AUTOMATIC MONITORING SYSTEMS FOR DETERMINING TIME WEIGHTED AVERAGE WORKPLACE LEVELS:

FOURIER INFRARED INTEREFEROMETERS

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ABSTRACT

A description of a unique approach to area monitoring for vinyl chloride, incorporating high resolution, high sensitivity Fourier Transform Infrared technology. The toxic gas monitoring system is specifically designed with the high resolution, sensitivity and speed capability to provide full compliance with OSHA regulations concerning requirements for monitoring vinyl chloride as well as other toxic gases. The system features unique sampling algorithms providing for multi-level sampling sequences based on adaptive techniques, provides for alarm annuciation and provides the statistical processing for required record keeping.

The basic gas analyzer consists of a rapid scanning Michelson interferometer modulator with beamsplitter, and infrared source, infrared detector, Wilks 40 meter sample cell and the required optics in its own free-standing optical bench and electronics console housing the system controller, data acquisition unit, minicomputer and recorder, audio alarm and I/O terminal for programming, systems diagnostics and printing the eight hour averages and alarm excursions.

Applications of the monitoring system will be discussed in detail for VCM as well as for other toxic compounds.

SUMMARY

I Requirements

The monitoring system must be viewed in light of the following major requirements:

- Speed
- Sensitivity
- Specificity
- Multi-compound adaptability
- Multi-sample station adaptability
- Output adaptability for comprehensive display and recording

The requirement for speed is obvious if one considers the aspect of multiple sampling points and the ability to detect toxic excursions that are of a transcient nature which must be considered in time weighted averages. The sensitivity requirement is also obvious as is the specificity. The better the specificity, the higher the integrity of the monitoring system. The ability to monitor more than one compound from a sample point is both a cost and performance advantage but further than that, the system should be capable of changing the compound to be monitored if required. The last two requirements are self-explanatory, and the specific details of sample point location, alarm annunciation, data recording (T.W.A.'s, alarm excursions, etc.) are a function of the individual monitoring installation.

II Technique

The study and analysis of compounds by observing their spectra in the infrared radiation region has long been performed. With the advent and implementation of Fourier Transform Infrared analytical equipment (FT/IR), the technology is well established in the laboratory. Second generation FT/IR equipment is now available which has been designed to bring the laboratory measuring the analytical capability to bear on industrial monitoring problems. The FT/IR technology satisfies all of the requirements of the prime sensor for a comprehensive area monitor yet is rugged enough and reliable enough to perform in the industrial environment. The result is a highly sensitive, fast, extremely specific sensor which requires no consumables, does not lose calibration, and is direct reading for most toxic compounds.

III System

The basic monitoring system consists of three major elements:

- Measurement Bench
- Controller and Data System
- Output and Display Interface

The measurement bench consists of the prime interferometer modulator, infrared source, infrared detector and pre-amp electronics, transfer optics and measurement (sample) cell.

The controller and data system consists of the signal conditioning electronics, analog-to-digital conversion, minicomputer, and digital interfaces to the computer and for output display. The function of this element is for data acquisition, measurement (concentration) calculation, parameter monitor and control and measurement bench control.

The output and display interface incorporates a printer and keyboard for operator control as well as a "dry contact" relay interface for alarm annunciators and mimic panel displays. This section annunciates the eight TWA data, excursion alarm messages, parameter diagnostics and measurement statistics.

IV Adaptive Control

Because the basic system incorporates a minicomputer, the system is easily adapted to what normally would be difficult and sophisticated monitoring techniques. For example, consider multi-level sample point control. Plants and plant processes for VCM can be characterized by virtue of where the potential VCM leaks can occur. By incorporating this data and considering the current concentration levels being measured, the system can automatically adapt the sampling point sequence to optimize the measurement function. Another obvious extension is the automatic calculation of worker TWA's based on his movements within the work area.

INTRODUCTION

The FMS^R Monitoring Concept

The EOCOM FMS 7200 Gas Monitoring and Analysis system consists of a high performance prime sensor based on Fourier Multiplex technology, with an integrated data acquisition, analysis and display system. EOCOM Corporation has conducted extensive development efforts and field application studies relating to industrial instrumentation systems for comprehensive real-time, multi-gas monitoring and analysis.

The EOCOM FMS 7200 Gas Monitoring System is a versatile and general gas monitor, capable of monitoring several gases simultaneously from as many as several hundred locations. The monitor is highly selective, thus reducing the chance of interference from other gases (false alarms); and highly sensitive, allowing part per billion measurement of most of the different gaseous substances currently listed by OSHA.

