data group were obtained from the Walden stratified gas final report, and consist of four sets of velocity and SO_2 concentration data obtained at a TVA power plant in Shawnee, Kentucky. These data are referred to as the TVA data.

The data were analyzed through use of the computer program described in the last section. In addition, the Exxon data were used to evaluate the Walden CO_2 tracer technique. Results are presented and discussed below.

6.1 EXXON DATA

The sample plane location is shown in Figure 6. It was located approximately 1.6 effective diameters downstream of an elbow. The duct cross-section is shown in Figure 7. The raw velocity data were changed to velocity at standard conditions, and the raw gas composition data were used directly.

6.1.1 Concentration Maps

Concentration data are presented in Figures 8-15 (4 gases - 2 runs each). Maps are shown as normalized concentration distribution, with lines representing deviation from the mean flow proportional concentration. The SO_2 and NO maps, Figures 10-13, did not show recognizable repeatable patterns. The CO_2 and O_2 maps, Figures 8, 9, 14, and 15, did show a predominance of excess air on the right side of the duct, which

ELECTROSTATIC
FLY-ASH
COLLECTOR

GAS FLOW
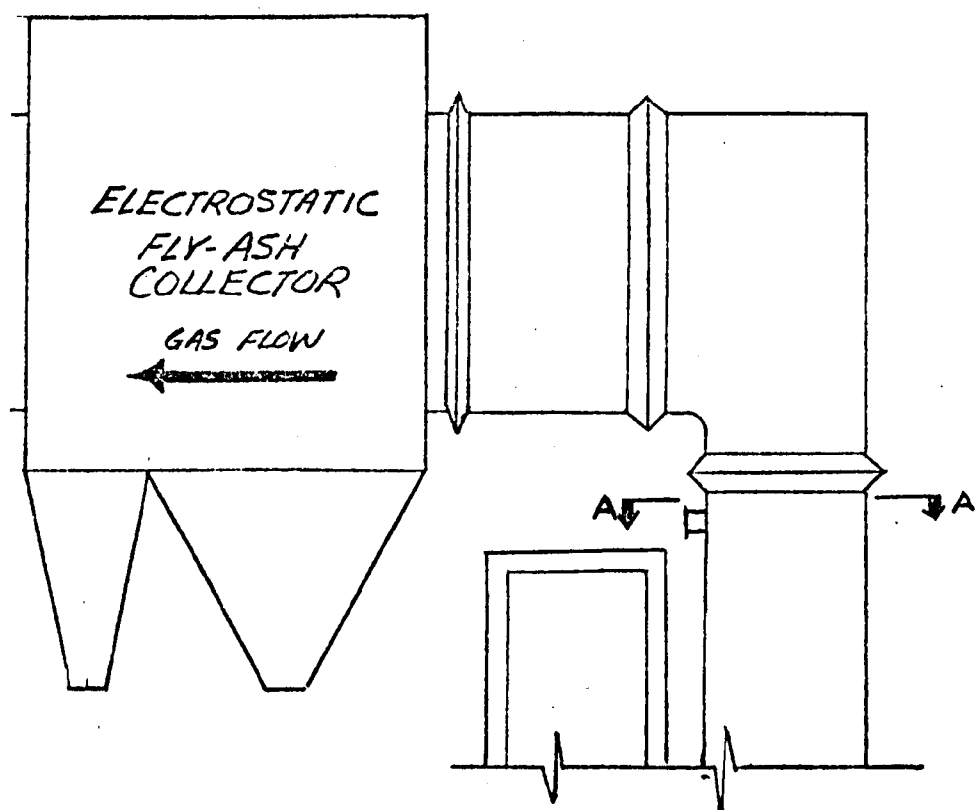
Sample plane located at A-A.
Short side of duct in plane of paper.

Figure 6.   Location of sampling plane for Exxon data -
            TVA Widows Creek Unit 7

8 PORTS THIS SIDE

8.27m

3.18m
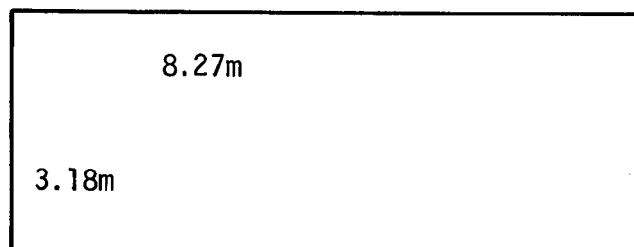
A. Duct for Exxon Tests

6 PORTS THIS SIDE

14.02m

7.32m
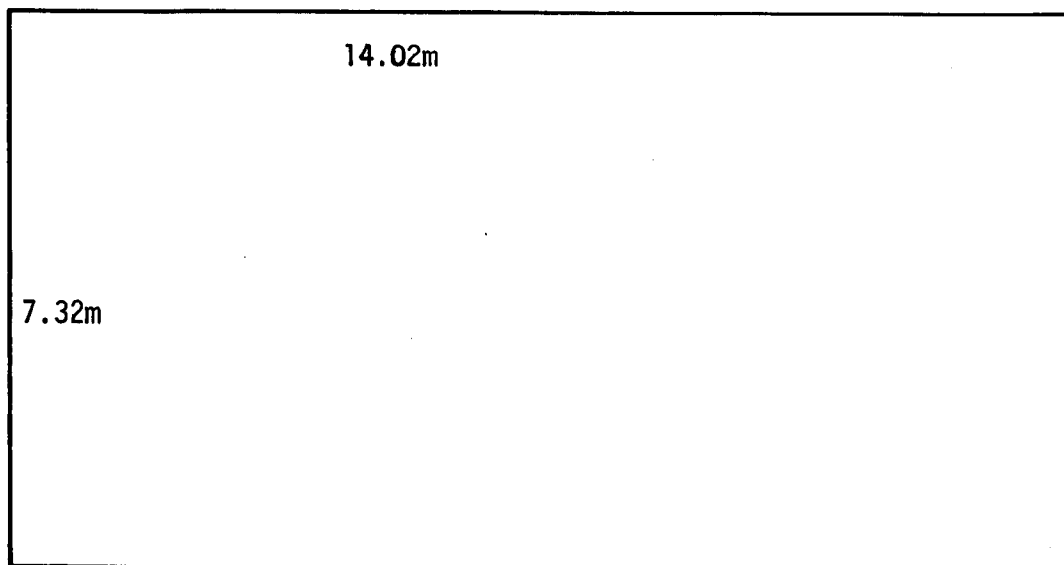
B. Duct for TVA Tests

Figure 7. Duct shapes for Exxon and TVA tests
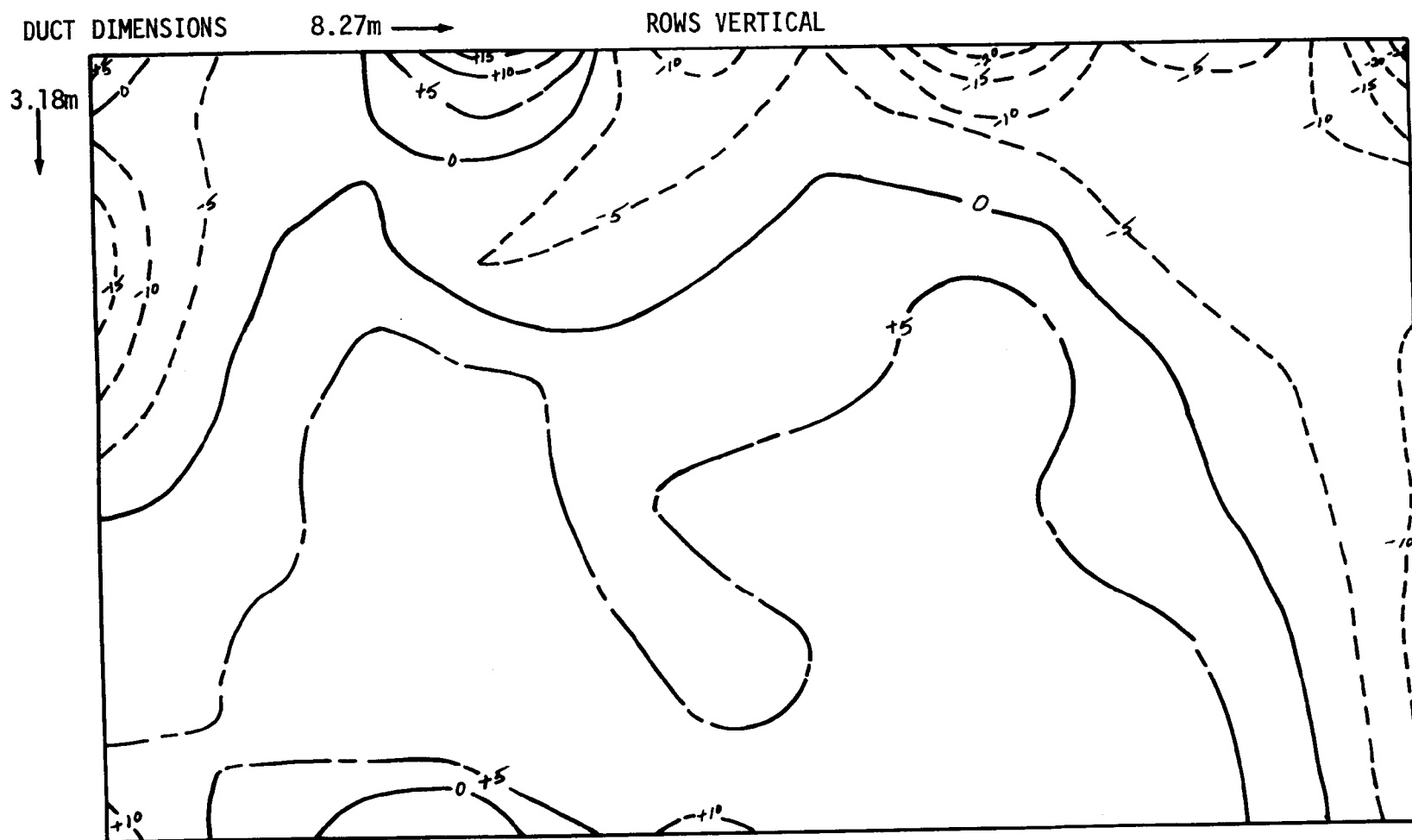
29

DUCT DIMENSIONS   8.27m ⟶   ROWS VERTICAL

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 13.69% (DRY GAS)

Figure 8. Normalized CO_2 concentration distribution--Exxon run 1

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 12.77% (DRY GAS)
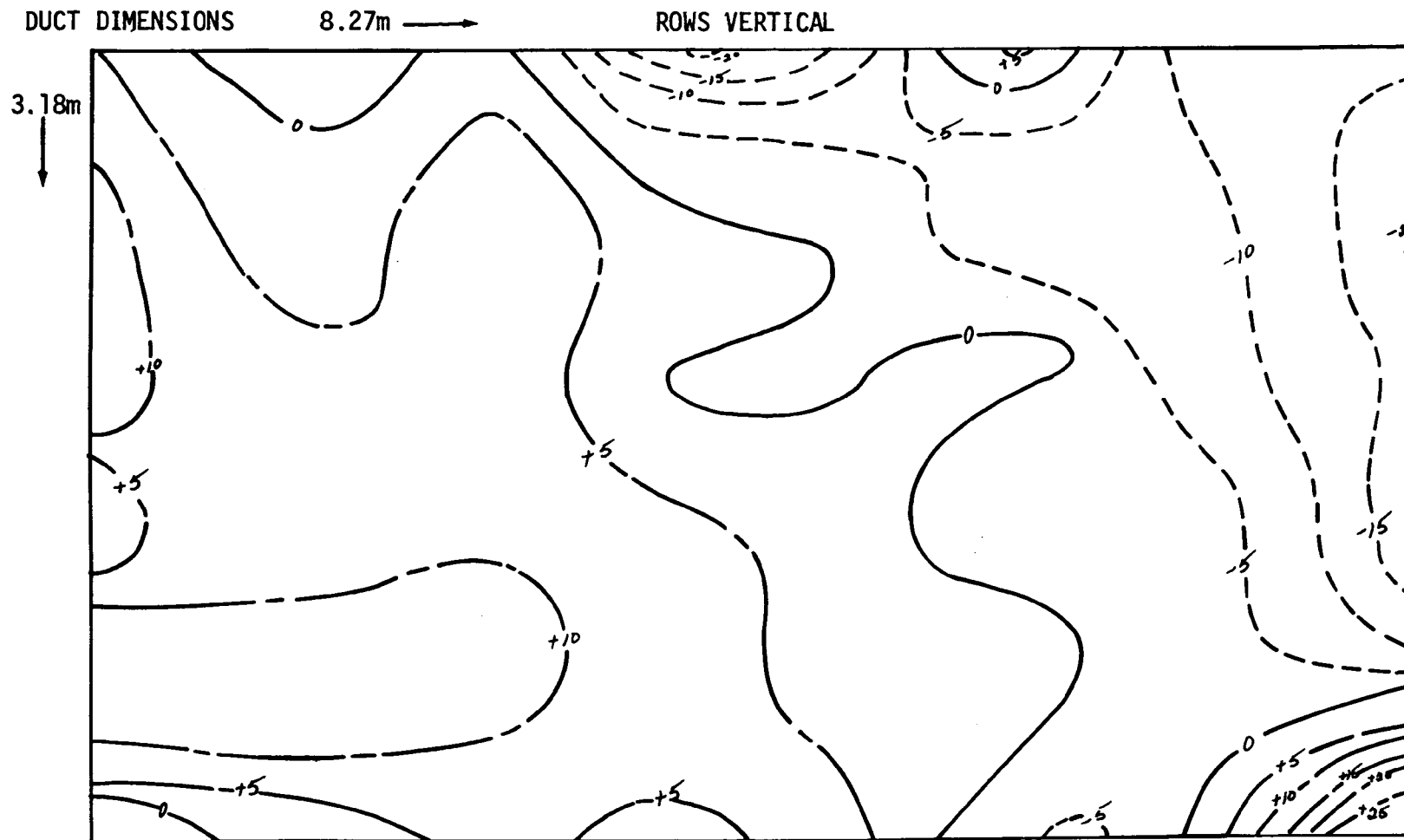
Figure 9. Normalized CO_2 concentration distribution--Exxon run 2
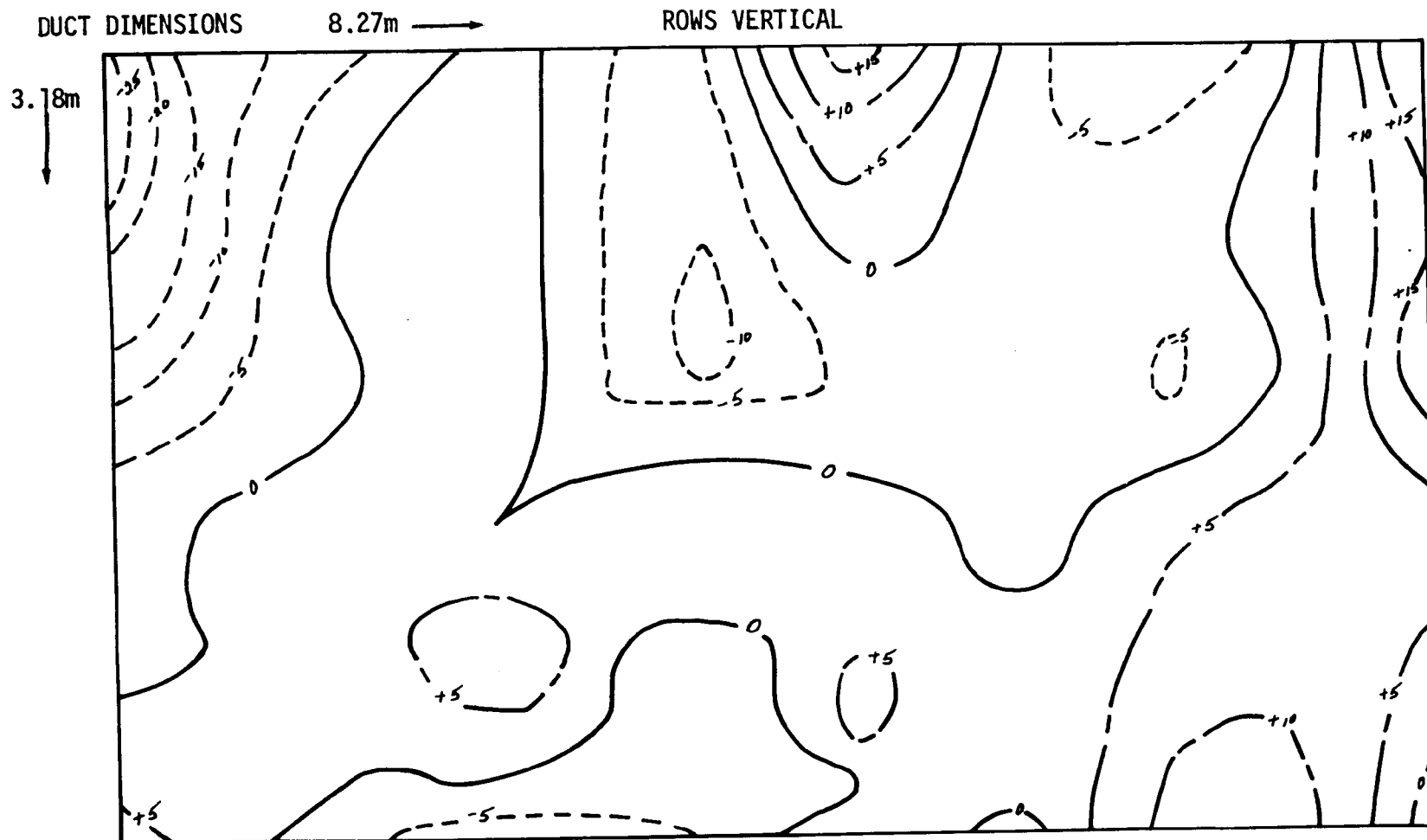
DUCT DIMENSIONS   8.27m ———▶   ROWS VERTICAL

3.18m

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 2706 PPM

Figure 10. Normalized SO_2 concentration distribution--Exxon run 1
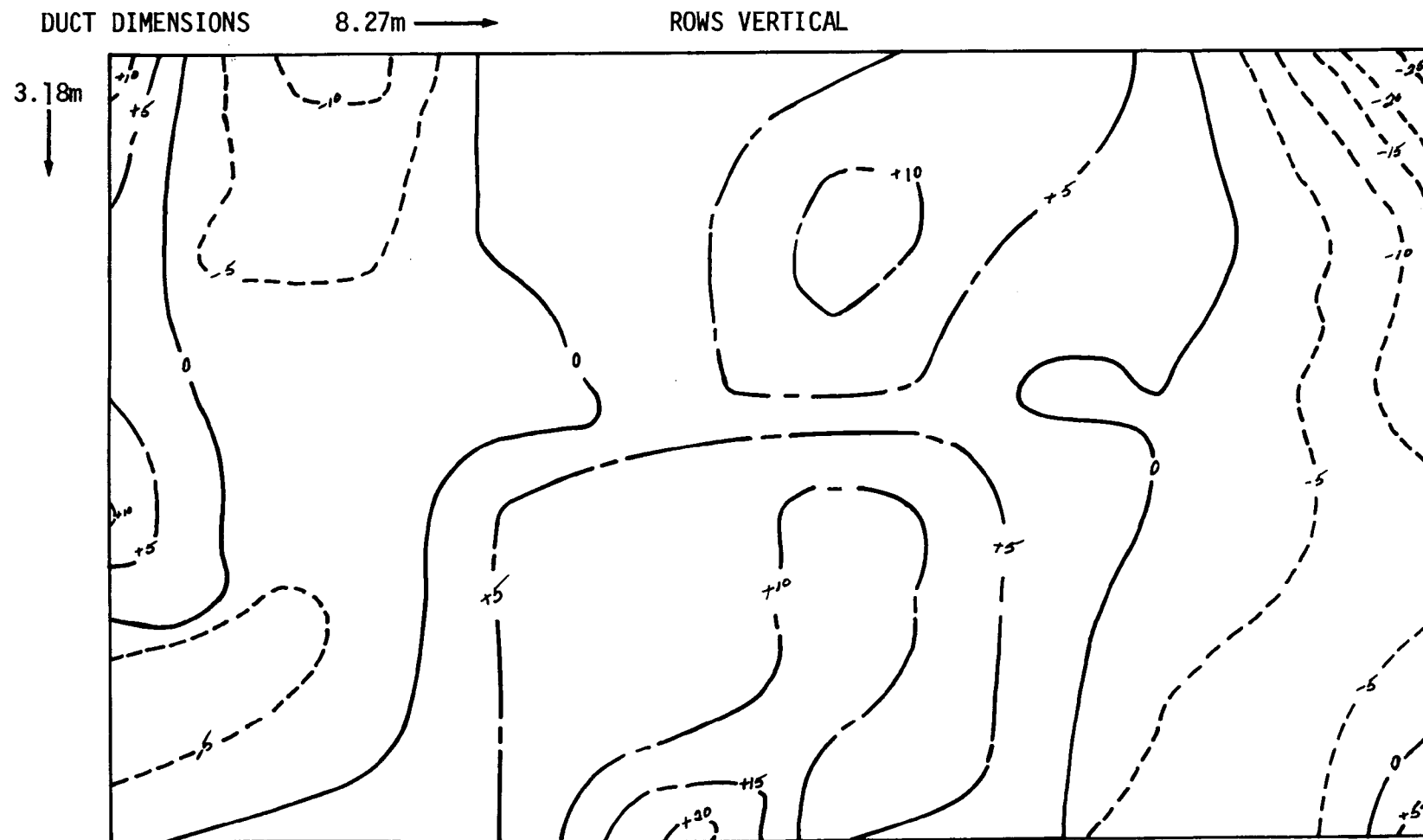
DUCT DIMENSIONS 8.27m ⟶ ROWS VERTICAL

3.18m

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 2042 PPM

Figure 11. Normalized SO_2 concentration distribution--Exxon run 2
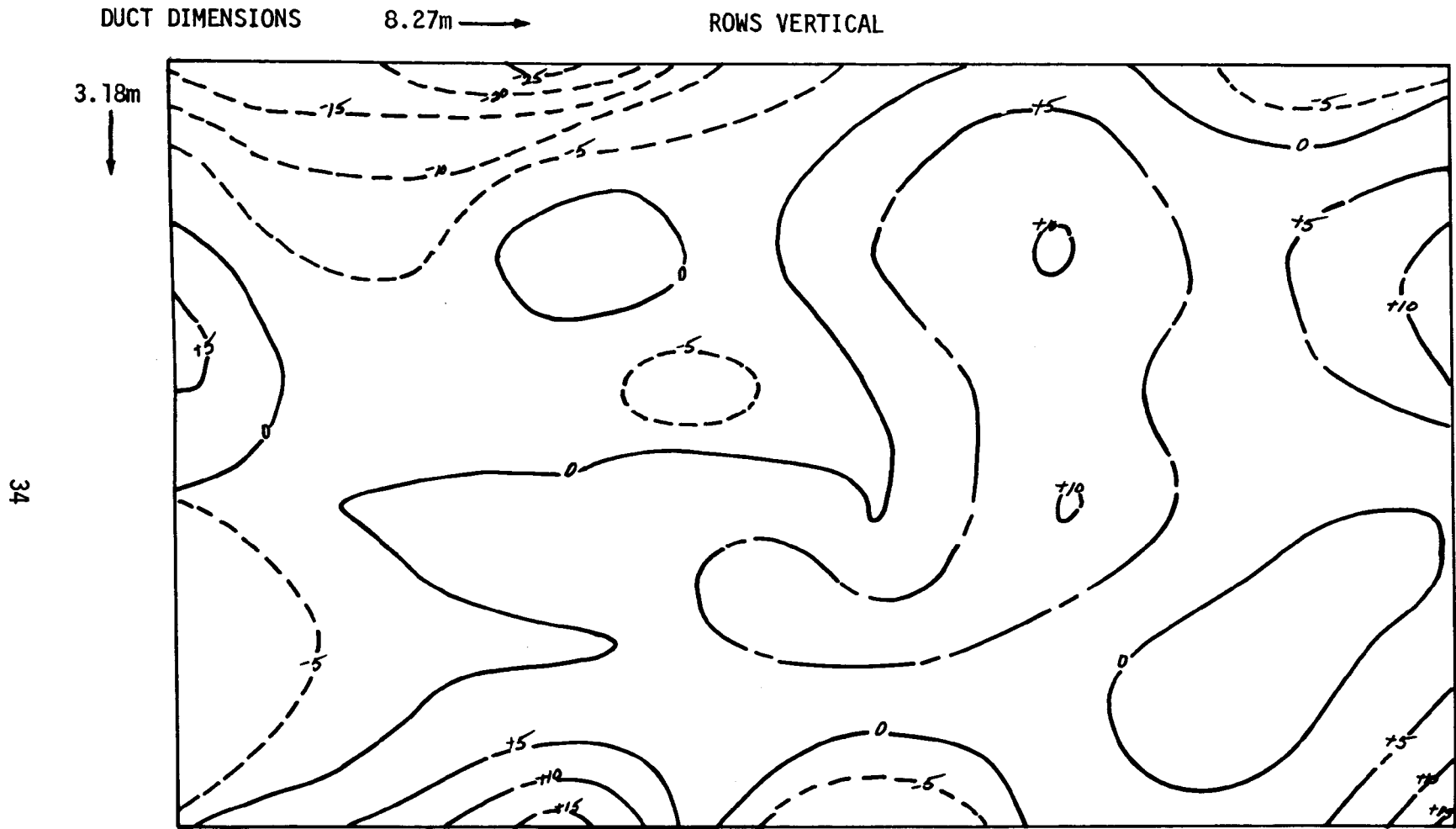
PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 305.3 PPM

Figure 12.   Normalized NO concentration distribution--Exxon run 1
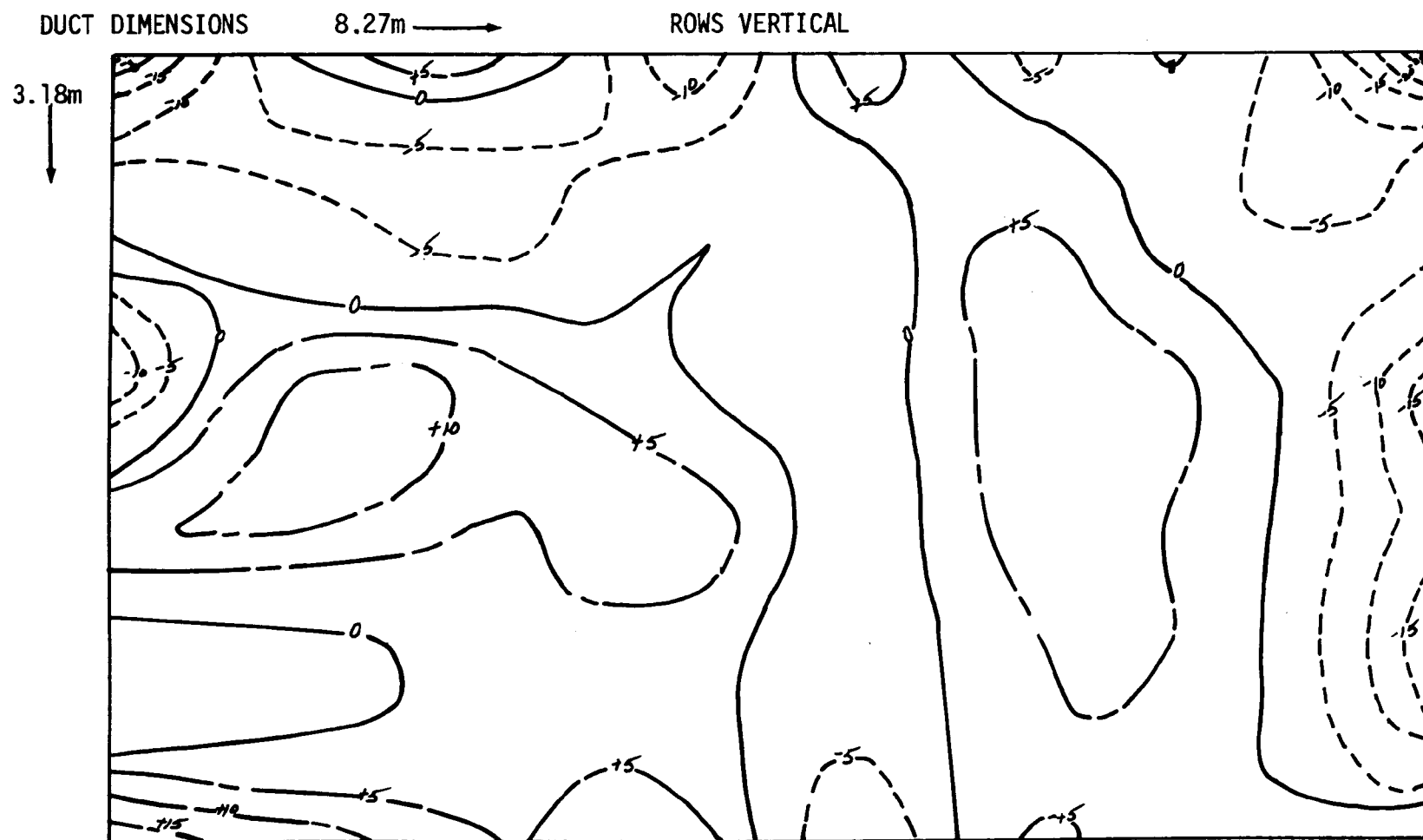
3.18m

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 322.5 ppm

Figure 13. Normalized NO concentration distribution--Exxon run 2

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 4.36% (DRY GAS)
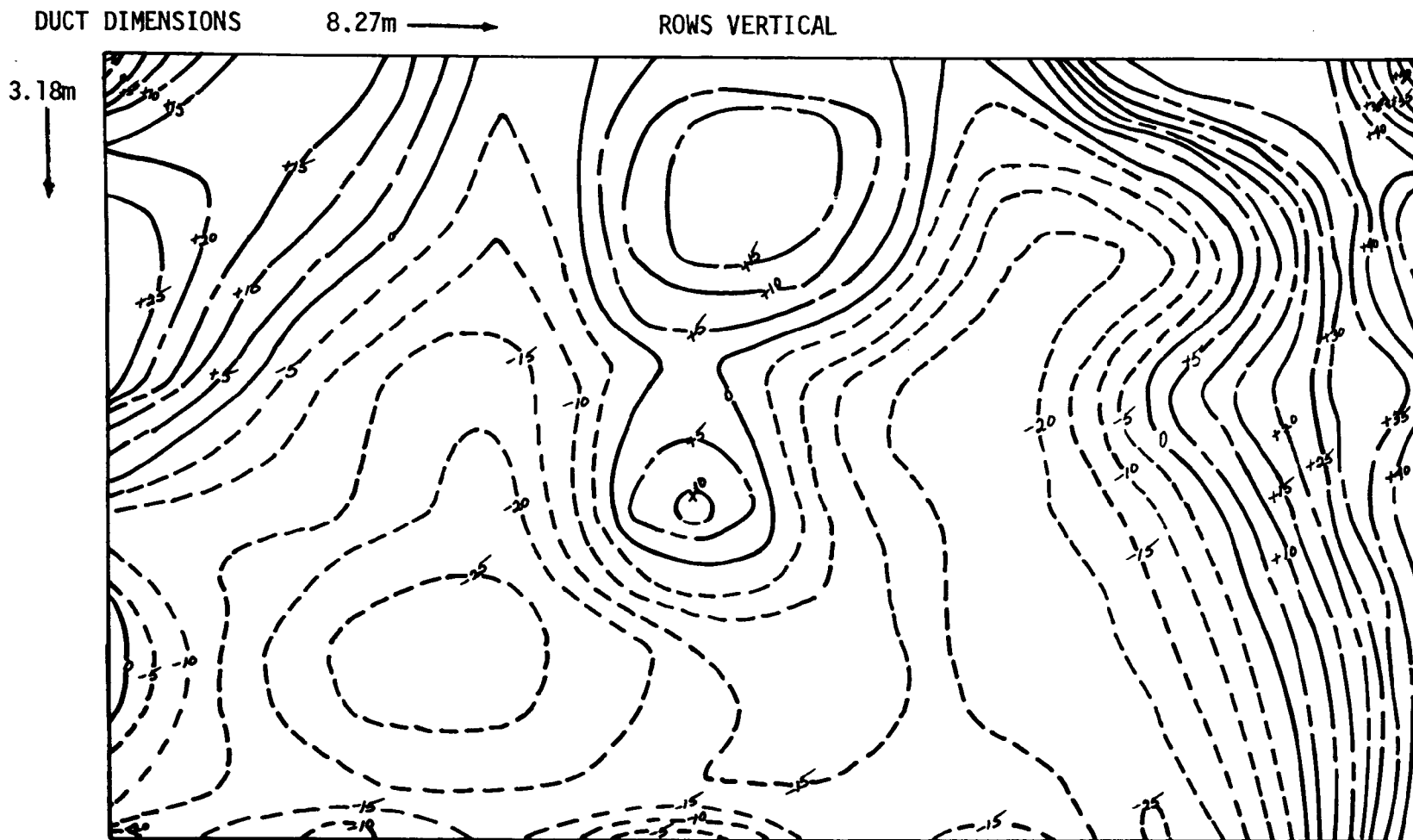
Figure 14. Normalized O_2 concentration distribution--Exxon run 1
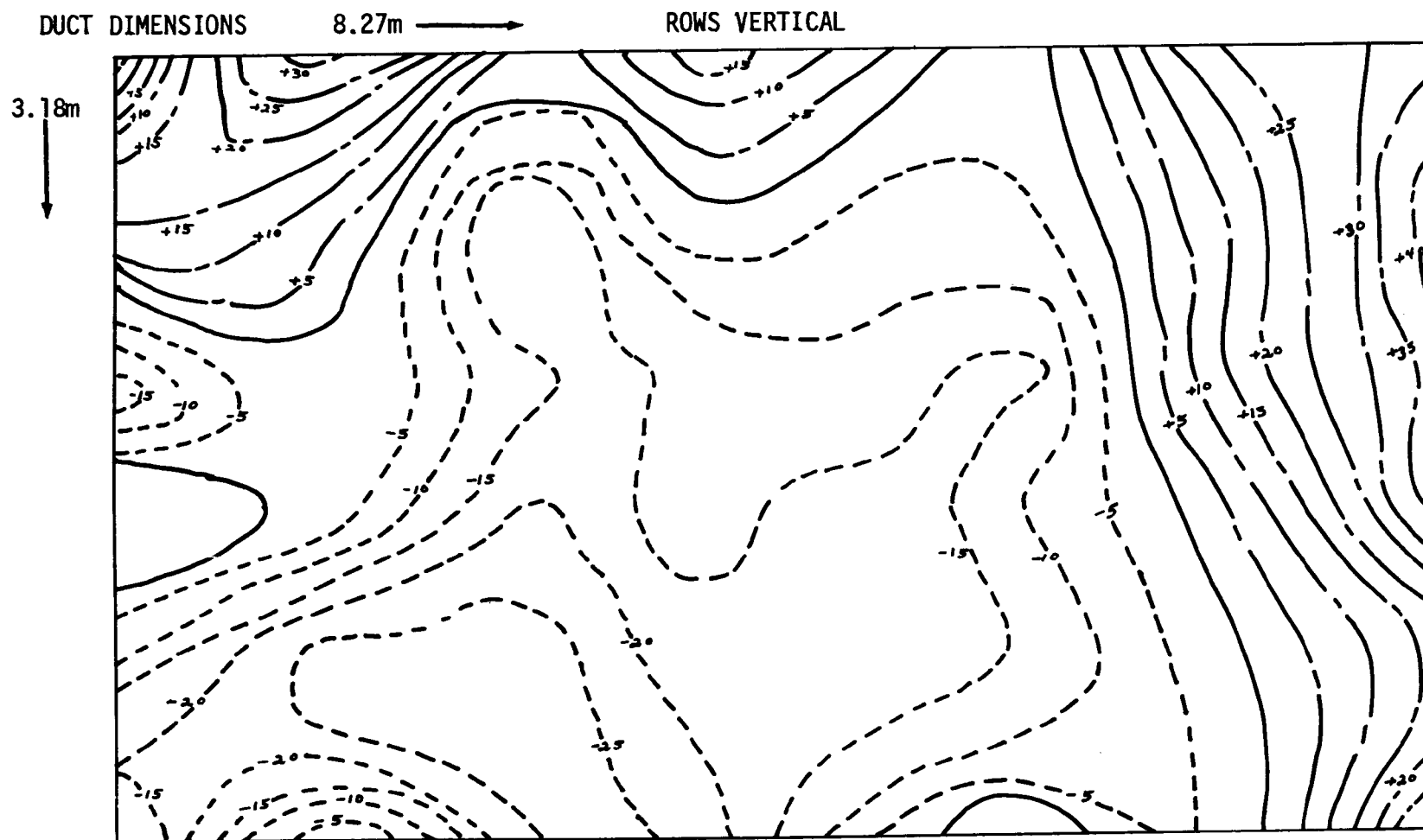
DUCT DIMENSIONS   8.27m ──────▶   ROWS VERTICAL

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 4.56% (DRY GAS)

Figure 15. Normalized O_2 concentration distribution--Exxon run 2

showed up as high O_2 values and low CO_2 values. Plant geometry would appear to suggest air leakage ahead of the sample plane as the cause for this stratification. There is no obvious explanation for the high SO_2 and NO levels toward the right side for the first run. The high O_2 levels would seem to suggest that the SO_2 and NO levels should be low, as they were for the second run.

The maps clearly show that O_2 was the most stratified of the gases. Since O_2 and CO_2 together make up about 20% of the dry gas composition, and since the mean CO_2 concentration is made higher than the O_2 concentration, it would be expected that the oxygen stratification would be greater than that for CO_2. The maps suggest similar stratification levels for CO_2, NO, and SO_2.

6.1.2 Mean Values and Stratification Levels

Mean values of gas concentration and stratification levels are shown in Table 3. Calculations from actual data points agreed with computer calculations within 1% for all cases. Of particular note is the fact that the spatial and flow proportional averages were in very close agreement -- the only variations larger than 1.1% were for oxygen, where the variation was less than 4%. This shows almost negligible coupling between velocity and concentration and leads to the preliminary conclusion that proportional sampling is not required for accurate measurements.

Stratification levels, as defined in Section IV, were on the order of $\pm 10\%$ of the mean value for CO_2, SO_2, and NO and were about $\pm 34\%$ for O_2. The higher O_2 stratification level was expected, as discussed above. Velocity stratification was notably higher than gas stratification: the level was above $\pm 65\%$ of the mean velocity. For all gases, the stratification level was sufficiently high to discourage suggesting that simple point monitoring would be adequate, especially since the concentration maps did not show good repeatability.

6.1.3 Evaluation of CO_2 Tracer Method

For each of the two runs, the ratios of SO_2 and NO concentrations to CO_2 concentration were calculated at each of the 48 traverse points. The mean ratio and standard deviation were then calculated. The deviations

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Table 3. MEAN VALUES AND STRATIFICATION LEVELS FOR EXXON DATA

MEAN VALUES	Velocity, m/sec		CO_2, %		SO_2, ppm		NO, ppm		O_2, %	
	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
FROM DATA POINTS Spatial	4.957	4.400	13.83	12.91	2712	2063	307.1	324.4	4.217	4.379
Flow Proportional	-	-	13.71	12.79	2705	2039	305.2	323.3	4.355	4.548
FROM COMPUTER Spatial	4.912	4.364	13.82	12.91	2711	2063	307.0	324.2	4.235	4.390
Flow Proportional	-	-	13.69	12.77	2706	2042	305.3	322.5	4.364	4.560
STRATIFICATION LEVEL, 2σ, % of mean value	±65.7	±70.2	±11.0	±14.6	±11.8	±12.4	±10.6	±10.8	±36.4	±32.2

Maximum variation between spatial and flow proportional average = 3.9%

Average variation between spatial and flow proportional average = 1.4%

in percent of the mean value are shown in Table 4. For each case, the 2σ deviation shown is about 50% higher than the stratification level of the gases, which suggests that uniformity of the ratios is not good.

6.1.4 Row Average Evaluation

For this analysis, rows were selected parallel to the short sides of the duct. This was done for several reasons. The first is that this is the same direction in which velocity row averages would be taken (see Reference 1). Other reasons are strictly practical: a row average could be acquired through use of a single continuous sampling probe, as described in Section VII. Existing ports in the duct are in the long side, which suggests that one of these ports could be used to install the probe, or at the least that there would be access if a new port were needed. Also, it would be much easier to handle a three meterprobe than an eight meter probe.

Row average data are shown in Figure 16. Results are not quite as good as had been hoped. As discussed in Reference 1, the Row Average technique works well for velocity measurement when the flow is conditioned to give fairly constant row averages across the duct. For velocity, this occurs immediately downstream of an elbow. For gas sampling, there is no common mechanism which conditions the flow in an analogous manner. The CO_2 row averages for run 1 show a desirable pattern: the row average deviates from the overall average by less than 3% over most of the duct. Conclusions to be drawn are that repeatability between runs 1 and 2 was not good, as noted previously, and that more uniform row averages would be obtained if the rows were taken horizontal instead of vertical in Figures 8-15. The latter is clear because there is obviously greater stratification from right to left than from top to bottom in those figures. The first rule established for selection of row directions for velocity measurement was that the rows should be parallel to the direction of greatest stratification. It is unfortunately true for these runs that the direction of highest gas stratification is perpendicular to the direction of highest velocity stratification.

The problem of poor temporal repeatability could not be reasonably assessed through analysis of only two runs, so the following TVA data were examined primarily for that purpose.

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Table 4. CO_2 TRACER METHOD ANALYSIS OF EXXON DATA

	2σ, % of mean value
RUN 1	
SO_2/CO_2	±15.2
NO/CO_2	±16.0
RUN 2	
SO_2/CO_2	±16.6
NO/CO_2	±15.2

Explanation of tabular values:

$2\sigma = \pm15.2\%$ of mean value for SO_2/CO_2 ratio means that there is a 95.4% probability that the ratio of the SO_2 reading to the CO_2 reading at any point in the duct will agree with the average SO_2/CO_2 ratio within $\pm15.2\%$

RATIO OF ROW AVERAGE CONCENTRATION
TO PROPORTIONAL AVERAGE CONCENTRATION
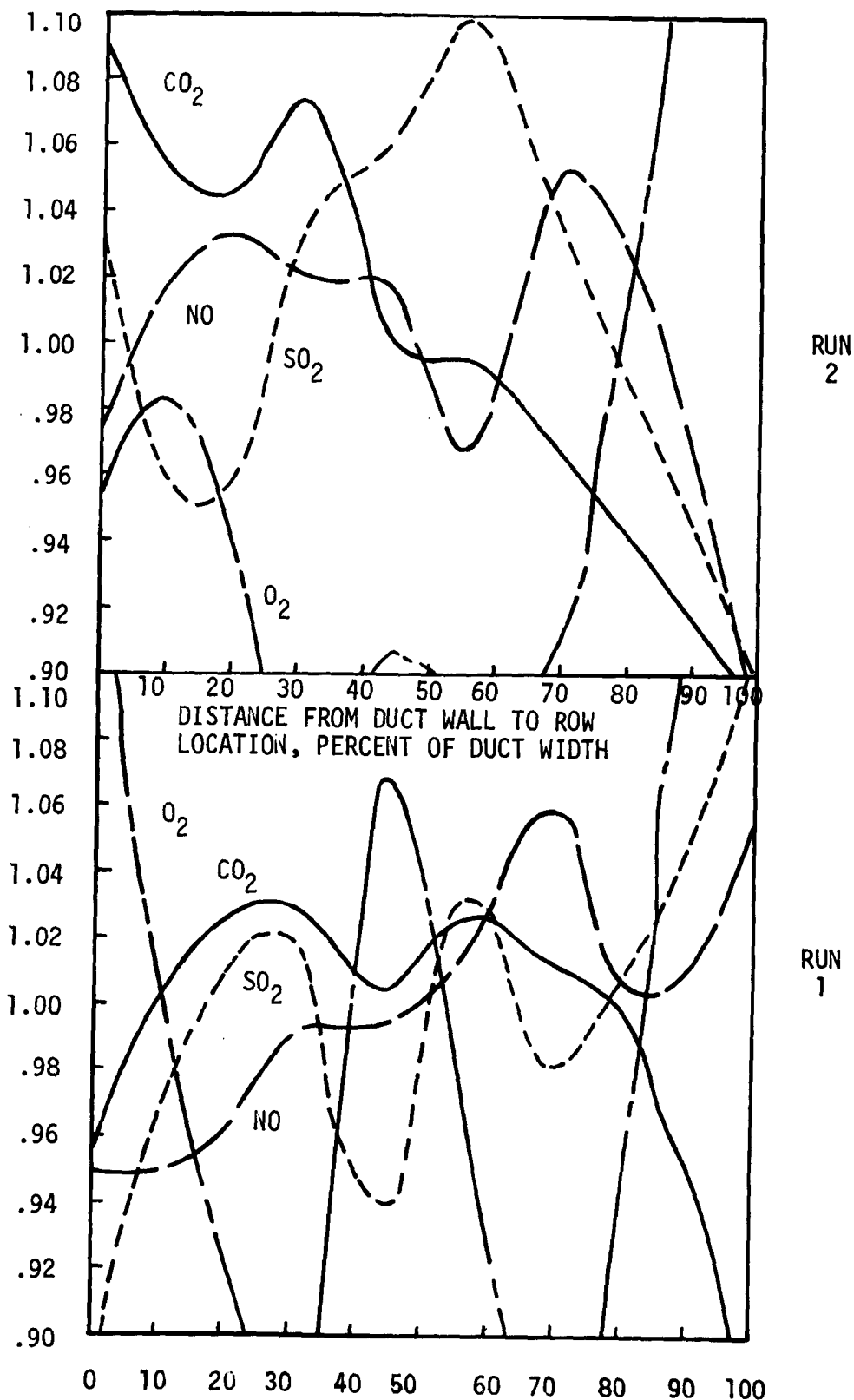
Figure 16. Row average analysis for gas
concentration maps--Exxon runs 1 and 2

6.2 TVA DATA

No drawings were available showing location of the sample plane. The duct cross-sectional shape is shown in Figure 7. A total of four pairs of SO_2 and velocity maps was examined. The velocity data were not obtained simultaneously with the SO_2 data, but it is felt that this does not compromise the results to be discussed.

6.2.1 Concentration Maps

Concentration data are presented in Figures 17-20, using the same format as for the Exxon data. There are again no immediately recognizable stratification patterns among the runs. Stratification does appear to be greater in the vertical than in the horizontal direction.

6.2.2 Mean Values and Stratification Levels

These values are shown in Table 5. Agreement between actual data point calculations and computer calculations was not quite so good as for the Exxon data. This is presumably due to the fact that the TVA traverses used only 24 points (4 x 6), whereas the Exxon traverses involved 48 points (6 x 8). The 1.75% average variation between spatial and flow proportional mean concentrations is compatible with the Exxon results, and continues to demonstrate the adequacy of spatial sampling. It would appear that the variation is proportional to the stratification level in the gas -- both the variation and the stratification level for the TVA data are higher than for the Exxon CO_2, NO, and SO_2 data, but lower than for the Exxon O_2 data.

6.2.3 Row Average Evaluation

Row Average data are presented in Figure 21.

The first three runs do not exhibit as great a uniformity as would be desired, but do show fairly good repeatability. The change in shape on the left side of the duct in Run 4 is clearly undesirable. A row average taken at the center of the duct would show good correlation for all four runs -- much better than would be attained for the Exxon data.
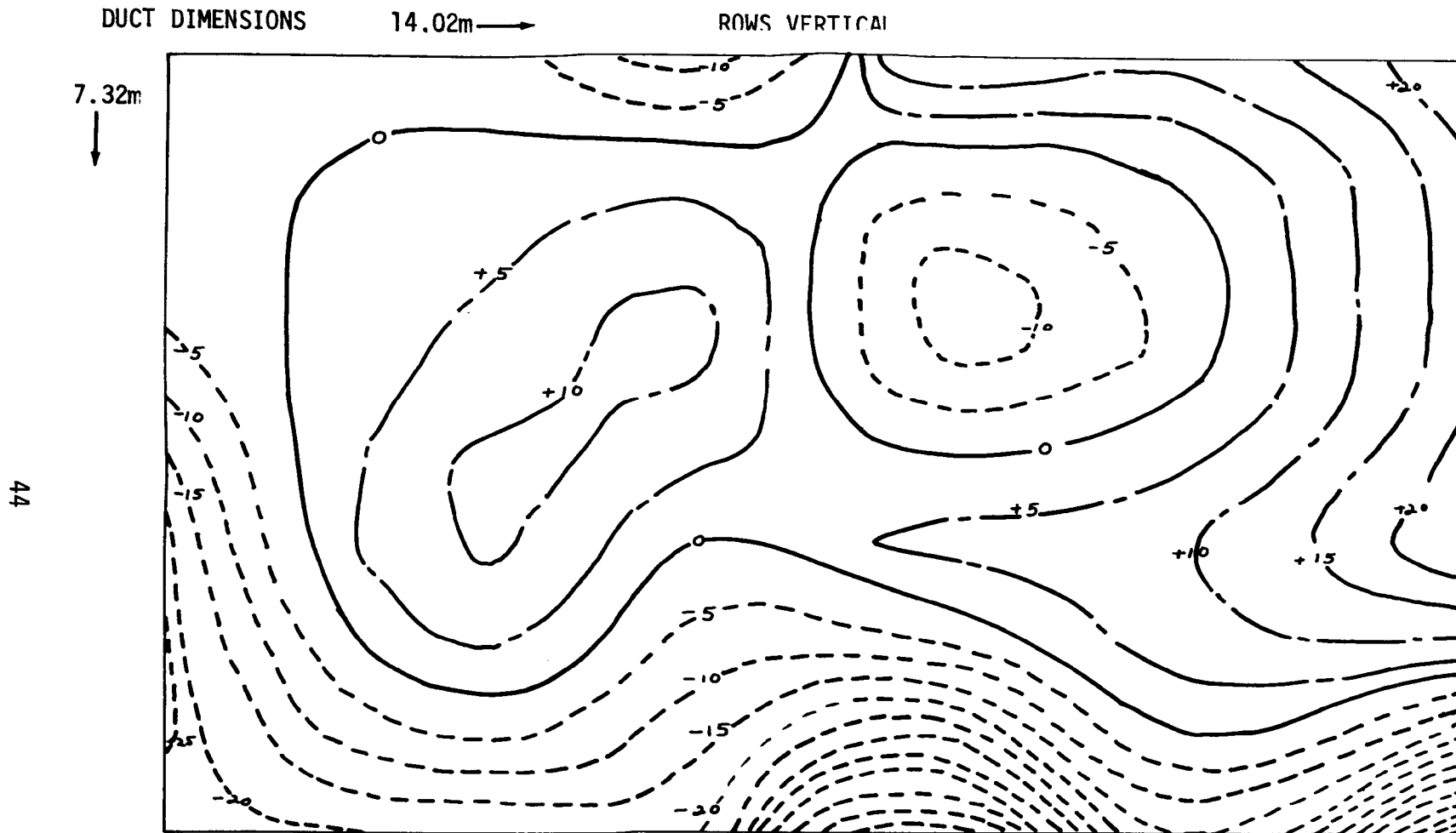
43

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 2011 PPM

Figure 17.   Normalized SO_2 concentration distribution--TVA run 1
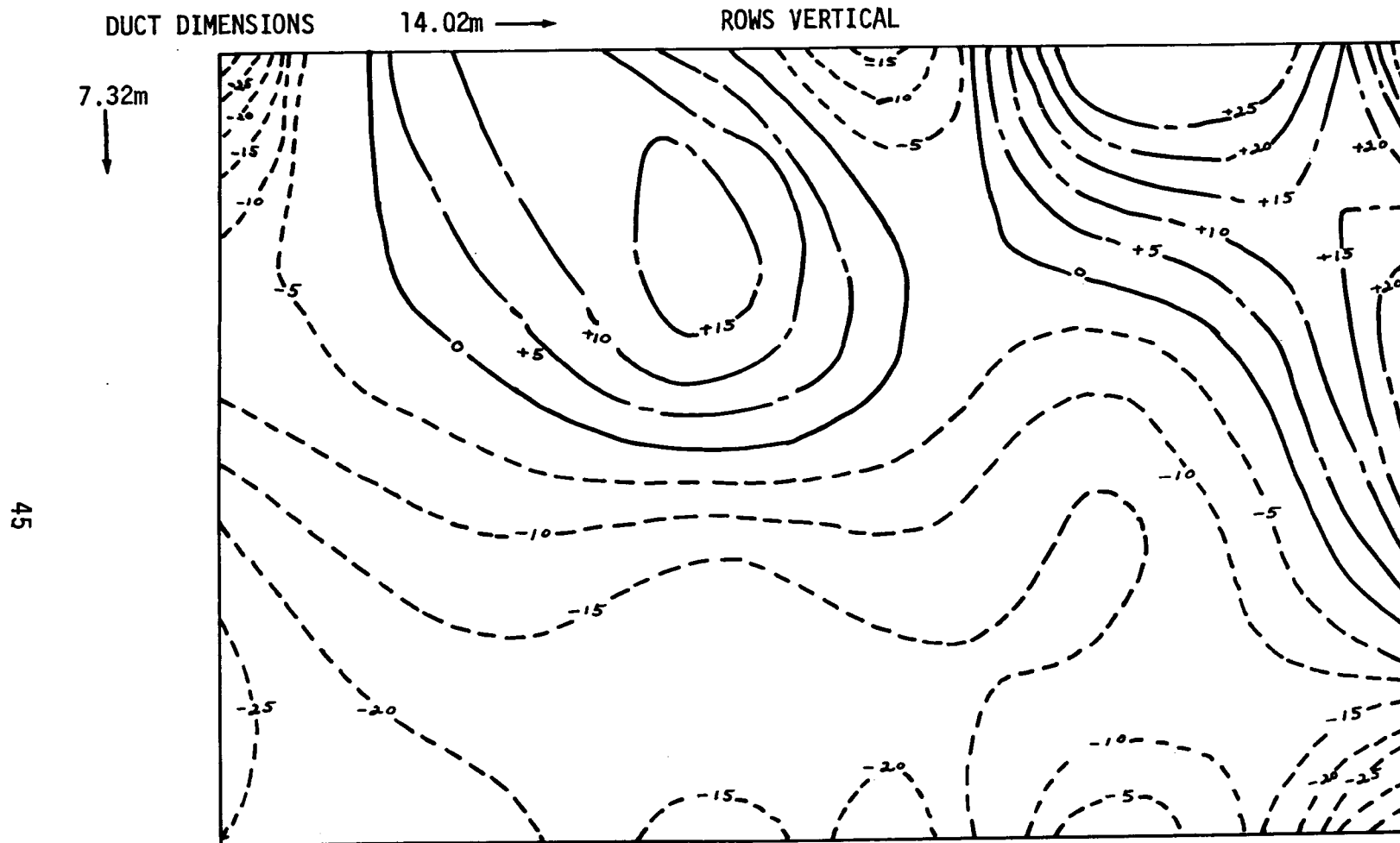
DUCT DIMENSIONS   14.02m ⟶   ROWS VERTICAL