The EOCOM Toxic Gas Monitoring System has demonstrated its reputation for high reliability (better than 90 percent up-time) and extemely stable measurement performance combined with high sensitivity. It can be programmed to monitor one or more of most any of the gaseous substances listed by OSHA in the regulations outlined in the Federal Register 1910.70, Volume 39, Number 125, dated June 27, 1974.

The system has the capability to automatically monitor the concentration of the selected gases at multiple sample points, control alarms and keep detailed records of station TWA (time weighted average) and, optionally, employee TWA. The sampling sequence is tailored to the plant site.

Options can be included such that stations will be sampled on demand from the central control or remotely. The automatic sampling and concentration measurements as well as all calculations, alarms and reports are program-controlled by the system minicomputer.

The block diagrams in Figures 1 and 1a show the major functions of the FMS[R] 7200 with all options. At the center is the system minicomputer which controls all functions. Sample gas is selected by the transfer manifold. The prime sensor determines the gas concentration. The employee TWA is determined from the employee data and/or badge reader inputs, The plant mimic panel, remote panels, alarms and controls, printer and CRT display terminal indicate the state of the system; alarm conditions, TWA reports and action taken to eliminate the alarm, if any.

The device in the FMS 7200 which actually determines the concentration (the prime sensor) is a fully-automated high-performance infrared spectrometer. Infrared spectroscopic techniques have been utilized for many applications through the years, ranging from atmospheric studies to chemical analysis. The infrared analytic technique is well founded with literally tens of thousands of infrared spectra on file for ready reference. The technique has proved to be a most useful method for identifying the chemical makeup of a substance as well as determining the concentration of each constituent.

The power of the Fourier method lies in the tremendous information capacity of the "interferogram" signal. This signal is processed by the computer to obtain highly selective information about a particular gas (s). The selectivity is extremely important because it means few, if any, interferences. In fact, and here is a major advantage, interferences can be eliminated by a <u>software change only</u>. This unique advantage is available because of the large information content in the Fourier signal. The fact that all this information is available allows the 7200 monitor the concentrations of several gases simultaneously.

An optional feature of the sampling algorithm is called "adaptive sampling". This means several stations can be sampled simultaneously and randomly, according to probable leakage of the contaminants. In other words, stations which are least likely to leak are sampled less often. Adaptive sampling reduces considerably the net time to detect a leak of the toxic agent and to isolate its source.

Another advantage of any infrared technique is that it uses no consumables other than standard utilities. There is little operating cost to the FMS[R] 7200. In Table 1, the major features and advantages are outlined.

TECHNICAL DISCUSSION

Interferometer Spectrometer Theory

A scanning Michelson interferometer is shown schematically in Figure 2. It consists of two perpendicular plane mirrors (A and B) and a semi-reflecting film, or beamsplitter mounted at 45^{0} to mirrors A and B. Mirror B is stationary, while mirror A is scanned at a constant velocity v(cm/sec). The infrared beam under investigation is brought to the interferometer on an optical axis perpendicular to mirror A. The partially reflecting beamsplitter divides the incident beam into two separate beams, one passing to mirror B and the other to mirror A. The two beams then recombine at the