7.32m

45

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION
MEASURED MEAN CONCENTRATION = 2149 PPM

Figure 18. Normalized SO_2 concentration distribution--TVA run 2
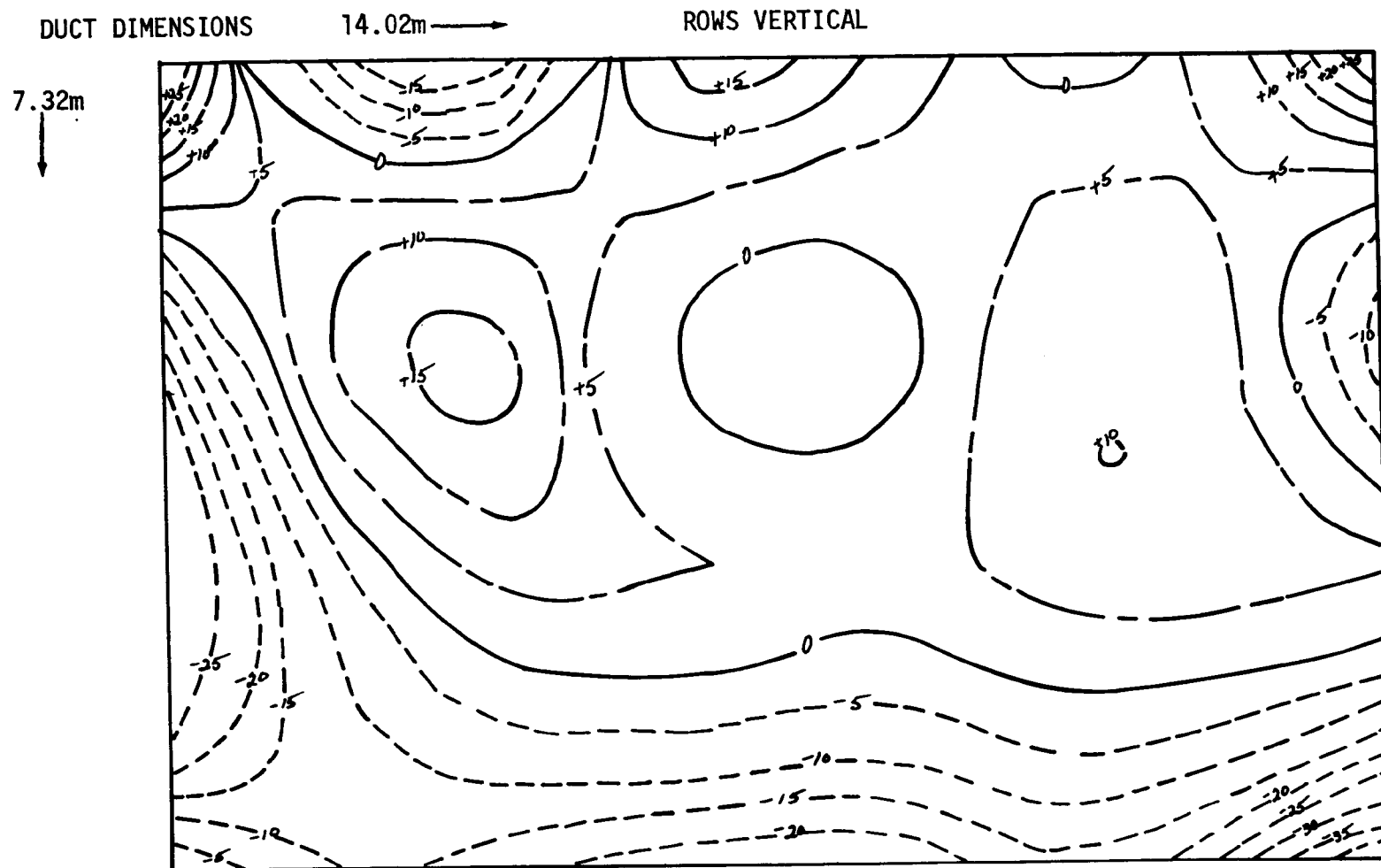
PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 2100 PPM

Figure 19. Normalized SO$_2$ concentration distribution--TVA run 3
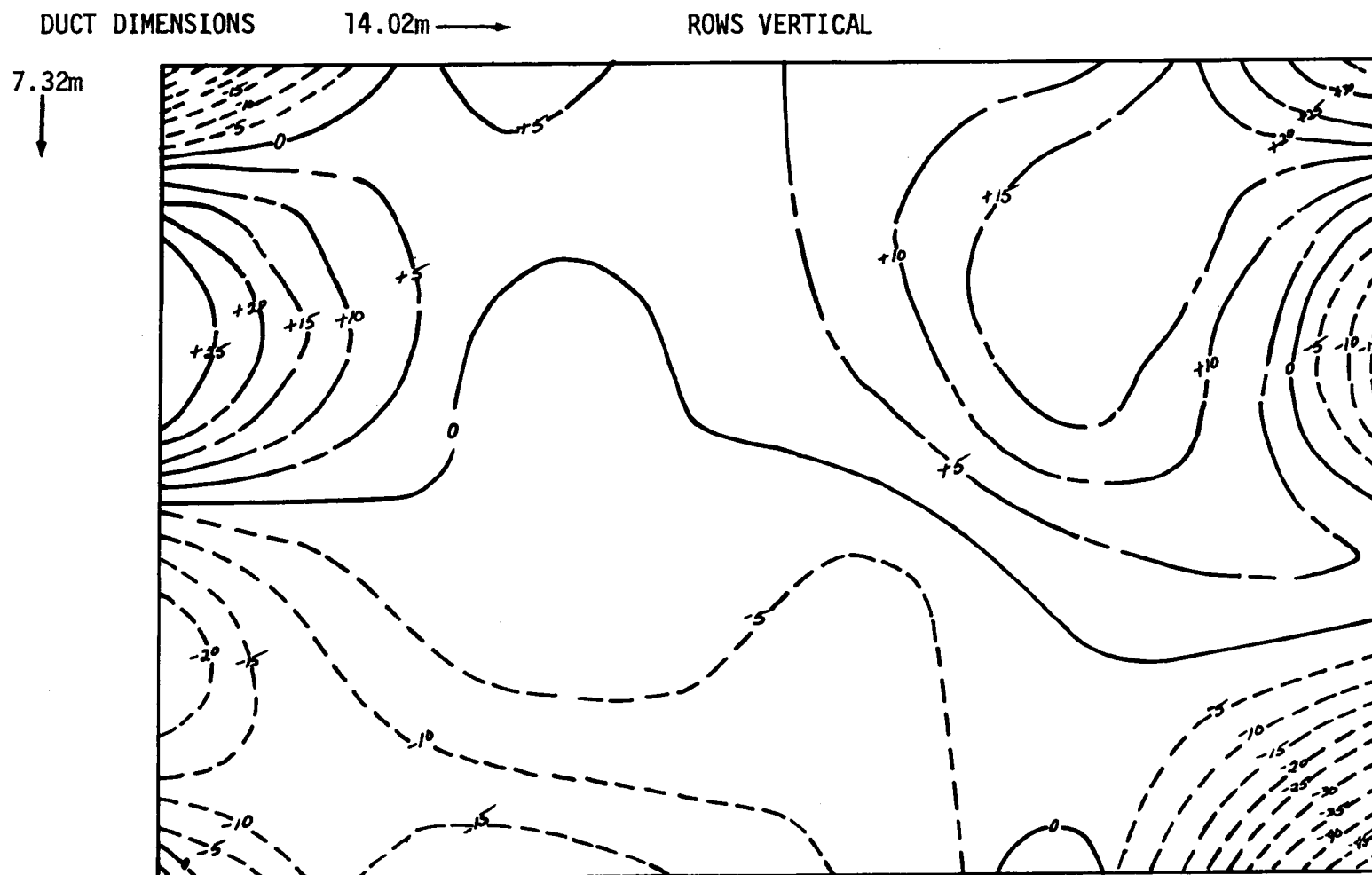
DUCT DIMENSIONS   14.02m ——————→   ROWS VERTICAL

7.32m ↓

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 2054 PPM

Figure 20. Normalized SO_2 concentration distribution--TVA run 4

Table 5. MEAN VALUES AND STRATIFICATION
LEVELS FOR TVA SO_2 CONCENTRATION DATA

MEAN VALUES, PPM OF SO_2	RUN			
	1	2	3	4
FROM DATA POINTS				
Spatial	2059.5	2204.4	2099.7	2036.5
Flow Proportional	2056.9	2207.2	2109.2	2047.5
FROM COMPUTER				
Spatial	1982.5	2085.0	2071.9	2029.5
Flow Proportional	2011.2	2148.7	2100.3	2054.5
STRATIFICATION LEVEL, 2σ, % of mean value	±20.4	±26.5	±17.1	±19.7

Average variation between spatial and flow proportional
average = 1.75%

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RATIO OF ROW AVERAGE CONCENTRATION
TO PROPORTIONAL AVERAGE CONCENTRATION
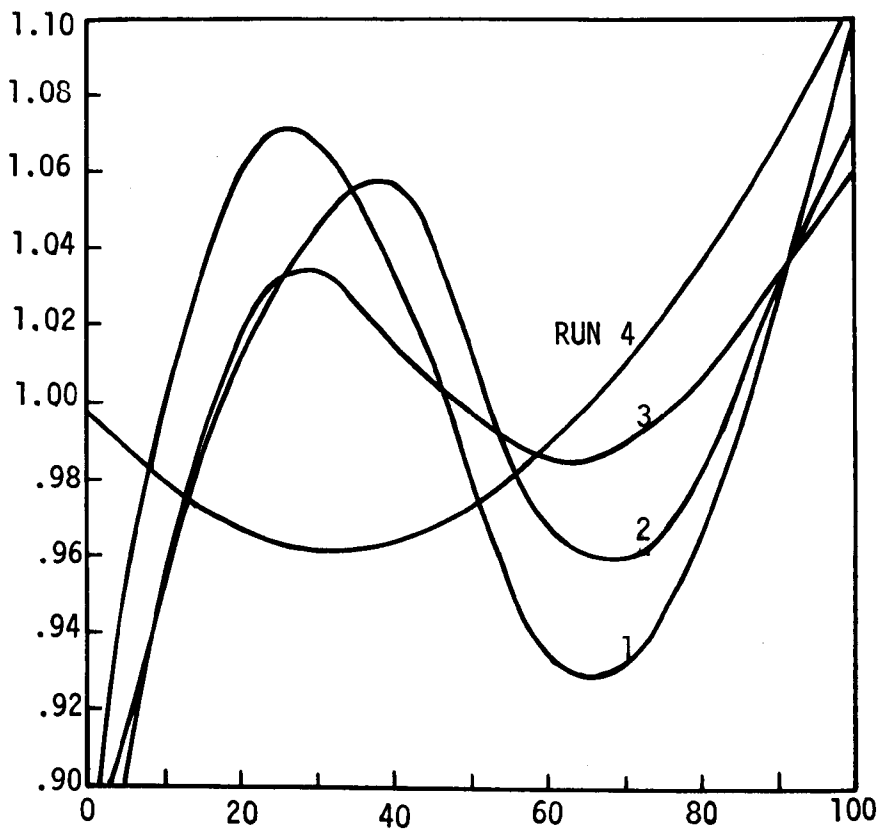
DISTANCE FROM DUCT WALL TO ROW
LOCATION, PERCENT OF DUCT WIDTH

Figure 21. Row average analysis for SO_2
concentration maps--TVA runs 1-4

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6.3 PRELIMINARY SAMPLING TECHNIQUE CONCLUSIONS

For any given gas concentration distribution, it is a trivial matter to select a sampling array which would obtain a representative sample. Problems arise when more than one gas species must be sampled, and when the gas distributions change as a function of time. The greatest difficulty with regard to continuous gas sampling is to effectively handle the temporal changes, since they cannot be predicted easily if at all. Temporal changes in velocity distributions are not such a problem. Velocity distribution is primarily a function of local duct geometry, which is normally fixed. Changes in gas distribution are much more a function of combustion characteristics and air leakage.

Two major conclusions are apparent from the data examined. The first is that stratification levels were too high to justify single point sampling for a continuous monitoring system. The stratification level itself is a measure of how accurate a single point sample is likely to be. For the twelve runs examined, the mean stratification level, 2σ, was $\pm$ 18.6%, which is far from the proposed desired accuracy of $\pm$ 6% for average concentration. Single point sampling is also intuitively more prone to temporal variation errors than any multi point sampling system. As a general rule, single point sampling should only be considered acceptable in situations where the stratification level is not worse than the desired accuracy of the concentration measurement.

The other conclusion is that spatial gas sampling is as accurate in determining effluent rates as flow proportional sampling, within about 2%. This justifies development of continuous monitoring systems which acquire spatial samples, rather than more difficult (therefore expensive) flow proportional samples. The spatial sampling method examined has been the Row Average method, which showed reasonably good results for the TVA data, but poorer results for the Exxon data. One reason for the latter was high stratification levels normal to the adopted row direction. Agreement between concentration levels of SO_2 and NO with respect to CO_2 was rather poor for the Exxon data. It was decided at this point to select the Row Average technique for field evaluation, due to its simplicity and easy adaption to hardware, as well as due to the promising results from the TVA data analysis.

SECTION VII
TASK IV SAMPLE PROBE DEVELOPMENT

The Row Average technique for gas sampling was discussed in the previous section. The next objective was to develop a sampling probe to satisfy the requirements of Row Average sampling. In this section, probe design requirements are formulated mathematically and fabrication of a prototype probe for the field demonstration is discussed. Also included are suggestions for improved probe designs.

7.1 PROTOTYPE PROBE DESIGN

One of the continuous sampling techniques considered in Section VI was the Row Average method. Since this method is probably the easiest one to develop hardware for, it was decided to produce prototype sampling probes for the Phase II field demonstration described in Section VIII. The basic design criteria for such a probe are quite simple:

- The probe should draw samples at a number of evenly spaced points along a line across the duct.

- The same sample rate should be maintained at each sampling point.

- The samples from each point should be mixed and drawn out through a single sampling line.

The probe design is illustrated in Figure 22. A small sampling hole was located at each of eight preselected locations corresponding to an even distribution along the probe. It was decided that control of flow distributuion among the holes would be accomplished by making the holes small enough that the pressure drop across each hole would be large compared to pressure changes along either the inside or outside of the probe. Mixing of the acquired samples from each port would clearly be accomplished within the probe body. The most direct alternative to the technique used would be to have a separate sample line from each point. Each line would then need a control value and flowmeter to insure equal

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DUCT
WALL

MIXING VOLUME

PROBE BODY

FLOW
OUT

SAMPLE PORT
(TYPICAL)
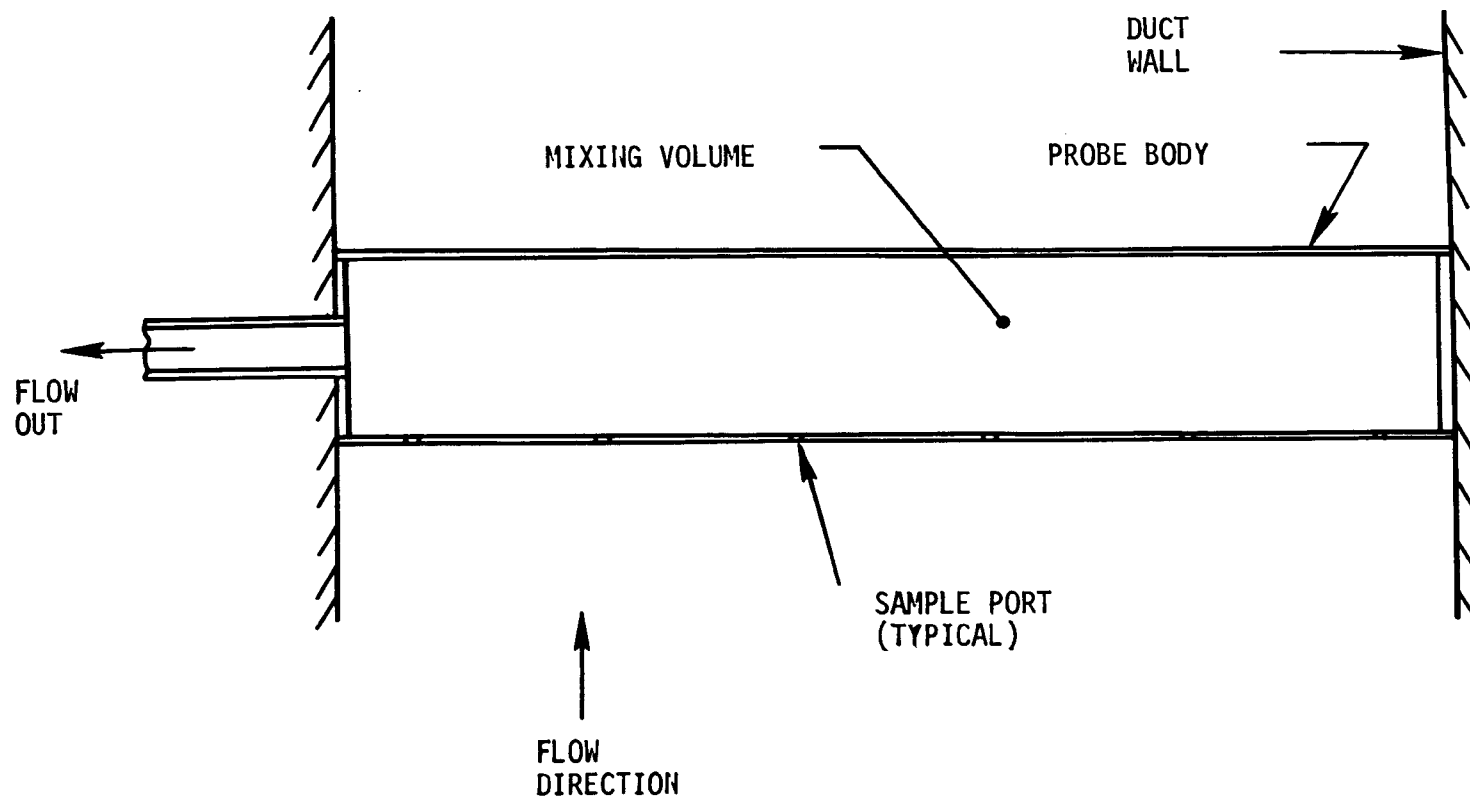
FLOW
DIRECTION

Figure 22. Multi-port sampling probe basic design

flow from each point. The lines would then feed into a suitable plenum chamber and be mixed for delivery to the analyzers.

Once the number and location of sampling holes have been selected, the only major analytical task is to select the hole sizes. This proceeded as follows:

- Determination of worst case pressure variation

  Outside the probe: The Phase II field demonstration was to be conducted at the same power plant as the Phase I field test (see Section VIII). The maximum observed velocity during the Phase I test was about 11 m/sec, which corresponded to a differential pressure of $p_o - p_\infty = \Delta p = .75$ torr. A sample flow rate of .5 1/sec ($\sim$1 CFM) was selected, along with a probe size of 2.54 cm (1 in.). This corresponded to a maximum flow velocity within the probe of about 1.2 m/sec. Since this was considerably below the expected variation in freestream conditions outside the probe, the external conditions determined the maximum expected pressure variation.

- Desired pressure drop across orifices

  It was arbitrarily decided that the duct pressure variation should not be more than 5% of the pressure variation across the sampling ports. This meant that the latter should be at best $20 \times .75$ torr = 15 torr.

- Determination of hole diameter

The sample volumetric flow is given by

$$\dot{V} = n\bar{v} \,(.61A) \tag{23}$$

where $\dot{V}$ = volumetric flow

n = number of sampling ports

$\bar{v}$ = average velocity of gas through sample ports

A = sample port area

.61 = sample port discharge coefficient

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In terms of the pressure drop in the orifices, this becomes

$$\dot{V} = .61 \ (\tfrac{\pi}{4})d^2 n \ \sqrt{2RT \ (\tfrac{p_0}{p_\infty} - 1)} \tag{24}$$

where

d = hole diameter

R = gas constant

T = absolute temperature

p_0 = absolute pressure ahead of orifice

p_∞ = static pressure in orifice

Solving for d, we get

$$d = \left(\frac{\dot{V}}{15.69 n \ \sqrt{T_\infty \ (\tfrac{p_0}{p_\infty} - 1)}} \right)^{1/2} \tag{25}$$

If

$\dot{V}$ = .5 1/sec

n = 8

T_∞ = 450°K

p_0 = 715 torr

p_∞ = 715-15 = 700 torr

then

d = 1.295 mm (.051 inches)

The nearest drill size was a #55 drill, 1.32 mm (.052 inches) diameter, so this size was used. See Section VIII for discussion of actual probe use.

7.2 SUGGESTIONS FOR IMPROVED PROBE DESIGN

The above design showed its capability to avoid clogging of the orifices with particulate, as discussed in Section VIII. The problem which did show up, however, was a buildup of particulate within the probe. In an operational continuous monitoring system, such problems would be unacceptable. It would appear that the only reasonable way to handle the particulate problem would be to filter out the particulate before it can enter the probe. Probe inlets to accomplish this are shown in Figure 23. In each case, the key element is the filter. The operating

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A. At each specified sampling point, a porous filter insert is installed. Uniformity of pressure drop, hence flow rate, is assured through control of insert porosity.

PROBE
BODY

POROUS
INSERT
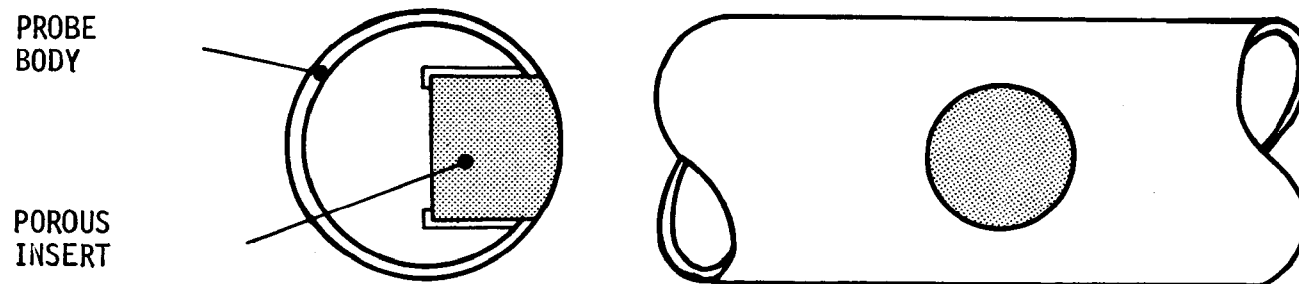
B. A combination filter/liner is used to obtain a sample along the entire probe length. This assumes that a true Row Average sample is acquired. The filter and liner form a one piece bonded unit.

PROBE
BODY

LINER

FILTER
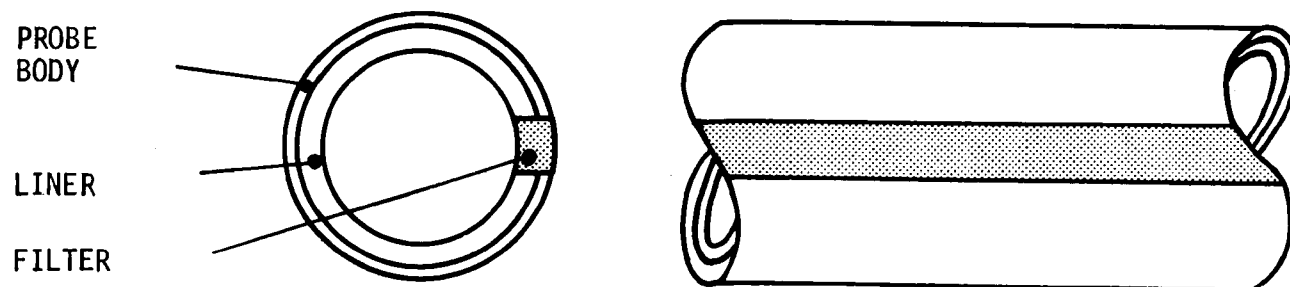
Figure 23. Suggestions for continuous gas sample probe modifications to prevent particulate entry into the probe

principle is exactly the same as for the fabricated probe: the pressure drop must be identical through each section and must be large compared with external pressure variations. This requires uniformity of the filter.

So long as the particulate is reasonably dry, a slow rate of buildup would be expected on the filters since a self-cleaning effect was noted on the prototype unit. To clean the probe, an automatic intermittent purge capability should be provided as part of the instrumentation system. The purge intervals would be determined by the application, and the accumulated dust would be blown back into the main stream. This type of purge system was successfully demonstrated in a different application as part of the Phase II field test (see Reference 1).

Recent TRW experience with Kapton liners for sampling probes and our knowledge of properties of various high temperature polymers suggests that such materials may be quite applicable in the production of filters for the application in Figure 23. The desirable properties of polymers for this application include chemical inertness and physical integrity for temperature as high as 500°C. They are also castable into any desirable shape, and it is believed that very accurate control of pore sizes can be obtained. The latter is the property which controls pressure drop across the filter.

SECTION VIII
TASK V - FIELD DEMONSTRATIONS

The task objective was to demonstrate the applicability of techniques and hardware for continuous gas sampling. Two field demonstrations were performed at the Reid-Gardner Station of the Nevada Power Company, located at Moapa, Nevada. The plant is about 72 km. northeast of Las Vegas. Each test lasted about eighteen days. The first was begun in September, 1974, and the second was begun in February, 1975. The primary purpose of the first test was to demonstrate hardware and techniques for volumetric flow measurement which had been successfully tested in the laboratory. Gas sampling data were taken in support of the volumetric flow measurements and to assess stratification levels. The primary purpose of the second test was to demonstrate techniques and hardware for continuous gas sampling. Volumetric flow measurements have been fully documented in Reference 1. Only flow data pertinent to this report are discussed below.

8.1 FACILITY DESCRIPTION

The plant presently consists of two Foster-Wheeler 120 megawatt boilers, with a third under construction. All work was performed on the #2 unit, shown schematically in Figure 24. Flow from the boiler is separated into two streams which pass through Lunjstrom rotary air pre-heaters. The ducts at the two preheater outlets go through a shape transition and then rejoin upon entering a mechanical dust collector. A row of test ports is located on each duct just ahead of the dust collector. This is shown in Figure 25. All rectangular duct mapping was done at these locations.

When the plant was first constructed, the dust collector exhausted directly into the stack. Subsequently, a venturi scrubber and separator were added by Combustion Equipment Associates. When the scrubber is on, the flue gas is diverted at the dust collector exit and routed to the scrubber, where it is processed and fed into the stacks. If the scrubber is not on, the flue gas goes directly into the stack after leaving the dust collector. The inlet to the stack is about 13 m above ground level.
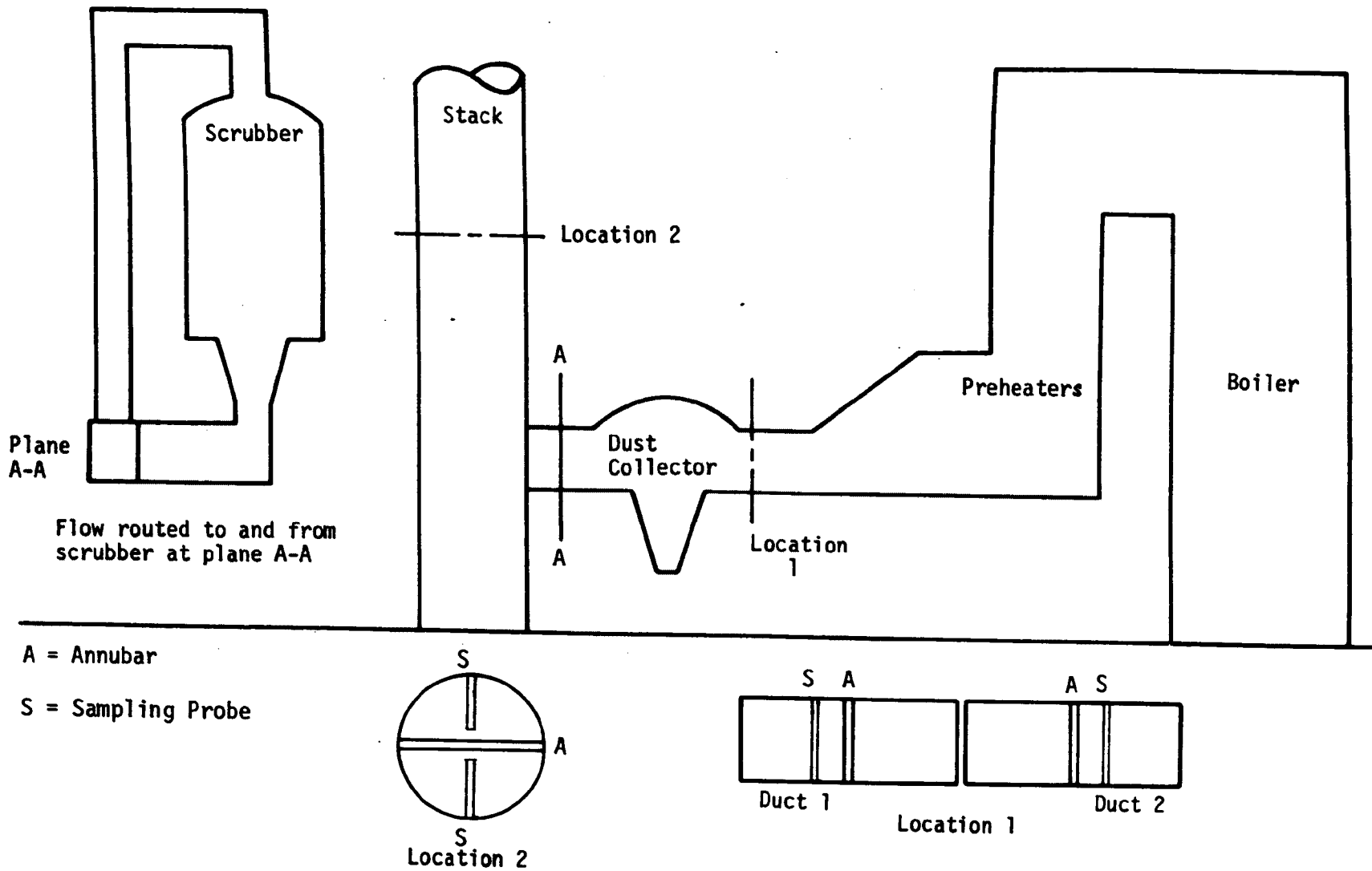
Figure 24. Schematic of Moapa power plant

Scrubber

Stack

Location 2

Plane A-A

Flow routed to and from scrubber at plane A-A

A

A

Dust Collector

Location 1

Preheaters

Boiler

A = Annubar

S = Sampling Probe

S

S

A

Location 2

S   A

A   S

Duct 1

Duct 2

Location 1

Duct 2 is a mirror image of duct 1

SAMPLE PORTS (ROW NUMBER)

7

6

5

4   ANNUBAR LOCATION

3

2

1

FLOW
DIRECTION

FLOW
DIRECTION

SAMPLING
PLANE

SAMPLE POINTS

1

7

TRAVERSE MAP –
49 POINTS
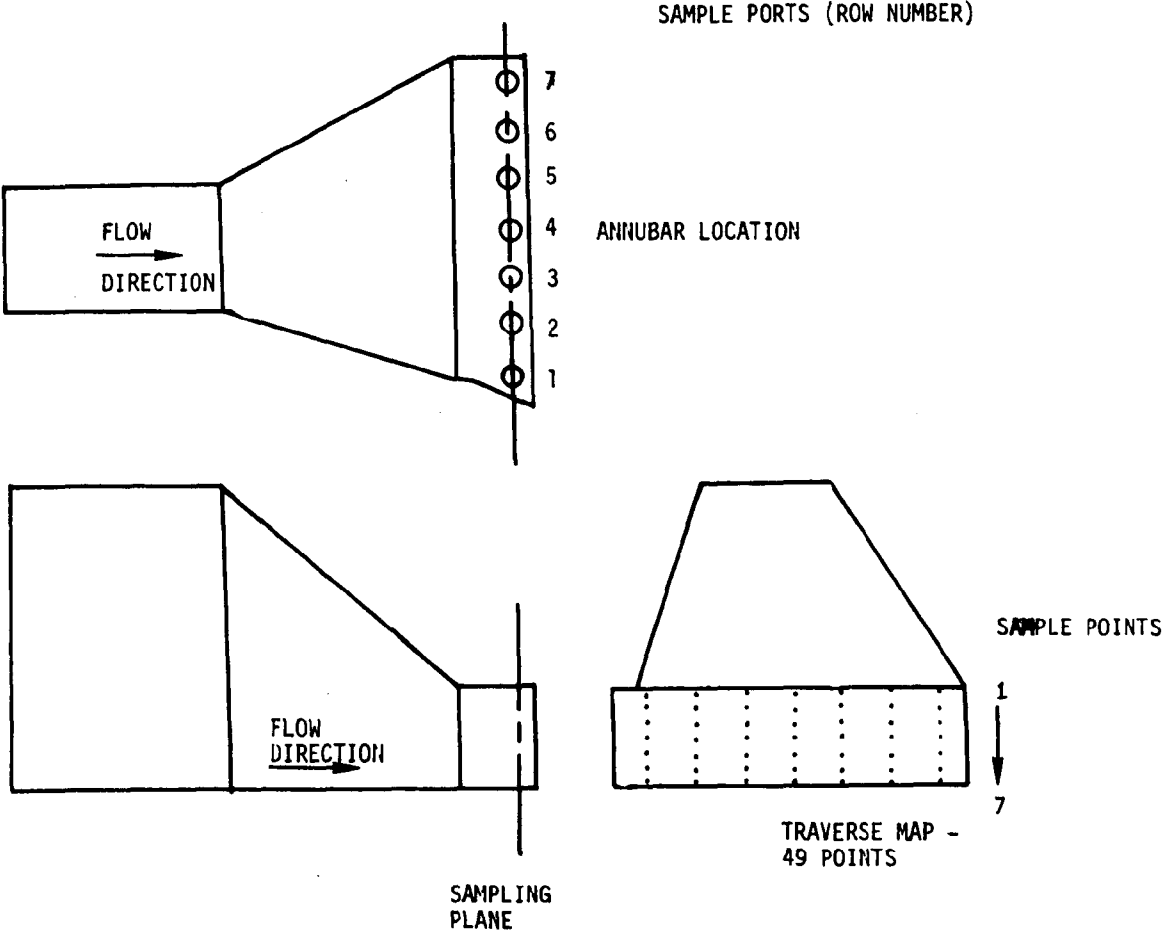
Figure 25.   Duct 1 geometry

Sample ports are located in the stack at the 31.4 m level, or about four stack diameters above the inlet. All circular duct testing was performed at this location in the stack.

8.2 TEST CONDUCT

8.2.1 Gas Sampling Hardware

Velocity instrumentation is described in Reference 1. The continuous flow monitors used were Ellison Annubars. Two were used in the first test -- one in duct 1 and one in the stack, as shown in Figure 24. A third was added for the second test and installed in duct 2. Gas analyzers used during the first test included a Beckman NDIR SO_2 analyzer, a Carle thermal conductivity gas chromatograph to measure CO, CO_2, N_2, and O_2 concentrations, and a Thermo Electron chemiluminescent NO_x analyzer. Post test data examination revealed that the SO_2 analyzer had a very slow time response ($\sim$20 minutes) which was not evident during the test, and which resulted in incorrect instrument calibration. The result was that the SO_2 data for the first test had to be discarded. Gas sampling for the first test involved point sampling only.

For the second test, a new Carle gas chromatograph was purchased. The new unit had an automatic sampling capability so that it could operate unattended. The older model required manual operation. A pulsed fluorescent SO_2 analyzer was loaned to us for the second test through the courtesy of the Thermo Electron Corporation and their Western Regional office manager, Mr. Jim Nelsen. The NO_x analyzer was the same one used during the first test. The gas chromatograph had its own integrator and digital paper tape printer. Outputs of the SO_2 and NO_x analyzers were fed through a scanner to a digital voltmeter and paper tape printer. Data output intervals varied from ten seconds to one hour, with a nominal ten minute interval. Data reduction was accomplished by use of a digital computer upon completion of field work.

The point sampling probe used during the second test is shown in Figure 26. The sample line was heat traced up to the condenser used to remove water vapor. Four continuous sampling probes were fabricated for the second test. Design is described in Section VII, and shown in

60

Nozzle

Thimble Filter
Assembly

Probe
Body

Heat Traced
Sample Tube

61

Heat Traced
Sample Line
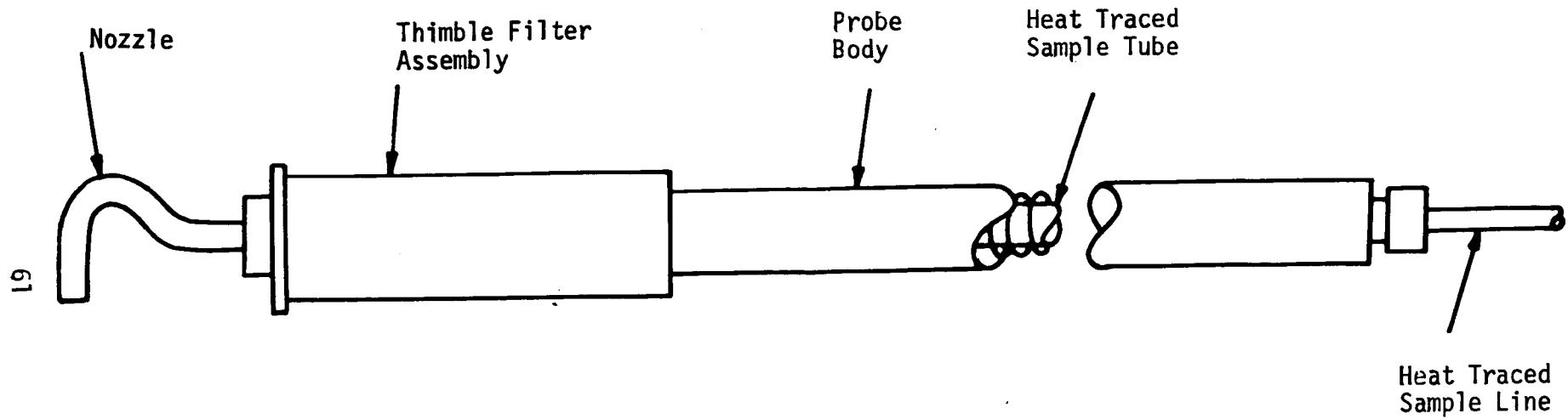
Figure 26. Point sampling probe

Figure 27. The probes were installed at the locations shown in Figure 24. Heat traced lines were used as far as the condenser.

A schematic of the sampling trains is shown in Figure 28. For the second test, two large plexiglas water knockouts (condensers) were fabricated to allow for continuous sampling (one for the duct area and one for the stack). Two pumps from Aerotherm "Super Sniffer" sampling trains were used to provide the desired flow rates. The second pump was used as a backup in case of failure.

8.2.2 Extent of Testing

Sample traverses were performed in duct 1 during the first test to assess stratification levels and provide composition data for flow calculations. In addition, time variation of concentrations at a fixed point was also investigated. Traverses were performed in both ducts 1 and 2 during the second test in addition to the data obtained from the multi-point probes.

A total of four basic plant conditions occurred during the first test, each about equally often. The unit load was held at maximum ($\sim$110-120 MW) during the PM hours and at about half that during the AM hours. The scrubber was on about 40% of the time. The unit was down about five days during the test. Full load was maintained during the second test, the variation being from about 100 to 123 MW. The scrubber was on full time except for one five hour period. There was no plant down time during the second test.

8.2.3 Problems

The only notable gas sampling problem during the first test was malfunction of the SO_2 analyzer. The absolute value of the NO_x data for the test seemed unusually high. The analyzer was factory serviced between tests and gave more reasonable data for the second tests. Since the objective during the first test was to determine variations rather than absolute values, the data were considered acceptable for that purpose. Many problems occurred with the velocity measurements during the first test, and these are documented in Reference 1.

62

Heat Traced
Sample Tube

Coarse
Particulate
Filter

Probe
Body

Purge
Plug

Duct
Wall

Approximate
Location of
Filter

Duct
Wall

Heat Traced
Sample Tube
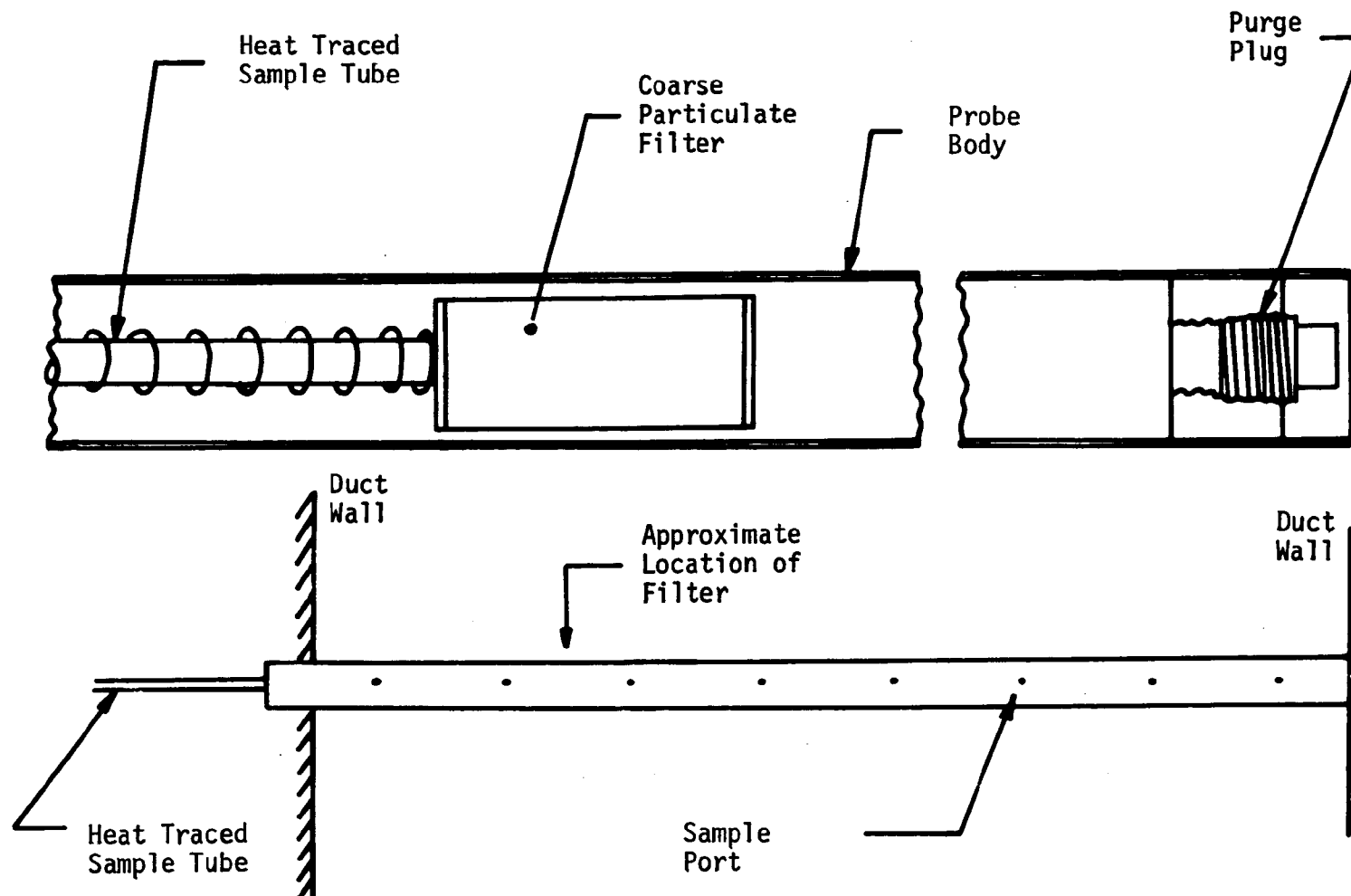
Sample
Port

Figure 27. Multi-hole sampling probe for field demonstration

A. Configuration for 1974 test, and configuration prior to pump leakage problem, 1975 test

B. Configuration after pump leakage problem discovered, 1975 test
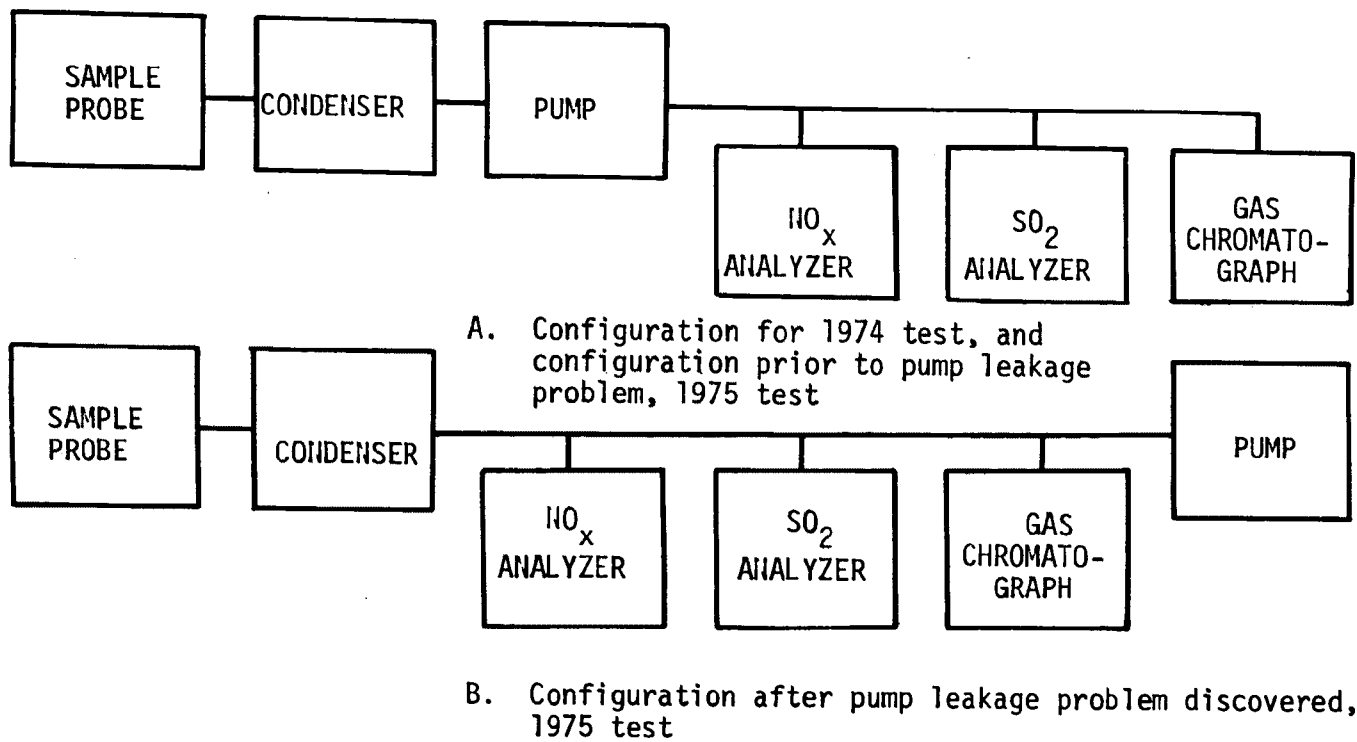
Figure 28. Schematic of gas sampling train for field demonstrations

The situation reversed for the second test. There were negligible problems with the velocity measurements, but many with the gas sampling work. In retrospect, the primary cause of difficulties was an unfortunately tight test schedule prior to the actual field work. Work on the program came to a virtual standstill during December of 1974 due to the fact that data from various sources were showing lower gas stratification levels than had been expected when the program was conceptualized. It was eventually recognized that although the stratification levels were lower than expected, the problem of obtaining a representative sample was far from trivial. Approval to proceed as originally planned was received early in January. For several reasons, it was decided that the second field demonstration should be conducted at the same place as the first. A severe time constraint became apparent when we were told that the unit would be down for an extended period, starting around the first of March, for annual maintenance. This gave us a month to develop the specialized hardware needed to perform the test, and still have a reasonable length of time to conduct the test. The major difficulties were with procurement: the new gas chromatograph did not arrive in time to be thoroughly checked out in the laboratory. This resulted in much down time for the instrument in the field. The SO_2 analyzer did not arrive until the sixth day of the test. A faulty integrated circuit (replacement cost 59¢) invalidated the output for several subsequent days until the problem could be located through consultation with the factory, and a replacement flown in from Los Angeles.

Other problems during the test included accidental damage to the water knockout units, and accidental ingestion of a large slug of water in the sample line, which rendered the SO_2 analyzer inoperable during the last two days of testing. A significant problem was the development of a leak in the Aerotherm pump midway through the test. The pump was initially placed upstream of the analyzers to provide an acceptably high inlet pressure to the instruments. The backup pump was also found to have too high a leak rate. The pump then had to be placed downstream of the analyzers, as shown in Figure 28. Since the analyzers could not maintain an adequate flow rate due to the low line pressure ahead of the pumps, it was necessary to manually throttle down the pump at each

sampling point to allow the line pressure to rise to an acceptable level. Data were not compromised using this procedure, but it precluded any further continuous sampling. As a result, the only continuous monitoring data obtained were in duct 1, since the data had been taken prior to the leakage problem.

It is felt that the gas sampling data obtained during the second test were adequate to demonstrate the chosen techniques. The problems which occurred simply reduced the amount of data which could be taken.

8.3 FLOW DATA CORRELATION

The gas analyzers were calibrated with bottled calibration gases. This was normally done twice a day, or before and after each traverse. Coal usage per day and coal analysis data were coupled with test composition measurements of CO_2 in the ducts to make independent flow calculations. Coal data were supplied by plant personnel.

8.4 TEST RESULTS

8.4.1 Composition Measurements and Plant Reference Data

Foster-Wheeler specifications for full load nominal bulk composition at the duct sampling planes are as follows:

Gas	% Wet Gas	% Dry Gas
N_2	76.13	80.14
CO_2	13.24	13.94
O_2	5.63	5.92
H_2O	5.00	-

Results of the 1974 sampling measurements in duct 1 are summarized in Table 6 for full load conditions. No full traverses were obtained at half load due to the plant schedule. We did obtain two "half traverses" on different days which were used to calculate nominal composition at half load. Averages for the 1974 test were:

Table 6. MEAN VALUES AND STRATIFICATION LEVELS
FOR 1974 FIELD DEMONSTRATION

GAS	DUCT	RUN	MEAN VALUES		STRATIFICATION LEVEL, 2σ, % of Mean Value
			Spatial	Flow Proportional	
CO_2 % of dry gas	1	-	15.84	15.85	± 7.4
NO_x, ppm	1	1	734	735	± 7.0
		2	800	805	± 16.0
O_2, % of dry gas	1	-	4.32	4.30	± 23.2

Gas	Full Load		Half Load	
	% Wet Gas	% Dry Gas	% Wet Gas	% Dry Gas
N_2	76.65	79.85	79.96	82.43
CO_2	15.22	15.85	8.81	9.08
O_2	4.13	4.30	8.23	8.49
H_2O	4.00	-	3.00	-

Results for the 1975 test are summarized in Table 7. Recall that the unit was only at full load during the 1975 test. Bulk composition for the 1975 test was as follows:

Gas	% Wet Gas	% Dry Gas
N_2	75.40	80.39
CO_2	12.99	13.85
O_2	5.40	5.76
H_2O	6.21	-

Water vapor content was calculated from ambient humidity and plant measurements of water content in the coal. In 1974 testing at half load, coal usage was half that at full load while the total flowrate was about 70% of the full load flow rate. Thus quite a bit more excess air was used at half load than at full load. During the 1975 test the unit was always at full load and the gas composition was very close to the nominal specifications.

Good correlation was obtained for total mass flow as well as for gas composition. Total flow measurements from the Annubars were compared to flow calculations based on daily coal usage and average CO_2 concentrations in the ducts. Results are presented in Tables 8 and 9, which are taken from Reference 1. Table 8 shows the calculation technique and results for two days of testing in 1974. Table 9 shows similar results for 1975 testing. The "insufficient data" designation in Table 9 means that the pressure transducer used to monitor the duct 2 Annubar was being used for other purposes on the days noted. Both Tables 8 and 9 show total flow correlations on the order of 2% between test and reference measurements.