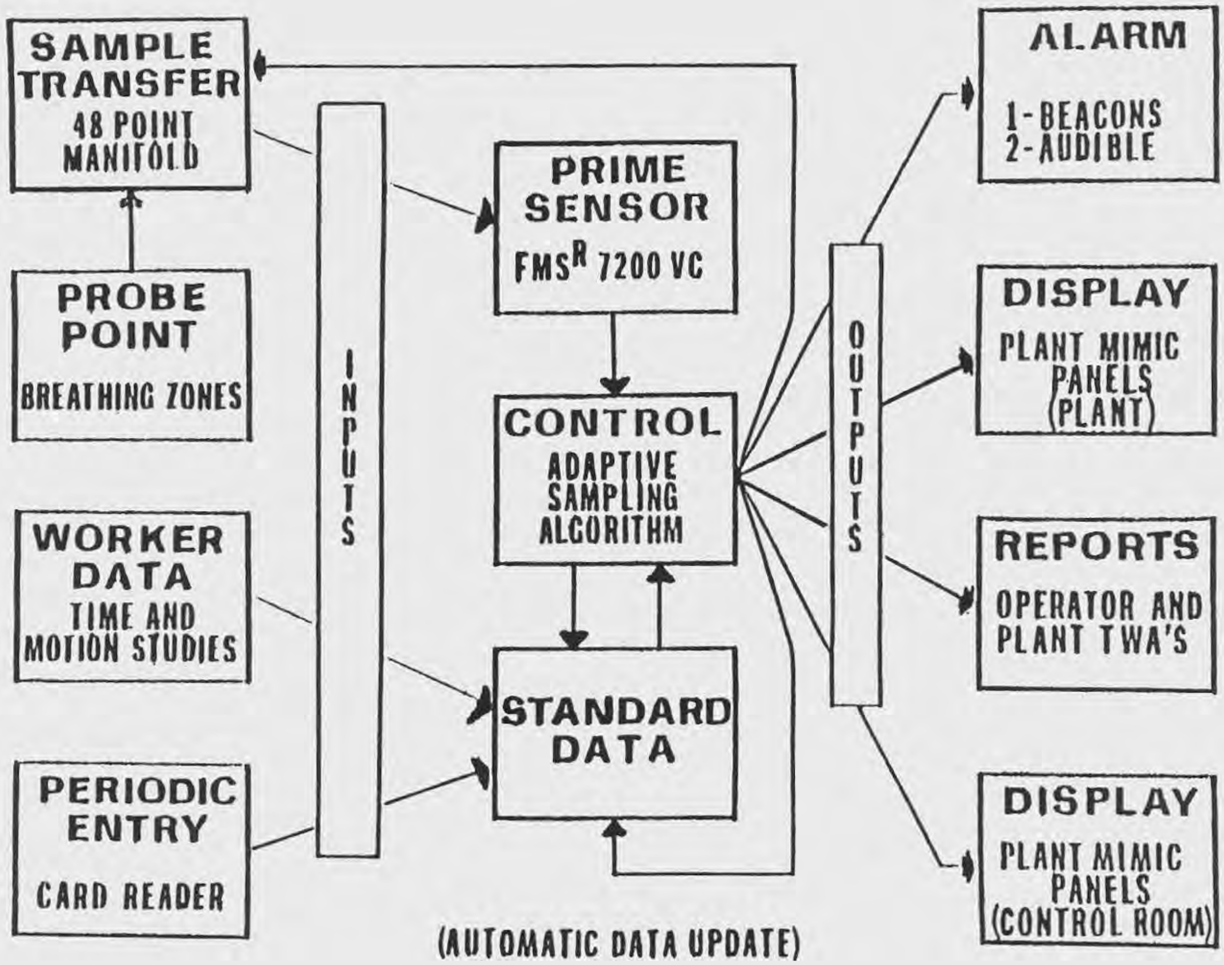


Figure 1. VCM monitoring system.