Table 7. MEAN VALUES AND STRATIFICATION LEVELS
FOR 1975 FIELD DEMONSTRATION

GAS	DUCT	RUN	MEAN VALUES		STRATIFICATION LEVEL, 2σ, % of Mean Value
			Spatial	Flow Proportional	
CO_2, % of dry gas	1	-	13.16	13.14	± 9.0
	2	-	14.54	14.55	± 9.0
SO_2, ppm	1	-	277	278	± 20.6
	2	-	344	345	± 19.7
NO_x,	1	1	373	373	± 8.6
		2	479	480	± 6.9
	2	1	449	451	± 14.3
		2	416	416	± 13.5
O_2, % of dry gas	1	-	5.79	5.76	± 13.4
	2	-	5.75	5.75	± 8.6

Table 8. COMPUTATION OF TOTAL FLOW FROM COAL ANALYSIS AND
MEASURED CO_2 CONCENTRATION, 1974

Date	Coal Used kg	Carbon Used kg	gm-moles	Average CO_2 %	Total Moles of Dry Gas	Total Moles of Wet Gas
10-2	3,251,380	2,752,618	4.729×10^7	11.89	3.977×10^8	4.122×10^8
10-3	3,571,480	3,023,614	5.195×10^7	12.74	4.078×10^8	4.226×10^8

Date	Annubar Average Flow Rate, SCMS	Annubar Total Flow SCM	Total Wet Gas Volume, SCM	Difference %
10-2	104.5	9.026×10^6	9.234×10^6	+ 2.3
10-3	109.4	9.451×10^6	9.466×10^6	+ 1.6

Table 9. AVERAGE DAILY FLOW THROUGH DUCTS, 1975

Date	Average Flow And Standard Deviation, Test SCM/SEC			Average Flow In Ducts From Plant Data SCM/SEC
	Duct 1	Duct 2	Total	
2-15	63.4 ± 1.7	X	X	132.0
2-16	63.5 ± 2.8	X	X	132.6
2-17	64.7 ± 2.3	64.6 ± 1.9	129.3	134.3
2-18	67.3 ± 2.2	64.5 ± 2.4	131.8	135.1
2-19	65.8 ± 2.3	65.2 ± 3.0	131.0	132.8
2-20	65.3 ± 1.6	66.7 ± 2.9	132.0	134.7
2-21	65.1 ± 0.9	64.3 ± 3.9	129.4	133.7
2-22	63.2 ± 2.6	67.3 ± 8.2	130.5	132.9
2-23	64.3 ± 5.2	X	X	128.1
2-24	60.1 ± 8.5	67.3 ± 3.0	127.4	130.6
2-25	62.5 ± 1.7	67.2 ± 0.9	129.7	130.1
2-26	62.7 ± 1.8	66.7 ± 2.1	129.4	132.7
2-27	60.8 ± 2.1	X	X	130.2
2-28	60.3 ± 1.6	X	X	126.3
Ave	63.5	66.0	129.5	131.9

X Indicates insufficient data

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8.4.2 Assessment of Stratification

Stratification levels for the various gases are shown in Tables 6 and 7. They are generally of the same order of magnitude as in the Exxon data, with the exception of relatively low O_2 stratification. In all cases, excellent agreement was obtained between spatial and flow proportional averages, further strengthening the validity of spatial gas sampling.

Concentration maps are presented in Figures 29-42. The only general comment to be made is that stratification is generally greater in the direction parallel to the long sides of the duct, as was the case for the Exxon data. This may be in part due to the fact that the rotary air preheaters just upstream of the test area have a vertical interface with the ducting, so any leakage at that point would tend to result in horizontal rather than vertical stratification. Thus results are as expected if we assume some leakage at the preheater area.

8.4.3 Technique Evaluation

Row Average analyses are presented in Figures 43-45. In Figure 43, the CO_2 curves show the most uniform row averages while the SO_2 data show the least desirable results. The NO_x data in Figure 44 show good results for three of the four runs, and fairly good agreement was attained for all gases in Figure 45.

Due to the problems described in Section 8.2.3, the only multi-hole probe sampling data were obtained in duct 1. Results for a twelve hour sampling period are shown in Table 10. The average CO_2 and O_2 concentrations for the multi-hole probe agree with the traverse averages for duct 1 in Table 7 within 3% and 2%, respectively. The row location was 35.7% of the duct width from the left wall. As can be seen in Figure 43, this location showed good agreement between row averages calculated from traverse data and the mean flow proportional concentration.

Evaluation of the Walden CO_2 tracer method is shown in Table 11. Correlation was about the same as for the Exxon data.

8.4.4 Assessment of Temporal Variations

Short term and overnight point sampling data were taken to determine changes in concentration at a point as a function of time. Data in

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PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION
MEASURED MEAN CONCENTRATION = 15.85% OF DRY GAS
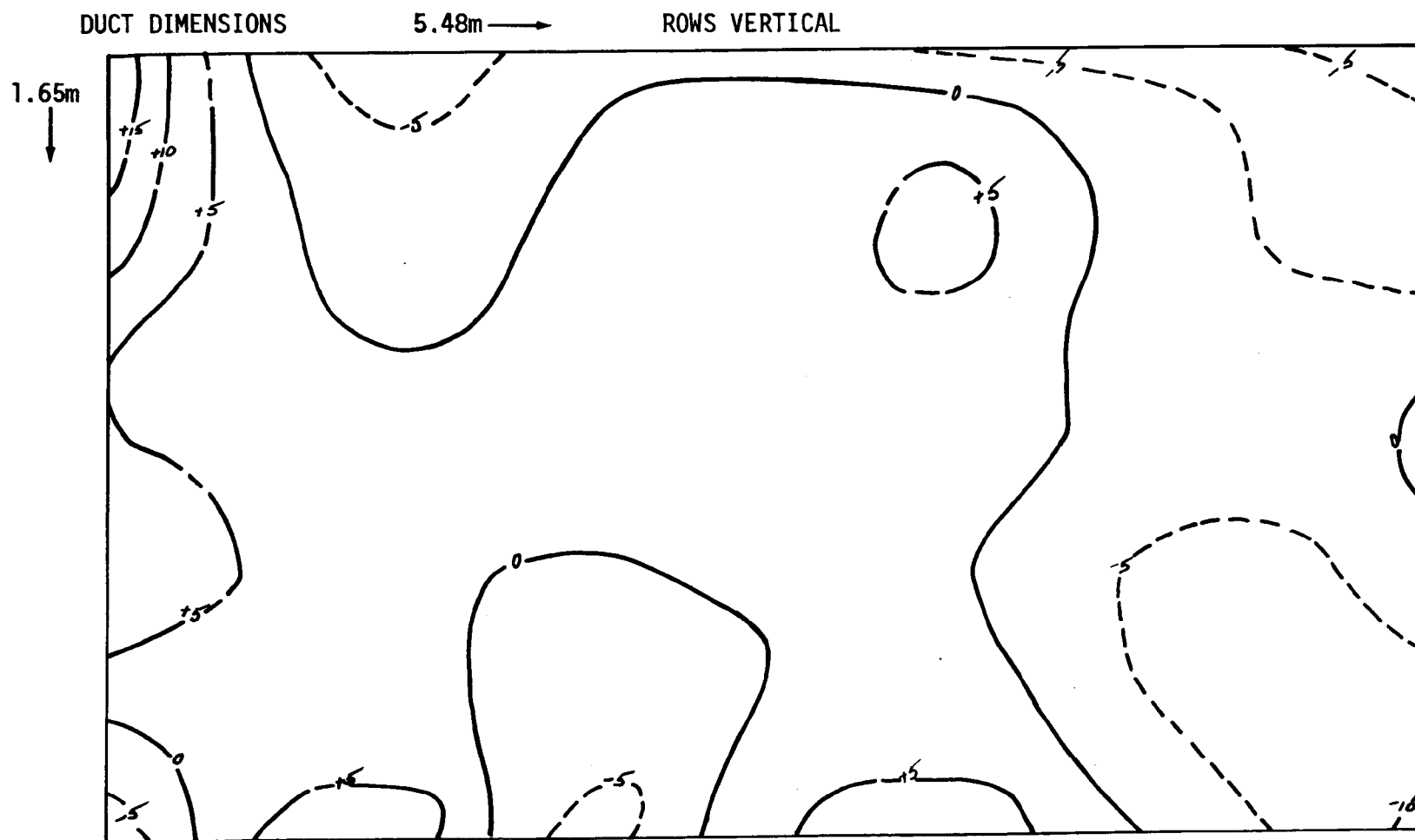
Figure 29. Normalized CO_2 concentration distribution-duct 1, 1974
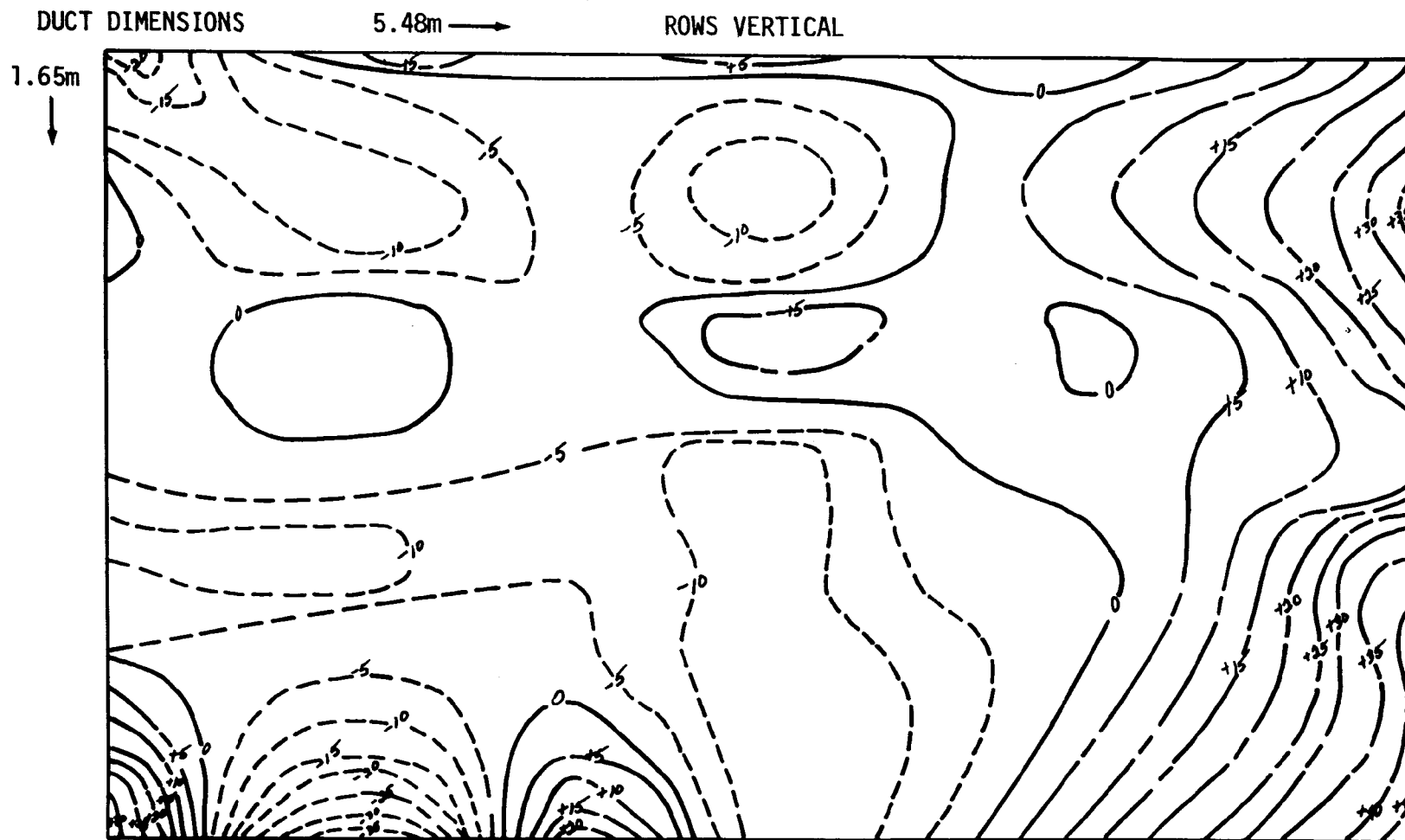
PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 4.30% OF DRY GAS

Figure 30. Nromalized O_2 concentration distribution--duct 1, 1974
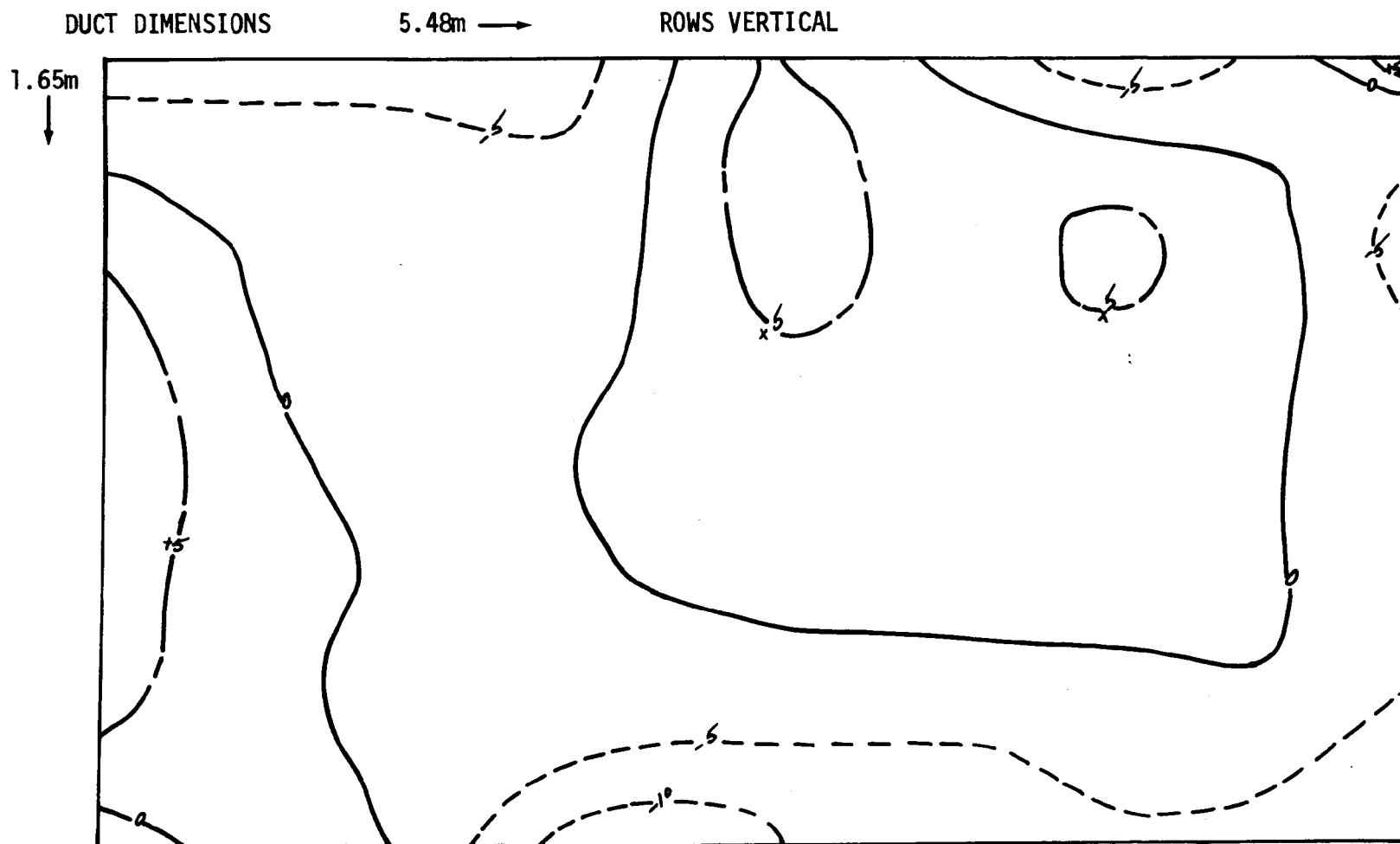
DUCT DIMENSIONS 5.48m ⟶ ROWS VERTICAL

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 735 PPM

Figure 31. Normalized NO_x concentration distribution--duct 1, 1974, run 1
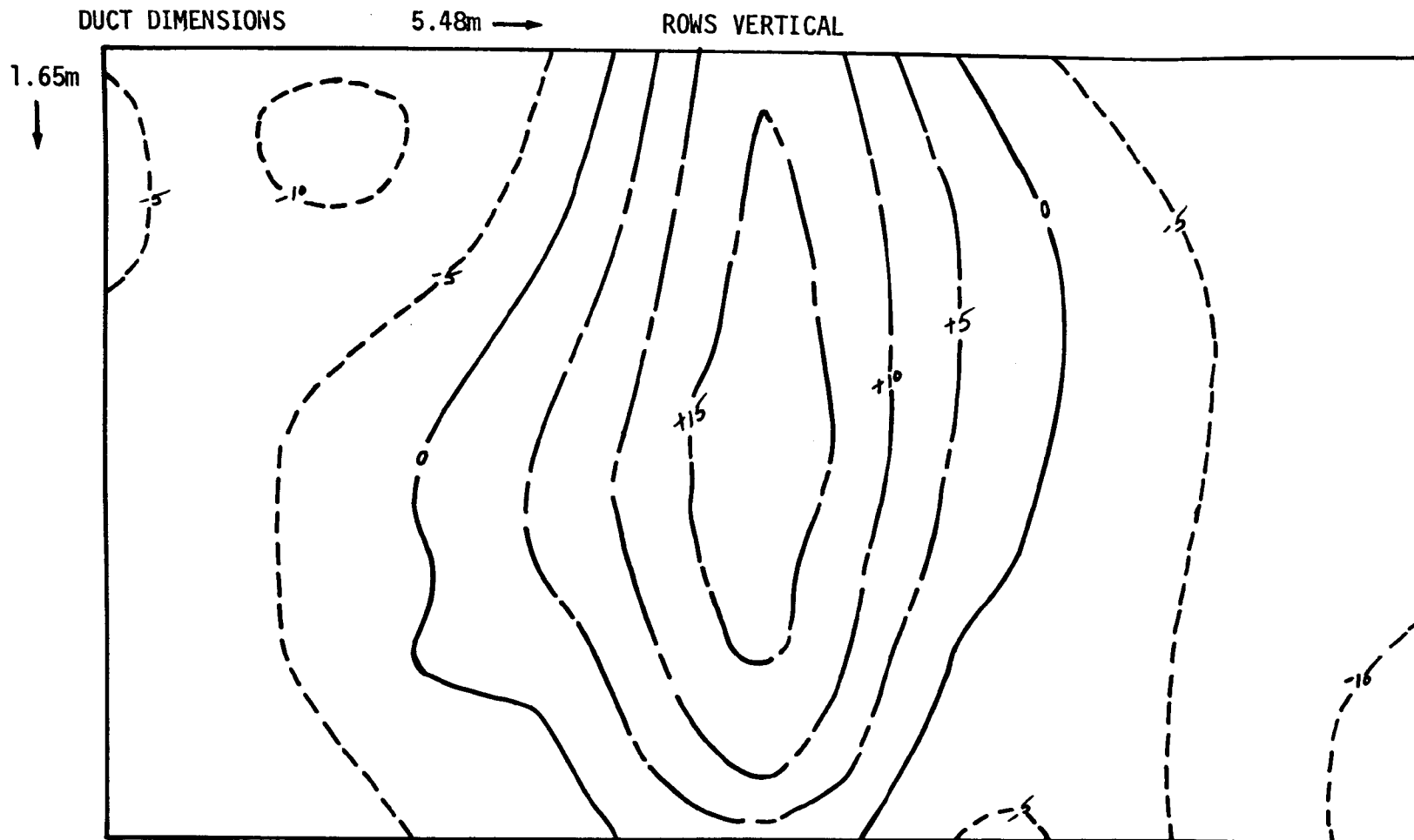
DUCT DIMENSIONS   5.48m ⟶   ROWS VERTICAL

1.65m

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 805 PPM

Figure 32.   Normalized NO_x concentration distribution--duct 2, 1974, run 2
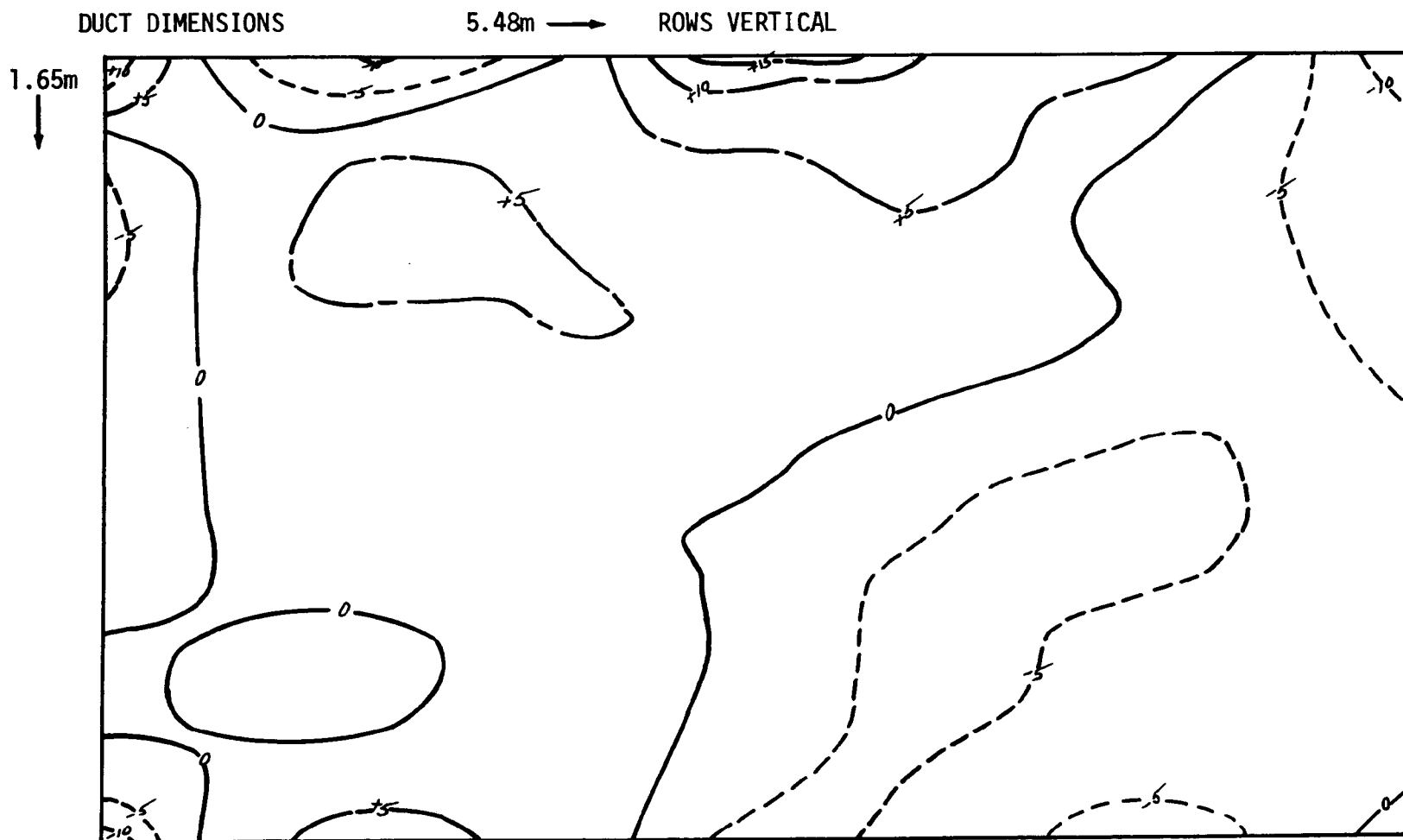
DUCT DIMENSIONS 5.48m ⟶ ROWS VERTICAL

1.65m

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 13.14% OF DRY GAS

Figure 33. Normalized CO_2 concentration distribution-duct 1, 1975
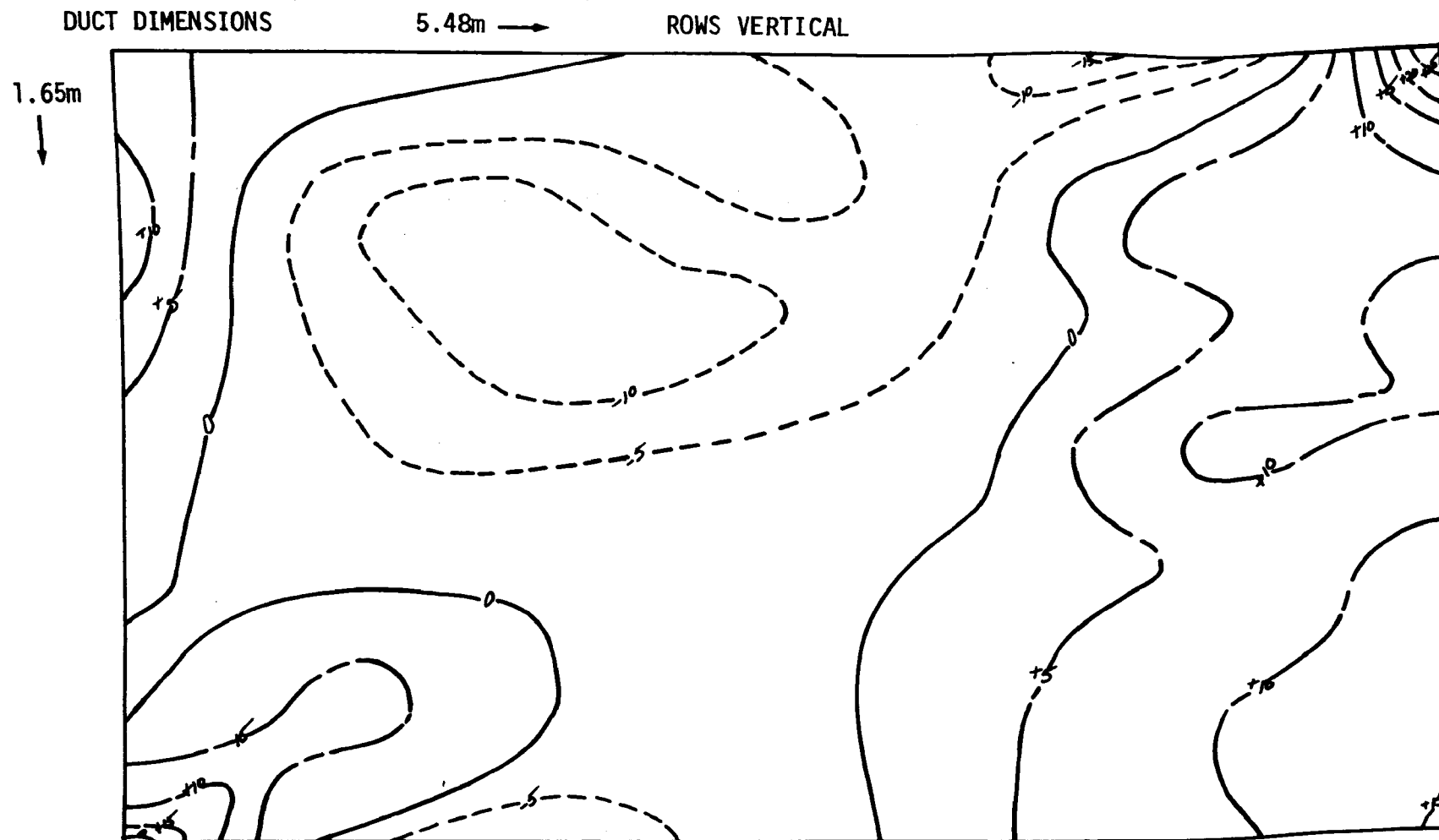
DUCT DIMENSIONS   5.48m ⟶   ROWS VERTICAL

1.65m

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION MEASURED

MEAN CONCENTRATION = 5.76% OF DRY GAS

Figure 34.   Normalized O_2 concentration distribution--duct 1, 1975
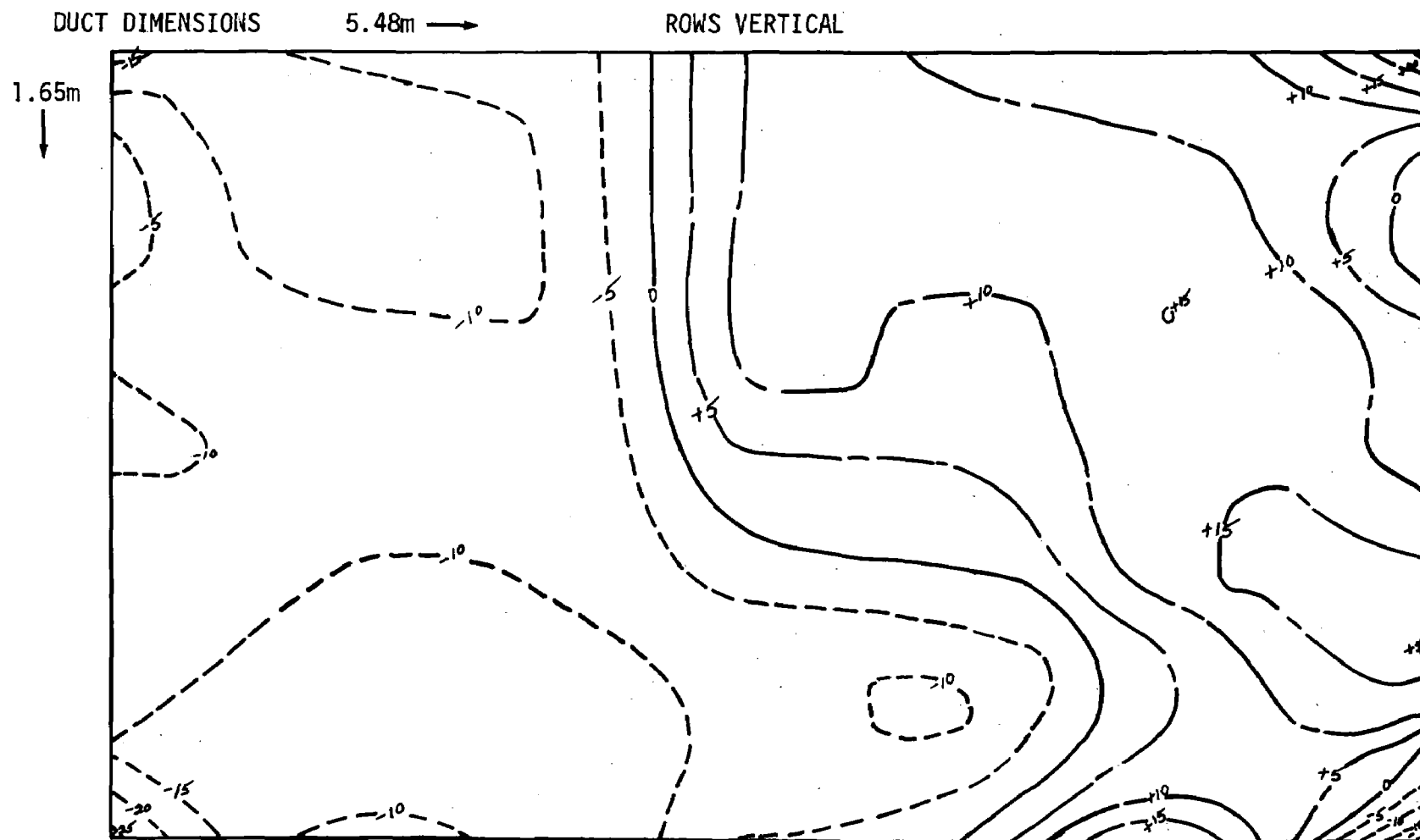
DUCT DIMENSIONS   5.48m ⟶   ROWS VERTICAL

1.65m
↓

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION
MEASURED MEAN CONCENTRATION = 278 PPM

Figure 35. Normalized SO_2 concentration distribution—duct 1, 1975

DUCT DIMENSIONS   5.48m ⟶   ROWS VERTICAL

1.65m
↓
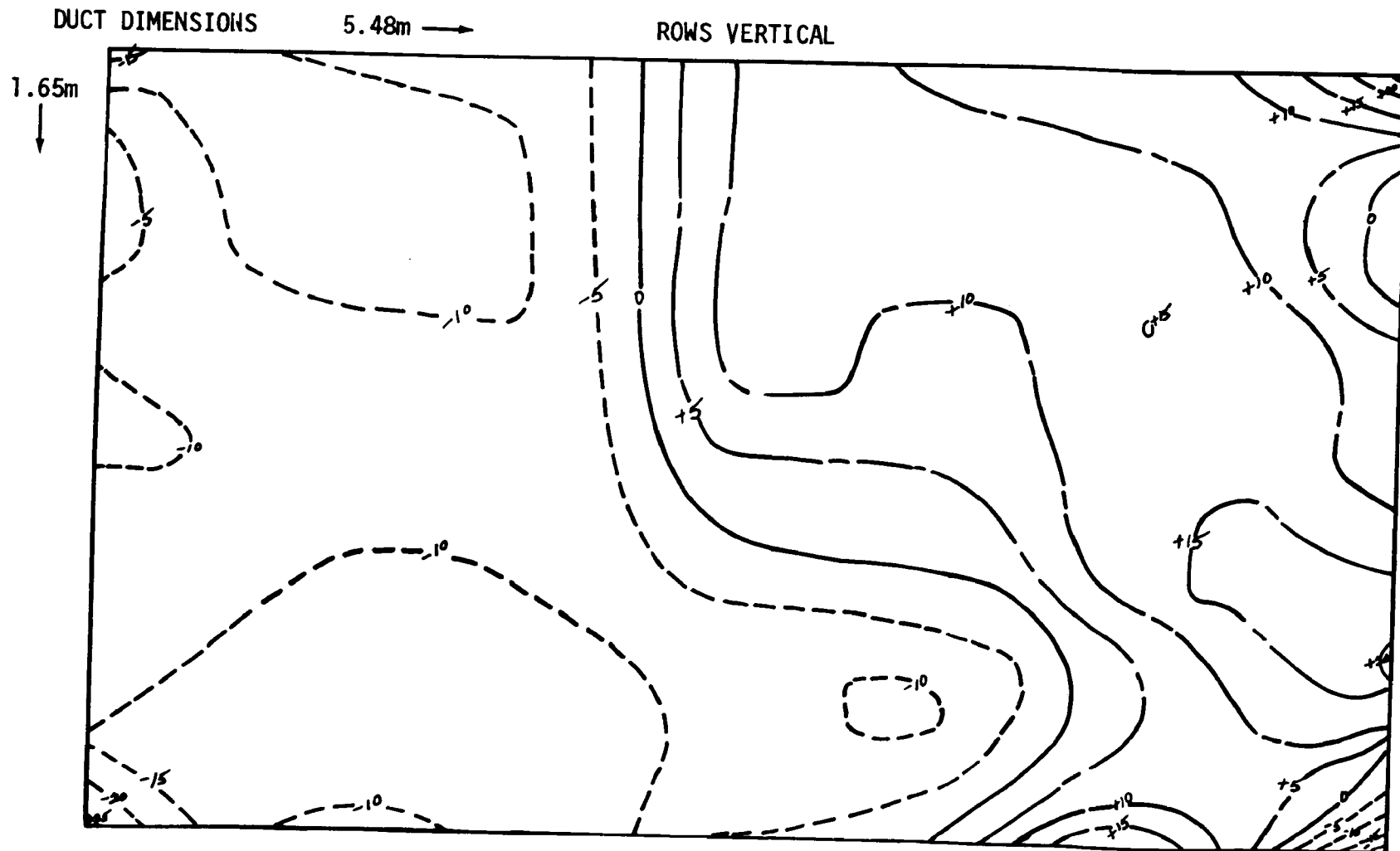
PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 278 PPM

Figure 35. Normalized SO_2 concentration distribution--duct 1, 1975

Figure 36. Normalized NO_x concentration distribution--duct 1, 1975, run 1
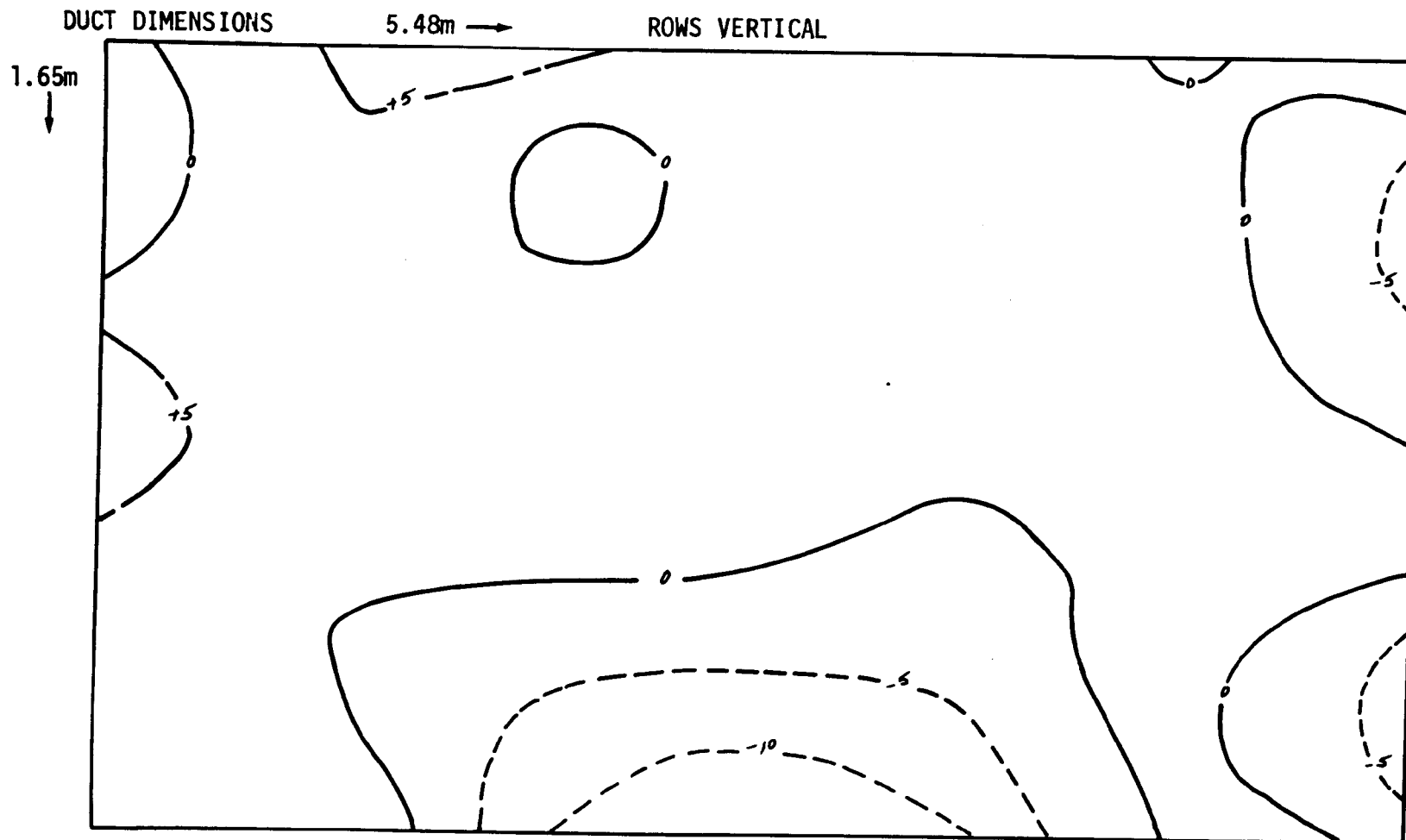
PROFILES ARE VARIATION IN %5 INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 480 PPM

Figure 37. Normalized NO_x concentration distribution--duct 1, 1975, run 2
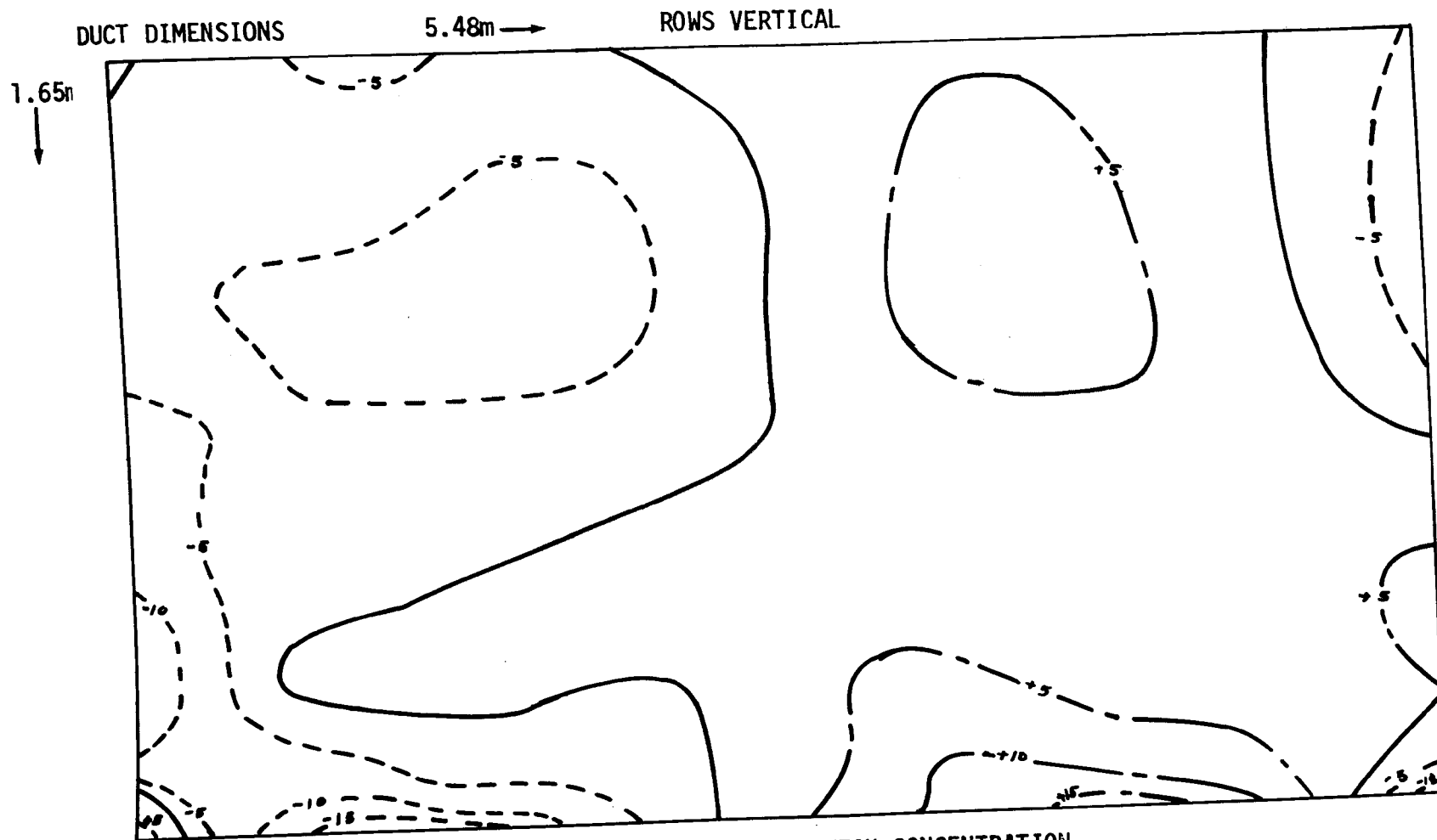
DUCT DIMENSIONS   5.48m ⟶   ROWS VERTICAL

1.65m

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PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 14.55% OF DRY GAS

Figure 38. Normalized CO_2 concentration distribution--duct 2, 1975

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION
MEASURED MEAN CONCENTRATION = 5.75% OF DRY GAS
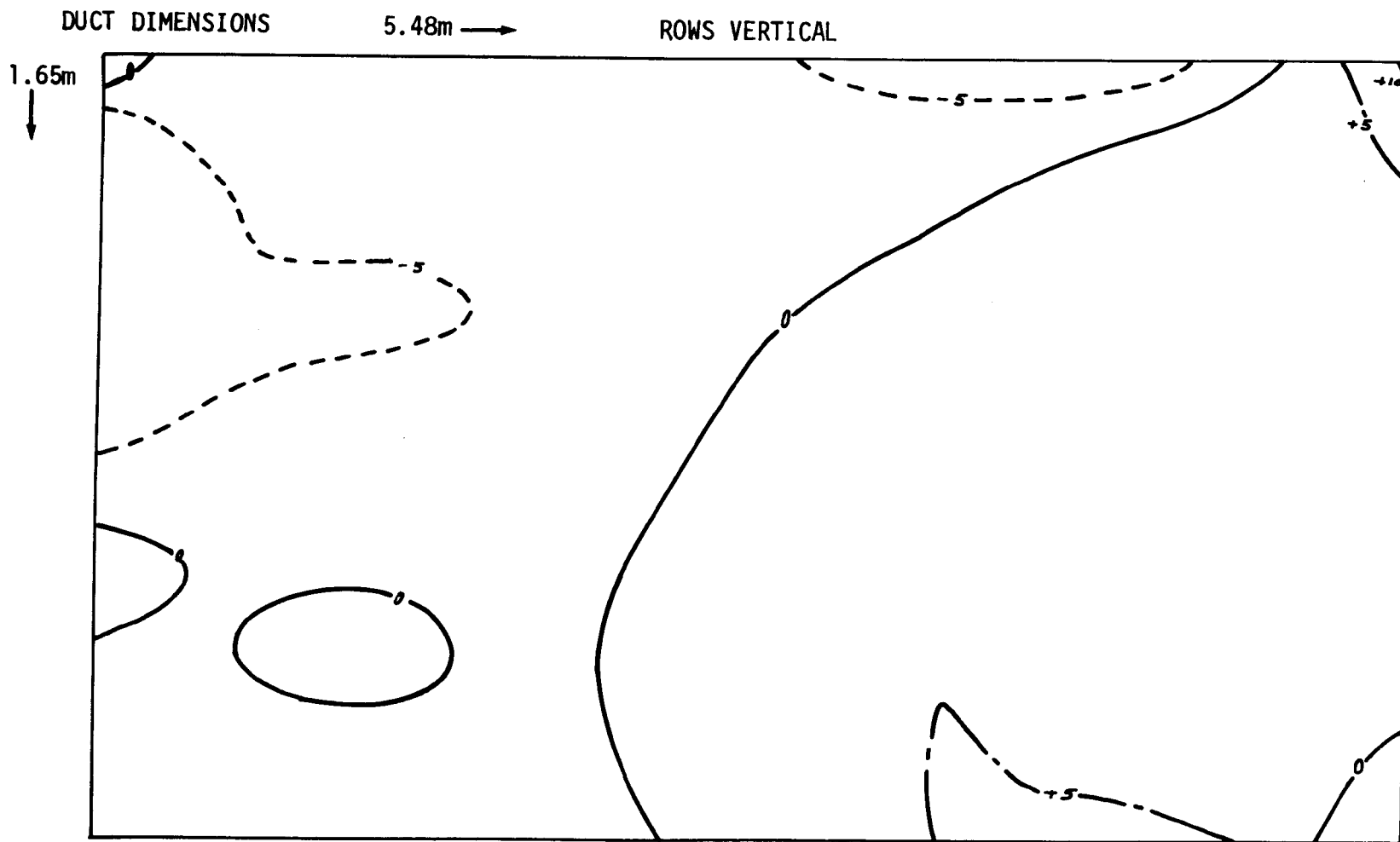
Figure 39. Normalized O_2 concentration distribution--duct 2, 1975
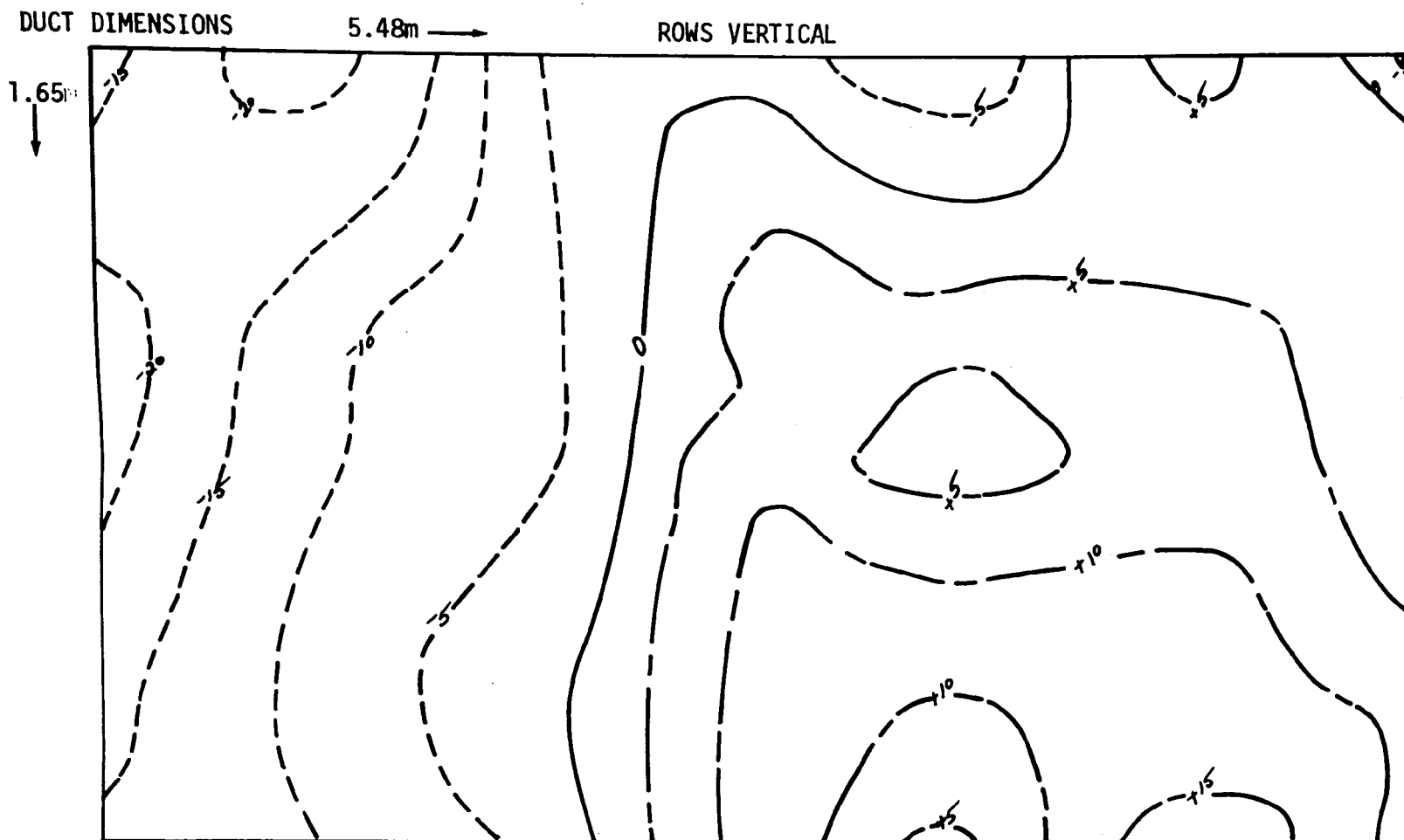
DUCT DIMENSIONS   5.48m ⟶   ROWS VERTICAL

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 345 PPM

Figure 40. Normalized SO_2 concentration distribution--duct 2, 1975
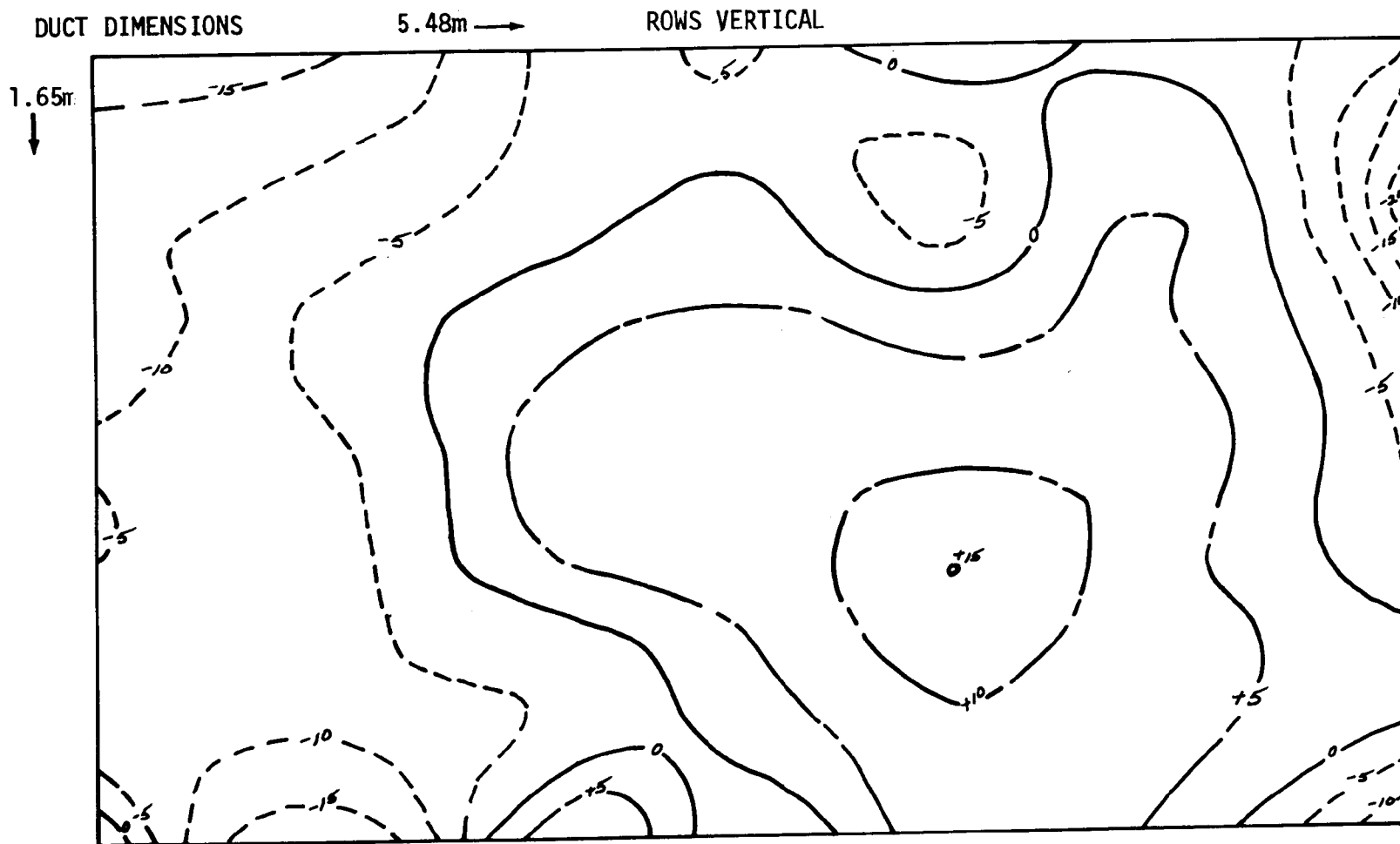
DUCT DIMENSIONS
5.48m →
ROWS VERTICAL