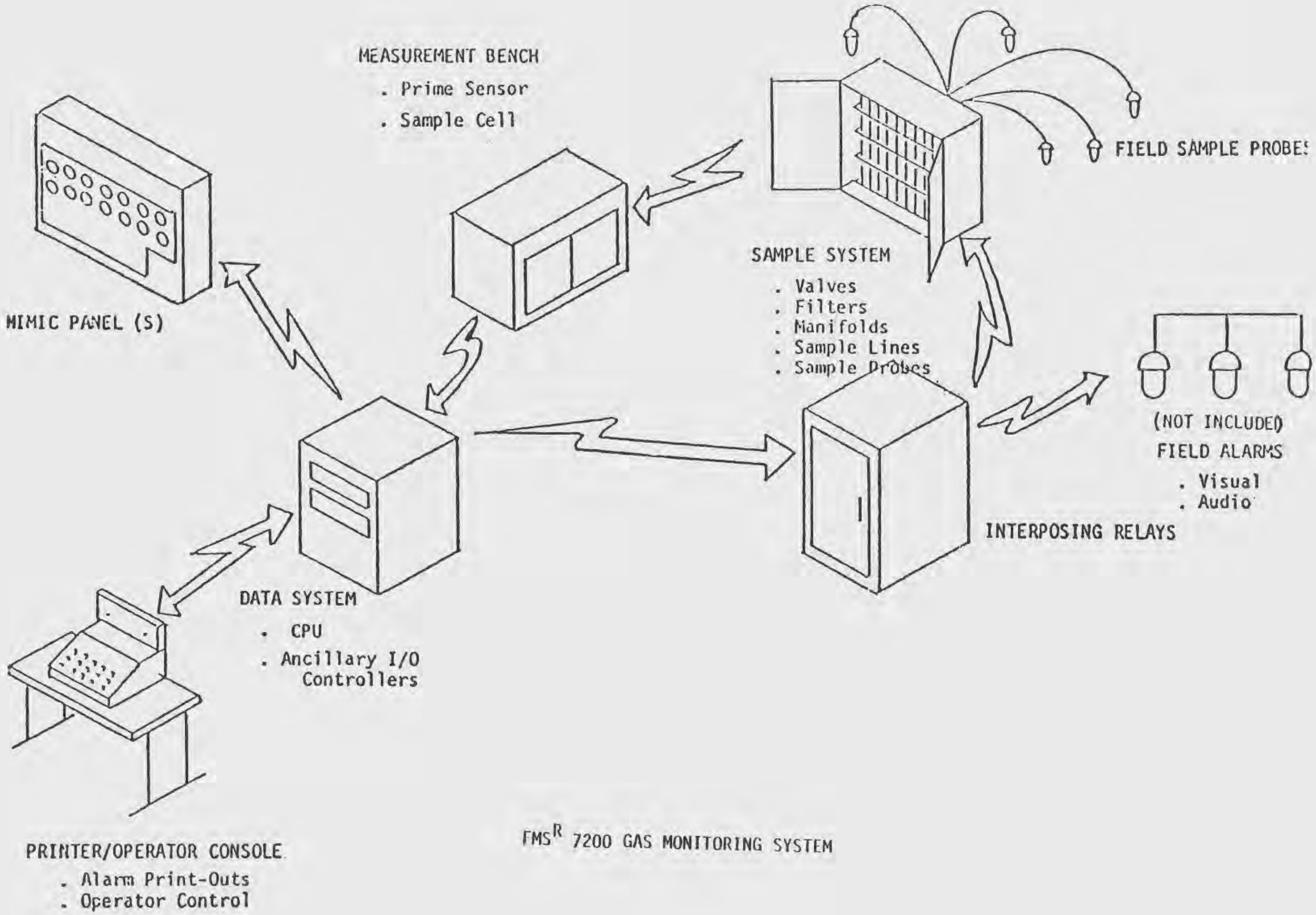

MEASUREMENT BENCH
. Prime Sensor
. Sample Cell
FIELD SAMPLE PROBES
MIMIC PANEL (S)
SAMPLE SYSTEM
. Valves
. Filters
. Manifolds
. Sample Lines
. Sample Probes
(NOT INCLUDED)
FIELD ALARMS
. Visual
. Audio
INTERPOSING RELAYS
DATA SYSTEM
. CPU
. Ancillary I/O Controllers
PRINTER/OPERATOR CONSOLE
. Alarm Print-Outs
. Operator Control
FMS[R] 7200 GAS MONITORING SYSTEM

Figure 1a.

Table 1. Advantages of FMS[R] gas monitor.

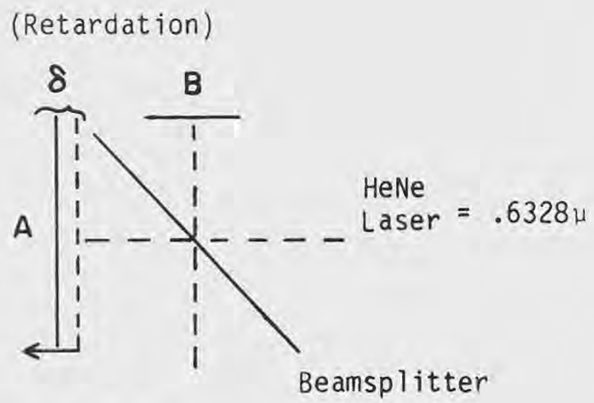
- High specificity and sensitivities
- Fast measurement time
- Eliminate interference with software change
- Accepted by OSHA equivalent personal monitoring
- Multi-gas capability, monitor several gases simultaneously
- Adaptive sampling, find leaks faster
- TWA records, as required by Federal Regulations
- Alarms and controls, for fast corrective action
- Reliable, only one moving part
- Unattended operation
- Low operating cost, consumes only water, air and electricity
- Automatic "zero" calibration
- No span drift
- Wide dynamic range (won't clog)
- Field proven - 99 percent up-time