1.65m

PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 451 PPM

Figure 41. Normalized NO_x concentration distribution--duct 2, 1975, run 1
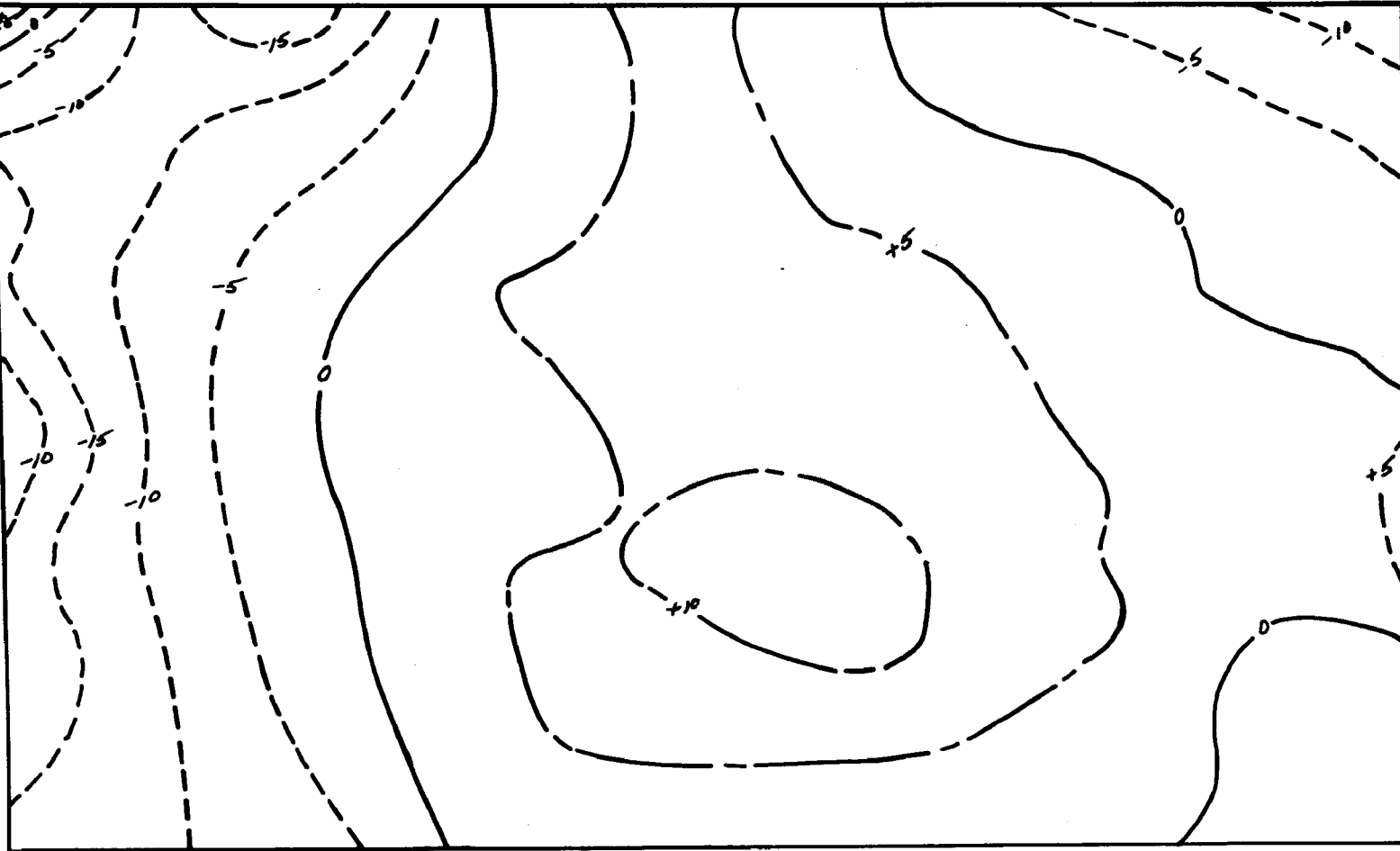
PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 416 PPM

Figure 42. Normalized NO_x concentration distribution--duct 2, 1975, run 2

RATIO OF ROW AVERAGE CONCENTRATION
TO PROPORTIONAL AVERAGE CONCENTRATION
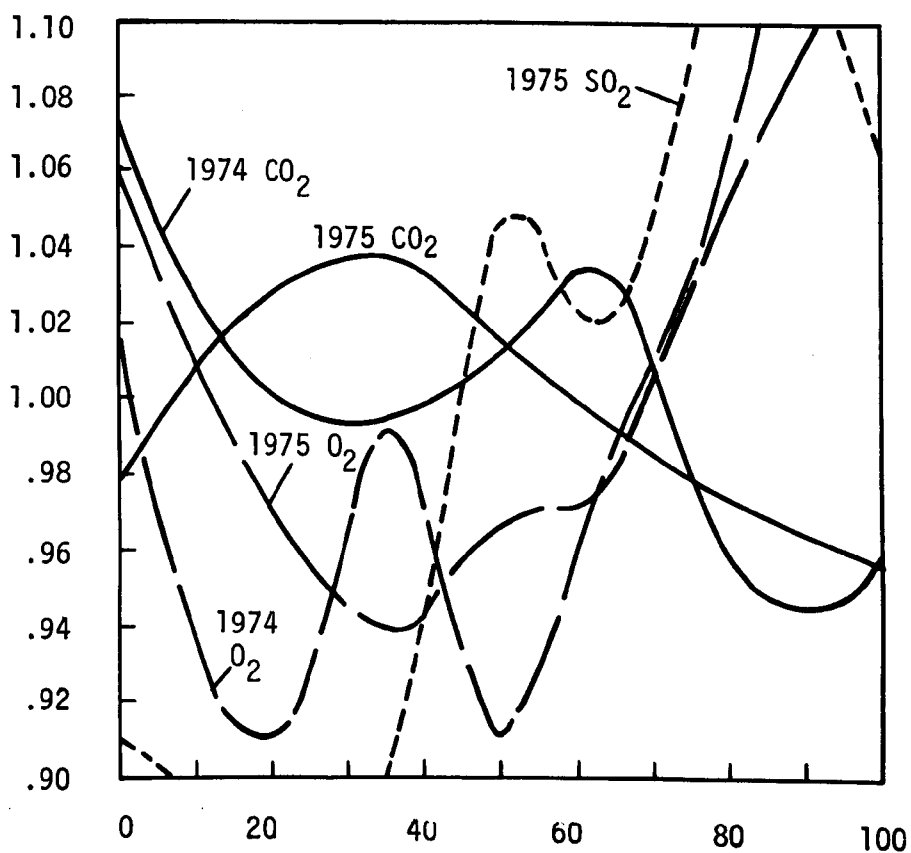
Figure 43. Row average analysis for CO_2, O_2, and SO_2 concentration maps--field demonstrations, duct 1

RATIO OF ROW AVERAGE CONCENTRATION
TO PROPORTIONAL AVERAGE CONCENTRATION
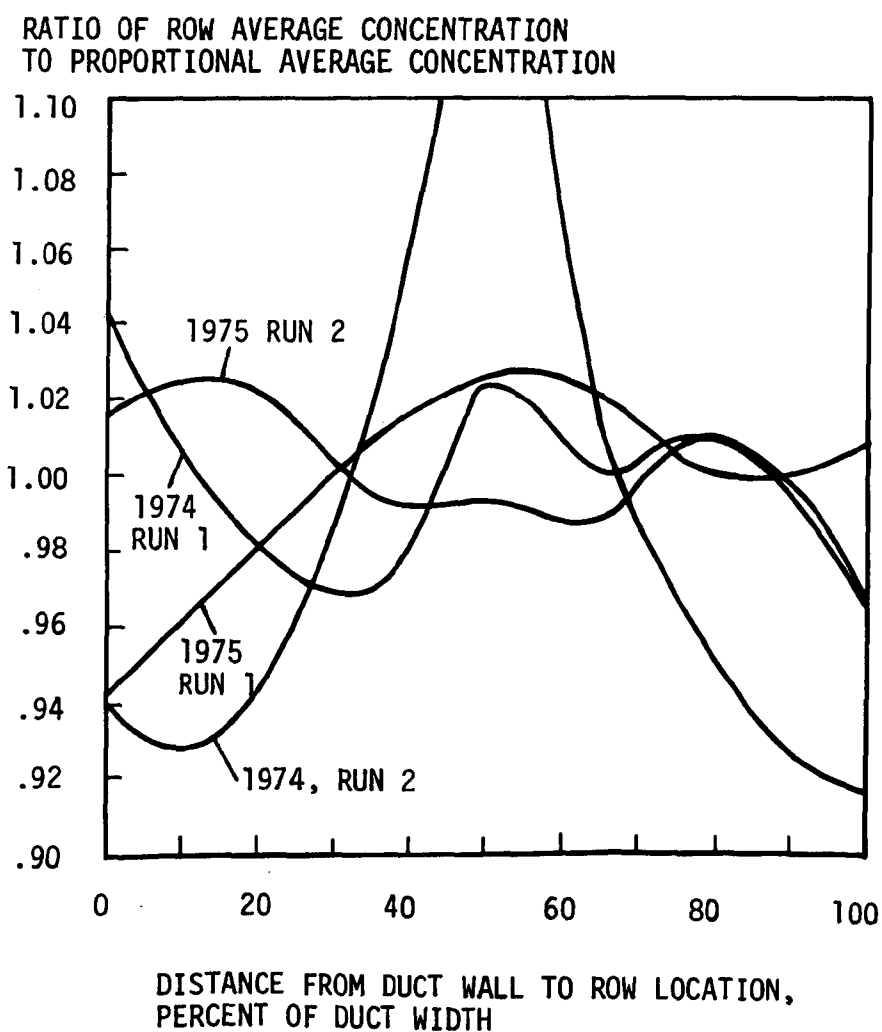
Figure 44. Row average analysis for NO_x concentration
maps--field demonstrations, duct 1

RATIO OF ROW AVERAGE CONCENTRATION
TO PROPORTIONAL AVERAGE CONCENTRATION
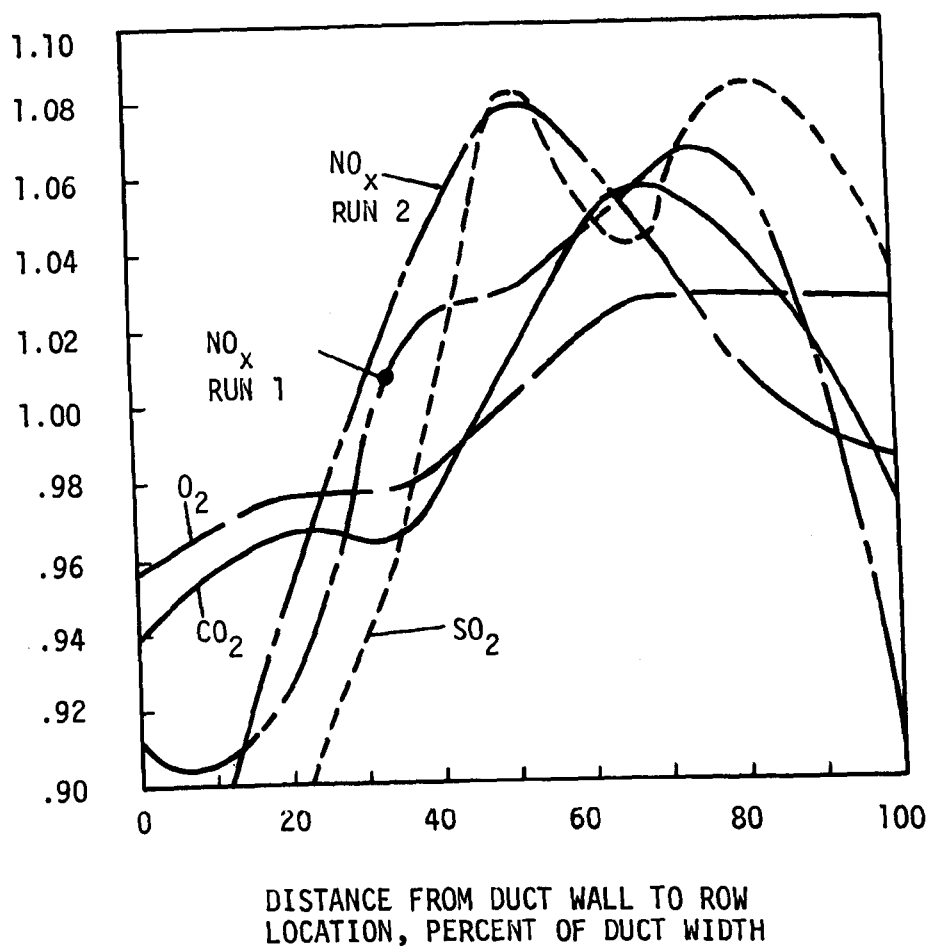
Figure 45. Row average analysis for CO_2, O_2, SO_2, and NO_x concentration maps--field demonstrations, duct 2

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Table 10. MULTI-HOLE SAMPLING PROBE OVERNIGHT
SAMPLING RESULTS, 1975

Start: 7 PM, 2-19

End: 7:10 AM, 2-20

Number of data points: 26 (taken on the hour and ten minutes
after the hour)

GAS	MEAN VALUE, % OF DRY GAS	2σ DEVIATION, % OF MEAN VALUE
CO_2	13.55	± 17.8
O_2	5.88	± 4.2
N_2	80.57	± 2.8

Probe position: Duct 1, Port 5

Table 11. CO_2 TRACER METHOD ANALYSIS
OF FIELD DEMONSTRATION DATA

	2σ, % OF MEAN VALUE
1974 TEST	
Duct 1	
NO_x/CO_2	± 8.9
1975 TEST	
Duct 1	
NO_x/CO_2	± 23.1
SO_2/CO_2	± 8.8
Duct 2	
NO_x/CO_2	± 12.1
SO_2/CO_2	± 15.7

Explanation of tabular values:

$2\sigma = \pm 8.9\%$ of mean value for NO_x/CO_2 ratio means that there is a 95.4% probability that the ratio of the NO_x reading to the CO_2 reading at any point in the duct will agree with the average NO_x/CO_2 ratio within $\pm 8.9\%$.

Table 12 showed that at a given point, concentrations were very constant for periods on the order of half an hour. Variations between points were clearly much larger. Overnight data, as shown in Table 13, showed significantly greater variations. Note that the standard deviation of 23 ppm is larger than most of the differences between successive readings. This demonstrates a "time constant" for variations that is more on the order of hours than minutes.

8.5 SUMMARY OF RESULTS

Average concentration determinations from gas sample traverses agreed well with nominal plant specifications. Correlation of total mass emission measurements with plant coal usage data was excellent. This agrees with the statement made in Section IV that better accuracy should be expected for total mass emission than for mass emission of any single gas. The Row Average data suggest possible measurement accuracies for individual species of about $\pm 4\%$, although the one twelve hour period of continuous sampling showed 2-3% agreement. It would appear likely that better correlation will be obtained for long sampling intervals rather than short ones. The rate of concentration variations at a single point suggests that sample traverses should be performed in as short a time as possible to avoid errors due to temporal variation. A traverse time of two hours or less would appear reasonable for this power plant. The CO_2 tracer technique showed fairly poor results, as was the case with the Exxon data. The test result which should have the greatest implication for future work was the continued excellent agreement between spatial and flow proportional mean values. The average stratification level, 2σ, was $\pm 13\%$, which is lower than the levels of the Exxon and TVA data, but still too high to justify single point sampling.

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Table 12. SHORT TERM STATIONARY POINT GAS SAMPLE DATA, 1974, DUCT 1

AVERAGE LOAD, MW	TIME DURATION, MINUTES	READINGS	POSITION, ROW-POINT	GAS	MEAN VALUE, % OF DRY GAS	2σ, % OF MEAN VALUE
109	26	7	2-4	N_2	79.67	$\pm.22$
				O_2	5.63	$\pm.24$
				CO_2	14.67	$\pm.24$
108	25	6	3-4	N_2	79.77	±1.06
				O_2	5.61	$\pm.86$
				CO_2	14.63	$\pm.38$
100	32	8	6-4	N_2	78.92	$\pm.30$
				O_2	5.29	$\pm.38$
				CO_2	15.80	$\pm.14$
88	26	6	7-4	N_2	77.67	$\pm.38$
				O_2	7.27	$\pm.38$
				CO_2	15.05	$\pm.30$
80	15	5	5-4	N_2	77.43	$\pm.44$
				O_2	7.09	$\pm.38$
				CO_2	15.43	$\pm.20$

Table 13.   OVERNIGHT NO$_x$ GAS SAMPLE DATA, 1974

Date	Time	Load MW	NO$_x$ Concentration, PPM
10-4	19:50	53	261
	20:50	54	308
	21:50	52	314
	23:40	53	282
10-5	0:30	53	273
	1:00	53	268
	3:00	55	250
	4:00	54	256
	5:00	54	234
	6:00	54	243
	7:00	55	236
	8:00	55	252
	9:00	53	273
	9:30	54	279

AVE =   266 $\pm$ 23

2σ = $\pm$17.6% of mean value

SECTION IX
DISCUSSION OF RESULTS

9.1   GENERAL

Current sampling techniques in large ducts tend to fall into two
extremes: careful manual sampling is done according to Federal Register
Method 1 (Reference 4), and often involves in excess of forty traverse
points.   Continuous monitoring is more often done at a single point for
reasons of cost and simplicity.   Data examined during this program have
shown stratification levels on the order of 10-15% and poor temporal
repeatability.   On this basis, we have concluded that single point
sampling is generally not acceptable if good accuracy is desired.
At the other extreme, we recognize the impracticability of large
sampling arrays.   Thus, our purpose has been to find an economically
feasible and technically acceptable (from the standpoint of accuracy)
middle ground, both for measurement of total volumetric flow and gaseous
emissions.

The accurate measurement of constituent gaseous emissions in process
streams is inherently more difficult than the measurement of total gaseous
emissions simply because the latter is required in order to determine
the former.   Methods to continuously monitor total gaseous emissions were
developed and evaluated during the first phase of the program.   Results
documented in Reference 1 showed that good accuracy could be attained
through proper use of as few as one flow sensor in large ducts with very
undeveloped flow profiles.   We therefore approached the gas composition
measurement phase of the program with the attitude that the simplest
hardware system for continous monitoring would probabily involve inde-
pendent flow and composition subsystems.   On this basis, we were extremely
pleased to discover the excellent correlation between spatial and flow
proportional mean concentrations.   This agreement justified the separation
of flow and composition measurements on the basis of accuracy.

There is an intuitive relationship between gas stratification levels
and the complexity of hardware required to obtain a representative sample.

One program objective was to establish a standard technique to specify the magnitude of stratification in a usable manner. The most obvious parameter for this purpose would be the standard deviation for a normal distribution (Reference 3, Chapters 8-9), since this parameter is the most commonly used in the evaluation of propagation of errors. The key question was whether concentration data followed a normal distribution in the sampling plane. Data from several runs showed a reasonably normal distribution, so the validity of the approach was accepted. It is suggested that consideration be given to adopting the "2σ" definition of stratification levels for purposes of standardization.

9.2 METHOD DEVELOPMENT AND EVALUATION

The correlation between spatial and flow proportional mean values was the basis for method development work. The primary proposed method is the Row Average technique developed originally for velocity measurement. This technique showed reasonable results for gas sampling, especially during the second field demonstration. The main problem with its use is a lack of predictability. The technique definitely works best when the row is in the direction of highest stratification. This direction can usually be predicted for velocity stratification by examining the local duct geometry. There is no analogous situation for gas sampling, so preliminary survey traversing must be considered a requirement for selection of an optimum gas sampling system. For the data examined during the program, the best Row Average correlation was obtained for the TVA data, since maximum stratification was in the row direction, which was not the case for most of the other data. Recall that this correlation was obtained even though the TVA data had higher stratification levels than did most of the other data.

The recommended procedure for application of the row average technique is as follows:

> Perform a preliminary traverse for the gases of
> interest at each desired flow condition

- Examine data to determine direction of highest stratification. Couple this with considerations of duct dimensions, access, and other physical constraints to determine the most desirable row direction

- Perform a Row Average analysis of the data to determine the optimum probe location

- Acquire and install sampling hardware

- Perform an in-place system calibration

The row average technique is being recommended for reasons of accuracy and hardware simplicity.

The Walden CO_2 Tracer method is as simple from a hardware standpoint as the Row Average method, but the accuracy does not appear to be as good for the data considered: a uniformly poor correlation was obtained for the ratios of NO_x and SO_2 to CO_2 concentrations. A good correlation may be expected for the SO_2/CO_2 ratio as long as there is little sulfur stratification in the fuel, but such correlation was not observed. The formation of NO_x and CO_2 take place through quite different mechanisms, so we see no obvious reason why the concentration ratio should be constant.

9.3 HARDWARE DEVELOPMENT

Development of gas sampling hardware was not strictly within the scope of the program. Consequently, work in this area was done at a very low level for the sole purpose of providing a way to demonstrate the Row Average technique in the field. The concept behind the probe design is valid for obtaining a representative line average sample. Particulate control was the major problem with the prototype units produced. We feel that validity of the Row Average method has been demonstrated sufficiently to justify serious development of a multi-point linear gas sampling probe for continuous use.

9.4 FIELD DEMONSTRATIONS

A most common problem in field testing is that of obtaining adequate traverse data in a short amount of time. During the field demonstrations,

a 49 point velocity traverse with a pitot-static probe took less than an hour. A full gas sample traverse took eight hours, primarily due to the fact that the gas chromatograph required about five minutes between sample injections. The most common guideline for selection of the number of sampling points is EPA Federal Register Method 1 (Reference 4). On the basis of the data examined, we feel that the number of sample points specified for most situations in Method 1 is overly conservative for gas sampling, and that work should be done to establish a proper minimum number of points for gas sample traverses.

9.5 FINAL COMMENTS

Total mass emissions can be accurately monitored on a continuous basis using hardware and techniques evaluated during the program. We also believe that the proposed Row Average method is acceptable for the continuous monitoring of gas concentration. However, there is no currently available sampling probe hardware for this application. Work should be performed to develop sampling hardware and to properly integrate the flow and sampling subsystems to produce complete real time continuous monitoring systems.

SECTION X
REFERENCES

1. "Continuous Measurement of Total Gas Flowrate from Stationary Sources", EPA-650/2-75-020, Brooks, et al, February, 1975.

2. "Procedures for Measurement in Stratified Gases," EPA-650/2-74-086-a and -b, Zakak, et al, September, 1974.

3. The Analysis of Physical Measurements, E. Pugh and G. Winslow; Addison-Wesley, 1966

4. "Standards of Performance for New Stationary Sources", Environmental Protection Agency; Federal Register, Vol. 36, No. 159, Part II, 9-17-71.