beamsplitter. The beam traveling to mirror A passes through a pathlength different from that traveled by the beam going to mirror B. Therefore, when the two beams are recombined, they interfere, either constructively or destructively. The intensity of the exit beam of the interometer I (δ,λ) is a function of the optical path difference (OPD) and between the beams reflected from mirrors A and B. The functional dependence of δ is measured in units of wavelength of the indicent infrared beam (λ). The actual expression for I (δ,λ) is:

$$I(\delta,\lambda) = 0.5\ H(\lambda)\ B(\lambda)[1 + M(\lambda) \cos \frac{2\pi\delta}{\lambda} + \theta\lambda]$$

where B (λ) is the intensity of the energy of the incident bean, $H(\lambda)$ less than unity, represent the departures from the actual spectral intensity B (λ) due to instrument characteristics, $\theta\lambda$ is a phase shift instrument function (unavoidable phase shifts from beamsplitter, detector and electronics), and $M(\lambda)$ (less than unity) is the modulation efficiency that represents the departure from theoretical performance of the beam-splitter and optical system.

Schematic Diagram
Scanning Michelson Interferometer



vm = .4 cm/S

$$f = \frac{2vm}{\lambda} = \frac{2 \times .4 \text{ cm/s} \times 10^4 \ \mu\text{/cm}}{.6328\mu} = 12{,}642.2 \text{ Hz}$$

For vm - 0.4 cm/s

λ	f
.6328μ	12,642.2 Hz
1.0μ	8,000 Hz
2.0μ	4,000 Hz
4.0μ	2,000 Hz
10.0μ	800 Hz
100.0μ	80 Hz

A continuum of these contained in interferogram as cosine waves with amplitude directly related to IR intensity.

Figure 2. Frequency to wavelength conversion - one mirror velocity.

The Interferogram

In a scanning Michelson interferometer the OPD (δ) is varied continuously by moving mirror A at a constant velocity. The effect of this sweeping is to modulate the output intensity $I(\delta,\lambda)$ in a sinusoidal fashion with a frequency $f(\lambda,v)$ that depends on wavelength λ and mirror velocity v,

$$f(\lambda,v) = \frac{2v}{\lambda}$$

The factor of two arises from the fact that a displacement of the moving mirror changes the OPD, or retardation, by twice that amount. The incident beam is a broad band source with a continuum of energy with respect to wavelength. Yet each frequency is modulated independently (each cosine function is linearly independent of all other cosine functions of different frequency) and can be sorted from the continuum by a Fourier Transform. Because of this independence, the modulated exit beam may be focused directly on an infrared detector without monochromatic filtering for a specific wavelength. The entire incident spectrum is recorded in a multiplexed form by the detector during a scan of the moving mirror.

The multiplex function is referred to as the interferogram $i(\delta)$,

$$i(\delta) = \int_0^\infty I(\nu) \cos (2\pi\nu\delta + \theta\nu) \cdot d\nu$$

whereas is in units of cm^{-1} or Kyser's and is defined as the number of wavelengths per cm, i.e., proportional to the frequency of the IR energy and this is proportional to $1/\lambda$. From the equations given above,

$$I(\nu) = .5\ H(\nu)\ B(\nu)\ M(\nu)$$

The interferogram is a function of δ. This parameter δ varies with a constant velocity and therefore $i(\delta)$ has a definite bandwidth of frequencies that is determined by the bandwidth of $I(\nu)$ and the moving mirror velocity v. For typical mirror velocities and IR spectra the frequency bandwidth f max is on the order of 10KHz. A typical interferogram is shown in Figure 3.

The interferogram $i(\delta)$ is sampled at equally spaced intervals with an analog to digital converter system. These intervals must be spaced close enough so that the complete interferogram is accurately represented by the sampled points. This sample spacing is controlled by an HeNe laser fringe reference system which assures correct sample accuracy as well as wavelength accuracy in the resultant spectra (see Figure 4). The fact that the interferogram has a finite bandwidth allows us to use the sampling theorem to specify a minimum necessary sample spacing (maximum necessary sample frequency). If bw is the bandwidth of the IR incident beam, then the sampling theorem states that the sampling frequency ν_{sp} must be at least twice that, $\nu_{sp} = 2\nu_{bw}$ (Nyquist Criteria).