SECTION XI
GLOSSARY

SYMBOL	USAGE	DIMENSIONS
A	area	m^2
c	concentration	$moles/cm^3$
d	diameter	m
$\vec{i}, \vec{j}, \vec{k}$	unit vectors	dimensionless
$\dot{m}$	mass flow rate	gm/sec
M	molecular weight	gm/mole
$\vec{n}$	unit normal vector	dimensionless
n	number	dimensionless
N	number	dimensionless
p	absolute pressure	torr
R	universal gas constant	$\dfrac{gm \cdot m^2}{mole \cdot sec^2 \cdot °K}$
R	gas constant	$\dfrac{m^2}{sec^2 \cdot °K}$
T	absolute temperature	°K
u	axial velocity component	m/sec
$\vec{u}$	total velocity vector	m/sec
$\dot{V}$	volumetric flow rate	m^3/sec
v	velocity	m/sec
μ	mole fraction	dimensionless
ρ	density	gm/cm^3
σ	standard deviation	--
$(\ )_i$	property relative to species i	--
$(\ )_s$	property at standard conditions	--
$\overline{(\ )}$	mean value	--

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SECTION XII
APPENDIX

FLOW ANALYSIS PROGRAM

A typical analysis program run is presented. The run shown is the analysis of SO_2 data taken in duct 2 during the 1975 field demonstration. Program development is presented in Section V. Notation shows various features of the program.

```
00100          PROGRAM CONTOUR(INPUT,OUTPUT,TAPE5=INPUT,TAPE7,
00110        1    TAPE6)
00120          REAL LX,LY,KSO2
00130          DIMENSION X1(9),Y1(9),X2(9),Y2(3),IX1(9),IY1(9)
00140        1    ,IX2(9),IY2(9),XX1(25),YY1(25)
00150        2    ,GG1(25,25),GG2(25,25),FX1(25),FY1(25),FF(25)
00160        3    ,ZT1(9,9),ZZ1(69),ZT2(9,3),ZZ2(69)
00170        4    ,FX2(25),FY2(25),FFY(25)
00180        5    ,XM(21),G1C(10),G2C(10),EST(3),SOL(3),SOLR(3),SOLI(3)
00190          COMMON /AU/  B1,B2,B3,GG
00200 C
00210          EQUIVALENCE (ZT1,ZZ1),(ZT2,ZZ2)
00220          NAMELIST /NAM/   LX,LY,A,IM,JM,NC,IG1,NSTOP,IOP,FACTOR
00230        2    ,G1MAX,G2MAX,G1RANGE,G2RANGE,XDIV,IFLAG1,IFLAG2,IFLAG
00240          NAMELIST /NAM1/   ZZ1,ZZ2,X1,Y1,X2,Y2,IX1,IY1,IX2,IY2,KSO2

        ZZ1(1)=   6790.,5260.,5608.,5983.,6759.,6433.,6867.,6790.,
                  6184.,4303.,4957.,5822.,6070.,5685.,6210.,6184.,
                  6255.,4925.,5183.,5763.,6302.,6114.,6134.,6255.,
                  6301.,4971.,5480.,5748.,6474.,6423.,6450.,6301.,
                  6324.,5037.,5496.,5750.,6565.,6102.,6449.,6324.,
                  6473.,5146.,5600.,5862.,6711.,6588.,6748.,6473.,
                  6639.,5240.,5663.,6003.,6748.,6624.,6730.,6639.,
                  6790.,5260.,5608.,5983.,6759.,6433.,6867.,6790.,
        ZZ2(1)=   8.351,7.660,7.108,10.178,9.443,8.087,7.907,8.351,
                  1.106,1.428,7.019,7.830,6.96,4.478,4.495,1.106,
                  6.783,7.400,5.365,7.942,9.309,8.978,8.693,6.783,
                  8.444,8.180,6.262,7.697,7.158,6.760,7.478,8.444,
                  5.994,8.480,6.649,8.148,6.769,6.022,6.625,5.994,
                  5.749,6.196,6.921,8.857,7.327,6.916,6.782,5.749,
                  5.818,7.05,6.722,10.759,8.883,6.513,7.464,5.818,
                  8.351,7.660,7.108,10.178,9.443,8.087,7.907,8.351,
        KSO2=.05725
```

RAW DATA
INPUT

```
0 0340        DATA(X1(I),I=1,8) /11.143,.857,2.571,4.286,6.,
0 0342       1    7.714,9.429,11.143/
0 0350        DATA(Y1(I),I=1,8) /18.571,1.429,4.286,7.143,10.,12.857,
0 0352       1    15.714,18.571/
0 0360        DATA(X2(I),I=1,8) /11.143,.857,2.571,4.286,6.,
0 0362       1    7.714,9.429,11.143/
0 0370        DATA(Y2(I),I=1,8) /18.571,1.429,4.286,7.143,10.,12.857,
0 0372       1    15.714,18.571/
0 0380        DATA(IX1(I),I=1,7)  /8,0,1,4,1,-1,8/
0 0390        DATA(IY1(I),I=1,5) /8,1,1,4,1/
0 0400        DATA(IX2(I),I=1,8)  /8,0,1,4,1,-1,8/
0 0410        DATA(IY2(I),I=1,5)  /8,1,1,4,1/
0 0420        LX=12
0 0430        LY=20
0 0440        A=240.

0 0450        IM=25
0 0460        JM=21
0 0470        IG1=1
0 0480        NC=11
0 0490        XDIV=12.
0 0500        MAXIT=12
0 0510        EPSI=1.E-3
0 0520        G1MAX=230C.
0 0530        G2MAX=100.
0 0540        G1RANGE=1000.
0 0550        G2RANGE=100.
0 0560        IFLAG1=0
0 0570        IFLAG2=0
0 0580        IFLAG=0
0 0590        FACTOR=.05
0 0592        IOP=0
0 0600 C
0 0610        REWIND 7
0 0620     5  READ(7,NAM1)
0 0623        DO 8 I=1,54
```

```
00625      8  ZZ1(I)=KSO2*ZZ1(I)
00630     10  READ(5,NAM)
00640         IF(EOF,5) 20,30
00650     20  GO  TO  40
00660     30  IF(NSTOP .EQ. 0)  GO  TO  50
00670     40  END FILE 6
00680         STOP
00690     50  CONTINUE
00700         WRITE(6,NAM)
00710         IMD=IM-1
00720         JMD=JM-1
00730         HI=LX/IMD
00740         HJ=LY/JMD
00750         L1=IMD/2
00760         M1=(IMD-2)/2
00770         L2=JMD/2
00780         M2=(JMD-2)/2
00790     60  XX1(1)=0.
00800         DO 200 I=2,IM
00810         XX1(I)=XX1(I-1)+HI
00820    200  CONTINUE
00830         YY1(1)=0.

00840         DO 210 I=2,JM
00850         YY1(I)=YY1(I-1)+HJ
00860     90  FORMAT(4X,I5,E12.4)
00870    210  CONTINUE
00880  C
00890         IF(IFLAG1 .EQ. 1)  GO  TO  330
00900         DO 320 J=1,JM
00910         Y=YY1(J)
00920         DO 300 I=1,IM
00930         X=XX1(I)
00940         CALL BVIC(X,Y,Z1,X1,Y1,ZT1,IX1,IY1)
00950         CALL BVIC(X,Y,Z2,X2,Y2,ZT2,IX2,IY2)
00960         Z12=Z1*Z2
```

```
0C970        FX1(I)=Z1
0 0980       FX2(I)=Z2
0 0990       FF(I)=Z1*Z2
0 1000       IF(IFLAG .EQ. 0)  GO  TO  300
0 1010       WRITE(6,77)  I,J,X,Y,Z1,Z2,Z12
0 1020   300 CONTINUE
0 1030       CALL  SIMP1(FX2,IM,HI,L1,M1,ANS)
0 1040       FY2(J)=ANS
0 1050       CALL SIMP1(FF,IM,HI,L1,M1,ANS)
0 1060       FFY(J)=ANS
0 1065       CALL SIMP1(FX1,IM,HI,L1,M1,ANS)
0 1068       FY1(J)=ANS/12.
0 1070       WRITE(6,177)  J,FY2(J),FFY(J),FY1(J)
0 1080   177 FORMAT(2X,*J=*,I5,4X,*INTG2X=*,E12.4,2X,*INTG12X=*,E12.4,
0 1082     1    2X*INTG1X=*,E 12.4)
0 1090    77 FORMAT(2X,2I5,5E12.4)
0 1100   320 CONTINUE
0 1110       CALL  SIMP1(FY2,JM,HJ,L2,M2,A2)
0 1120       CALL  SIMP1(FFY,JM,HJ,L2,M2,A12)
0 1125       CALL  SIMP1(FY1,JM,HJ,L2,M2,A1)
0 1127       GB1=A1/20.
0 1130       GB2=A2/A
0 1140       GB12=A12/A2
0 1150       WRITE(6,47)  A2,A12,GB2,GB12,GB1
0 1160    47 FORMAT(//2X,*A2=*,E14.6,3X,*A12=*,E14.6/
0 1170     1    2X,*G2BAR=*,E14.6,5X,*G12BAR=*,E14.6,5X,*G1BAR=*,E14.6//)
0 1172 C
0 1180   330 IF(G1MAX  .EQ. 0)  GO  TO  10
0 1190       IO=XDIV+1

0 1200       HXM=LX/XDIV
0 1210       XM(1)=C.
0 1220       DO  340  I=2,IO
0 1230       XM(I)=XM(I-1)+HXM
0 1240   340 CONTINUE
0 1250       IF(IOP .EQ. 0)  GO  TO  360
```

```
01260          DO   350  I=1,NC
01270          G1C(I)=G1MAX-I*G1RANGE/NC
01280          G2C(I)=G2MAX-I*G2RANGE/NC
01290     350  CONTINUE
01300          GO   TO   380
01302   C
01310     360  DIF1=FACTOR*GB12
01320          DIF2=FACTOR*GB2
01330          G1C(1)=GB12-(NC-1)/2 *DIF1
01340          G2C(1)=GB2-(NC-1)/2 * DIF2
01350          DO   370  I=2,NC
01360          G1C(I)=G1C(I-1)+DIF1
01370          G2C(I)=G2C(I-1)+DIF2
01380     370  CONTINUE
01390     380  JJ=JMD
01400          DO   530   IX=1,ID
01410          X=XM(IX)
01420          DO   500   IY=1,JM
01430          Y=YY1(IY)
01440          CALL   BVIC(X,Y,Z1,X1,Y1,ZT1,IX1,IY1)
01450          IF(Z1 .LT. 0)   Z1=0.
01460          GG1(IY,IX)=Z1
01470          CALL   BVIC(X,Y,Z2,X2,Y2,ZT2,IX2,IY2)
01480          IF(Z2 .LT. 0)   Z2=0.
01490          GG2(IY,IX)=Z2
01500     500  CONTINUE
01502   C
01510          DO 510   IG=IG1,2
01520          GO   TO   (460,470) IG
01530     460  WRITE(6,1020)
01540    1020  FORMAT(/6X,*Y*,10X,*SP*,9X,*Y*,10X,*SP*,
01550         1   9X,*Y*,10X,*SP*/)
01560          GO   TO   480
01570     470  WRITE(6,1030)
01580    1030  FORMAT(/6X,*Y*,9X,*VEL*,9X,*Y*,9X,*VEL*,
01590         1   9X,*Y*,9X,*VEL*/)
```

```
01600    480 DO   490   IX=1,ID
01610        X=XM(IX)
01620        WRITE(6,1040)   X
01630   1040 FORMAT(2X,*X=*,F5.2)
01640        IF(IG .NE.1)  GO  TO  485
01650        WRITE(6,1050)   (YY1(IY),GG1(IY,IX)  ,IY=1,JM)
01660   1050 FORMAT(2X,3(E10.2,E12.4))
01670        GO  TO  490
01680    485 WRITE(6,1050)   (YY1(IY),GG2(IY,IX)  ,IY=1,JM)
01690    490 CONTINUE
01700    510 CONTINUE
01710 C
01720        DO  800 IG=IG1,2
01730        WRITE(6,277)
01740    277 FORMAT(////)
01750        DO  800  I=1,NC
01760        IF(IG .NE. 1)  GO  TO  520
01770        GG=G1C(I)
01780        GO  TO  540
01790    520 GG=G2C(I)
01800    540 DO  740   J=1,ID
01810        X=XM(J)
01820        DO  610   IJ=1,JM
01830        Y=YY1(IJ)
01840        IF(IG .NE. 1)  GO  TO  560
01850        FX1(IJ)=GG1(IJ,J)
01860        GO  TO  610
01870    560 FX1(IJ)=GG2(IJ,J)
01880    610 CONTINUE
01890    620 DO  720  K=1,JJ
01900        KN=2
01910        YLEFT=YY1(K)
01920        YRIGHT=YY1(K+1)
01930        IF(GG .LE. FX1(K) .AND. GG .GE. FX1(K+1)) GO TO 710
01940        IF(GG .GE. FX1(K) .AND. GG .LE. FX1(K+1)) GO TO 710
```

```
01950          GO  TO  720
01960     710 ZD1=FX1(K+1)-FX1(K)
01970         YD2=YY1(K+1)-YY1(K)
01980         YY=(GG-FX1(K))*YD2/ZD1+YY1(K)
01990         IF(IG .EQ. 2)  GO  TO  715
02000         WRITE(6,1000)  IG,I,K,GG,X,YY
02010         GO  TO  720

02020     715 WRITE(6,1010) IG,I,K,GG,X,YY
02030    1010 FORMAT(2X,*IG=*,I2,2X,*I=*,I3,2X,*K=*,I2,2X,
02040       1    *VEL=*,F6.1,2X,*X=*,F4.1,2X,*Y=*,F5.2)
02050    1000 FORMAT(2X,*IG=*,I2,2X,*I=*,I3,2X,*K=*,I2,2X,
02060       1    *SP=*,F6.1,2X,*X=*,F4.1,2X,*Y=*,F5.2)
02070     720 CONTINUE
02080         WRITE(6,975) K,X
02090     975 FORMAT(2X,*K=*,I2,2X,*X=*,F5.1)
02100     740 CONTINUE
02110         WRITE(6,980) J,X
02120     980 FORMAT(2X,*J=*,I3,2X,*X=*,F5.1)
02130     800 CONTINUE
02140         GO  TO  10
02150         END
02160 C
02200         SUBROUTINE SIMP1(Y,N,DEL,L,M,ANS)
02210         DIMENSION Y(1)
02220         SUM1=0
02230         DO  2  I=1,L
02240         I1=2*I
02250       2 SUM1=SUM1+Y(I1)
02260         SUM2=0
02270         IF(M)  5,5,3
02280       3 DO  4  J=1,M
02290         I2=2*J+1
02300       4 SUM2=SUM2+Y(I2)
02310       5 ANS=.333333333333*DEL*(Y(1)+Y(N)+4.*SUM1+2.*SUM2)
02320         RETURN
02330         END
```

```
$ NAM
LX        = 1.2E+01,
LY        = 2.0E+01,
A         = 2.4E+02,
IM        = 25,
JM        = 21,
NC        = 11,
IG1       = 1,
NSTOP     = 0,
IOP       = 0,
FACTOR    = 5.0E-02,
G1MAX     = 2.3E+03,
G2MAX     = 1.0E+02,
G1RANGE   = 1.0E+03,
G2RANGE   = 1.0E+02,
XDIV      = 1.2E+01,
IFLAG1    = 0,
IFLAG2    = 0,
IFLAG     = 0,
$END
```

CONSTANTS

		VELOCITY		FLOW PROPORTIONAL AVE.		SPATIAL AVE.	
J=	1	INTG2X=	8.7929E+01	INTG12X=	2.4306E+04	INTG1X=	2.8139E+02
J=	2	INTG2X=	8.0849E+01	INTG12X=	2.3247E+04	INTG1X=	2.8744E+02
J=	3	INTG2X=	7.6854E+01	INTG12X=	2.2711E+04	INTG1X=	2.9395E+02
J=	4	INTG2X=	7.5942E+01	INTG12X=	2.2937E+04	INTG1X=	3.0092E+02
J=	5	INTG2X=	7.8115E+01	INTG12X=	2.4112E+04	INTG1X=	3.0836E+02
J=	6	INTG2X=	8.4794E+01	INTG12X=	2.6816E+04	INTG1X=	3.1601E+02
J=	7	INTG2X=	9.6083E+01	INTG12X=	3.1180E+04	INTG1X=	3.2386E+02
J=	8	INTG2X=	1.0451E+02	INTG12X=	3.4894E+04	INTG1X=	3.3320E+02
J=	9	INTG2X=	1.0483E+02	INTG12X=	3.6438E+04	INTG1X=	3.4683E+02
J=	10	INTG2X=	1.0038E+02	INTG12X=	3.6514E+04	INTG1X=	3.6295E+02
J=	11	INTG2X=	9.5234E+01	INTG12X=	3.5608E+04	INTG1X=	3.7308E+02
J=	12	INTG2X=	9.0006E+01	INTG12X=	3.3498E+04	INTG1X=	3.7099E+02
J=	13	INTG2X=	8.4400E+01	INTG12X=	3.0790E+04	INTG1X=	3.6301E+02
J=	14	INTG2X=	8.1104E+01	INTG12X=	2.9323E+04	INTG1X=	3.5939E+02
J=	15	INTG2X=	8.1941E+01	INTG12X=	2.9958E+04	INTG1X=	3.6393E+02
J=	16	INTG2X=	8.4051E+01	INTG12X=	3.1240E+04	INTG1X=	3.7073E+02
J=	17	INTG2X=	8.3560E+01	INTG12X=	3.1304E+04	INTG1X=	3.7386E+02
J=	18	INTG2X=	8.0522E+01	INTG12X=	3.0156E+04	INTG1X=	3.7342E+02
J=	19	INTG2X=	7.5675E+01	INTG12X=	2.8177E+04	INTG1X=	3.7053E+02
J=	20	INTG2X=	6.9018E+01	INTG12X=	2.5417E+04	INTG1X=	3.6518E+02
J=	21	INTG2X=	6.0551E+01	INTG12X=	2.1950E+04	INTG1X=	3.5738E+02

ROW AVERAGES

A2= 1.702184E+03   A12= 5.876611E+05
G2BAR= 7.092432E+00   G12BAR= 3.452395E+02   G1BAR= 3.439082E+02

MEAN VALUES

Y	SP	Y	SP	Y	SP
X= 0.00					
C.	3.0353E+02	1.00E+00	2.8592E+02	2.00E+00	2.7553E+02
3.00E+00	2.7234E+02	4.00E+00	2.7636E+02	5.00E+00	2.9023E+02
6.00E+00	3.1412E+02	7.00E+00	3.3422E+02	8.00E+00	3.4199E+02
9.00E+00	3.4284E+02	1.00E+01	3.3958E+02	1.10E+01	3.2865E+02
1.20E+01	3.1443E+02	1.30E+01	3.1143E+02	1.40E+01	3.2828E+02
1.50E+01	3.5147E+02	1.60E+01	3.6355E+02	1.70E+01	3.6477E+02
1.80E+01	3.5846E+02	1.90E+01	3.4459E+02	2.00E+01	3.2319E+02
X= 1.00					
0.	2.9537E+02	1.00E+00	2.8398E+02	2.00E+00	2.7800E+02
3.00E+00	2.7745E+02	4.00E+00	2.8232E+02	5.00E+00	2.9441E+02
6.00E+00	3.1385E+02	7.00E+00	3.3120E+02	8.00E+00	3.4122E+02
9.00E+00	3.4722E+02	1.00E+01	3.4875E+02	1.10E+01	3.4221E+02
1.20E+01	3.3170E+02	1.30E+01	3.2808E+02	1.40E+01	3.3647E+02
1.50E+01	3.4889E+02	1.60E+01	3.5635E+02	1.70E+01	3.5806E+02
1.80E+01	3.5671E+02	1.90E+01	3.5199E+02	2.00E+01	3.4390E+02
X= 2.00					
0.	2.8668E+02	1.00E+00	2.8223E+02	2.00E+00	2.8124E+02
3.00E+00	2.8371E+02	4.00E+00	2.8964E+02	5.00E+00	2.9998E+02
6.00E+00	3.1482E+02	7.00E+00	3.2909E+02	8.00E+00	3.4077E+02
9.00E+00	3.5113E+02	1.00E+01	3.5675E+02	1.10E+01	3.5378E+02
1.20E+01	3.4630E+02	1.30E+01	3.4259E+02	1.40E+01	3.4539E+02
1.50E+01	3.5044E+02	1.60E+01	3.5386E+02	1.70E+01	3.5571E+02
1.80E+01	3.5671E+02	1.90E+01	3.5687E+02	2.00E+01	3.5619E+02
X= 3.00					
0.	2.7690E+02	1.00E+00	2.8055E+02	2.00E+00	2.8542E+02
3.00E+00	2.9149E+02	4.00E+00	2.9877E+02	5.00E+00	3.0736E+02
6.00E+00	3.1726E+02	7.00E+00	3.2795E+02	8.00E+00	3.4065E+02
9.00E+00	3.5455E+02	1.00E+01	3.6360E+02	1.10E+01	3.6358E+02
1.20E+01	3.5875E+02	1.30E+01	3.5565E+02	1.40E+01	3.5581E+02
1.50E+01	3.5689E+02	1.60E+01	3.5768E+02	1.70E+01	3.5818E+02
1.80E+01	3.5865E+02	1.90E+01	3.5906E+02	2.00E+01	3.5943E+02

EXPANDED
MATRIX
CONCENTRATION
DATA

(CONTINUES)

Y	VEL	Y	VEL	Y	VEL

X= 0.00

Y	VEL	Y	VEL	Y	VEL
0.	0.	1.00E+00	0.	2.00E+00	3.1954E-02
3.00E+00	4.9294E+00	4.00E+00	8.1768E+00	5.00E+00	9.5144E+00
6.00E+00	8.9230E+00	7.00E+00	7.7681E+00	8.00E+00	6.7795E+00
9.00E+00	5.4959E+00	1.00E+01	4.0990E+00	1.10E+01	2.4245E+00
1.20E+01	6.8234E-01	1.30E+01	0.	1.40E+01	0.
1.50E+01	3.8426E-01	1.60E+01	1.9805E-01	1.70E+01	0.
1.80E+01	0.	1.90E+01	0.	2.00E+01	0.

X= 1.00

Y	VEL	Y	VEL	Y	VEL
0.	0.	1.00E+00	1.1152E+00	2.00E+00	3.3428E+00
3.00E+00	5.1307E+00	4.00E+00	6.4788E+00	5.00E+00	7.3405E+00
6.00E+00	7.7122E+00	7.00E+00	7.8397E+00	8.00E+00	7.8660E+00
9.00E+00	7.7004E+00	1.00E+01	7.3279E+00	1.10E+01	6.5908E+00
1.20E+01	5.6700E+00	1.30E+01	5.0624E+00	1.40E+01	5.0880E+00
1.50E+01	5.2453E+00	1.60E+01	4.8668E+00	1.70E+01	3.9617E+00
1.80E+01	2.6572E+00	1.90E+01	9.5323E-01	2.00E+01	0.

X= 2.00

Y	VEL	Y	VEL	Y	VEL
0.	7.1645E+00	1.00E+00	6.2705E+00	2.00E+00	5.7031E+00
3.00E+00	5.4624E+00	4.00E+00	5.5482E+00	5.00E+00	6.0519E+00
6.00E+00	6.9801E+00	7.00E+00	7.8532E+00	8.00E+00	8.4185E+00
9.00E+00	8.3356E+00	1.00E+01	9.0260E+00	1.10E+01	8.8660E+00
1.20E+01	8.4897E+00	1.30E+01	8.2003E+00	1.40E+01	8.1660E+00
1.50E+01	8.1234E+00	1.60E+01	7.7398E+00	1.70E+01	7.0200E+00
1.80E+01	6.0272E+00	1.90E+01	4.7614E+00	2.00E+01	3.2225E+00

X= 3.00

Y	VEL	Y	VEL	Y	VEL
0.	1.1130E+01	1.00E+00	8.7881E+00	2.00E+00	7.0610E+00
3.00E+00	5.9487E+00	4.00E+00	5.4511E+00	5.00E+00	5.7155E+00
6.00E+00	6.7557E+00	7.00E+00	7.7896E+00	8.00E+00	8.3751E+00
9.00E+00	8.7928E+00	1.00E+01	9.0462E+00	1.10E+01	9.0773E+00
1.20E+01	8.9527E+00	1.30E+01	8.8556E+00	1.40E+01	8.8673E+00
1.50E+01	8.8607E+00	1.60E+01	8.6919E+00	1.70E+01	8.3629E+00
1.80E+01	7.9010E+00	1.90E+01	7.3064E+00	2.00E+01	6.5789E+00

EXPANDED
MATRIX
VELOCITY
DATA

(CONTINUES)

```
IG= 1   I=   6   K=15   SP= 345.2   X=  0.0   Y=14.73
IG= 1   I=   6   K=19   SP= 345.2   X=  0.0   Y=18.95
K=20   X=    0.0
IG= 1   I=   6   K= 9   SP= 345.2   X=  1.0   Y= 8.67
IG= 1   I=   6   K=11   SP= 345.2   X=  1.0   Y=10.54
IG= 1   I=   6   K=15   SP= 345.2   X=  1.0   Y=14.71
IG= 1   I=   6   K=20   SP= 345.2   X=  1.0   Y=19.83
K=20   X=    1.0
IG= 1   I=   6   K= 9   SP= 345.2   X=  2.0   Y= 8.43
IG= 1   I=   6   K=13   SP= 345.2   X=  2.0   Y=12.28
IG= 1   I=   6   K=14   SP= 345.2   X=  2.0   Y=13.95
K=20   X=    2.0
IG= 1   I=   6   K= 9   SP= 345.2   X=  3.0   Y= 8.33
K=20   X=    3.0
IG= 1   I=   6   K= 9   SP= 345.2   X=  4.0   Y= 8.26
K=20   X=    4.0
IG= 1   I=   6   K= 9   SP= 345.2   X=  5.0   Y= 8.19
K=20   X=    5.0
IG= 1   I=   6   K= 9   SP= 345.2   X=  6.0   Y= 8.10
K=20   X=    6.0
IG= 1   I=   6   K= 8   SP= 345.2   X=  7.0   Y= 7.91
K=20   X=    7.0
IG= 1   I=   6   K= 8   SP= 345.2   X=  8.0   Y= 7.64
K=20   X=    8.0
IG= 1   I=   6   K= 8   SP= 345.2   X=  9.0   Y= 7.31
K=20   X=    9.0
IG= 1   I=   6   K= 8   SP= 345.2   X=10.0   Y= 7.17
K=20   X=   10.0
IG= 1   I=   6   K= 8   SP= 345.2   X=11.0   Y= 7.26
K=20   X=   11.0
IG= 1   I=   6   K= 8   SP= 345.2   X=12.0   Y= 7.51
K=20   X=   12.0
```

LOCUS OF MEAN CONCENTRATION
PROFILES

(CONTINUES FOR OTHER
CONCENTRATIONS)

```
IG= 2   I=   6   K= 4   VEL=     7.1   X=  0.0   Y= 3.67
IG= 2   I=   6   K= 8   VEL=     7.1   X=  0.0   Y= 7.68
K=20    X=   0.0
IG= 2   I=   6   K= 5   VEL=     7.1   X=  1.0   Y= 4.71
IG= 2   I=   6   K=11   VEL=     7.1   X=  1.0   Y=10.32
K=20    X=   1.0
IG= 2   I=   6   K= 1   VEL=     7.1   X=  2.0   Y=  .08
IG= 2   I=   6   K= 7   VEL=     7.1   X=  2.0   Y= 6.13
IG= 2   I=   6   K=17   VEL=     7.1   X=  2.0   Y=16.90
K=20    X=   2.0
IG= 2   I=   6   K= 2   VEL=     7.1   X=  3.0   Y= 1.98
IG= 2   I=   6   K= 7   VEL=     7.1   )=  3.0   Y= 6.33
IG= 2   I=   6   K=20   VEL=     7.1   X=  3.0   Y=19.29
K=20    X=   3.0
IG= 2   I=   6   K= 3   VEL=     7.1   X=  4.0   Y= 2.41
IG= 2   I=   6   K= 7   VEL=     7.1   X=  4.0   Y= 6.11
K=20    X=   4.0
IG= 2   I=   6   K= 3   VEL=     7.1   X=  5.0   Y= 2.83
IG= 2   I=   6   K= 6   VEL=     7.1   X=  5.0   Y= 5.71
IG= 2   I=   6   K=10   VEL=     7.1   X=  5.0   Y= 9.34
IG= 2   I=   6   K=16   VEL=     7.1   X=  5.0   Y=15.93
K=20    X=   5.0
```

LOCUS OF MEAN
VELOCITY
PROFILES

(CONTINUES FOR
OTHER PROFILES)

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4. TITLE AND SUBTITLE Continuous Measurement of Gas Composition from Stationary Sources		5. REPORT DATE July 1975
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) E. F. Brooks, C. A. Flegal, L. N. Harnett, M. A. Kolpin, D. J. Luciani, and R. L. Williams		8. PERFORMING ORGANIZATION REPORT NO.
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15. SUPPLEMENTARY NOTES

16. ABSTRACT

 The program objective was to develop and evaluate methods for the continuous measurement of gaseous emissions from stationary sources, specifically in large or complex ducts where total flow processing techniques are not practical. This report is concerned with the measurement of mean gas concentrations in rectangular ducts. Work consisted of a review of related programs, development of a computer program to assess stratification levels and evaluate sampling techniques, formulation and evaluation of point sampling methods for continuous monitoring, development of a multi-port continuous gas sampling probe, and field demonstration of hardware and techniques. Results showed that emissions can be accurately monitored using as few as one flow sensor and one sampling probe, even in the presence of significant velocity and compositional stratification, although stratification levels were too high for single point samples to be acceptable. It was shown for all data examined that good accuracy can be attained by taking a spatial concentration average -- flow proportional sampling is not required. The field demonstration verified the acceptability of the proposed methodology.

17.		KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS		c. COSATI Field/Group
Air Pollution Flue Gases Chemical Analysis Continuous Sampling Measurement Stratification		Air Pollution Control Stationary Sources		13B 21B 07D 14B

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