Or in terms of OPD the sample spacing δ_{sp} must satisfy

$$\frac{1}{\delta_{sp}} \geq 2\nu_{bw}$$

Once the interferogram is digitized and stored in a manner accessible by a computing system, the digitized equivalent of a complex Fourier Transform can be performed on the interferogram to decode the multiplexed information to obtain a complex spectrum

$$I_R(\nu) + j\ I_I\ (\nu) = \int_0^\infty i\ (\delta)\ e^{-2\ \pi j\delta\nu} d\ \delta$$

The integration of i (δ) provides the identity.

$$I_R(\nu) = I(\nu)\ \cos\theta_\nu$$

$$I_I(\nu) = I(\nu)\ \sin\ \theta_\nu$$

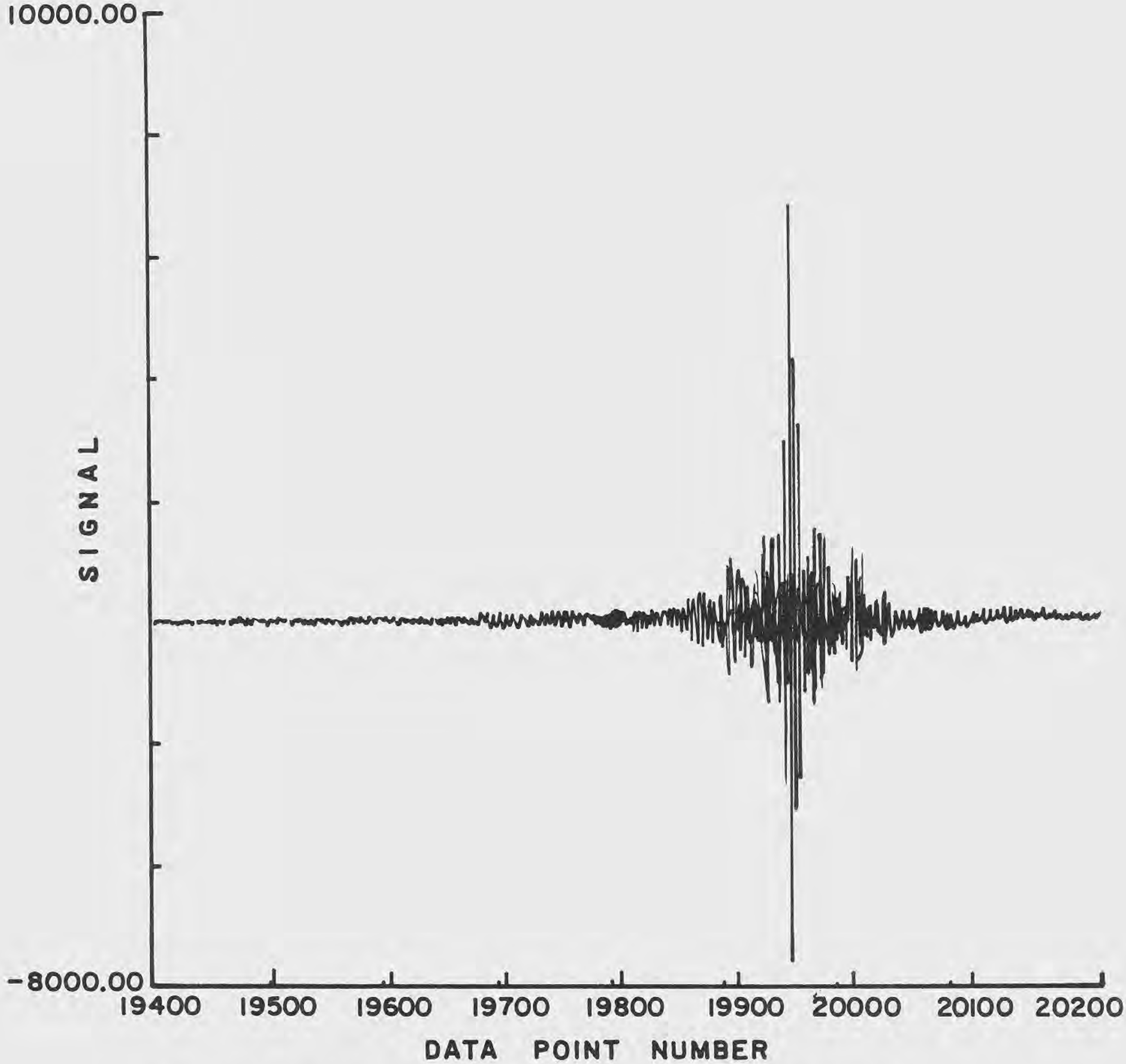
To eliminate the instrumental effects that introduced the phase angle one has to perform the process of phase correction. In this process is measured as a property of the instrument and then one can calculate $I(\nu)$ via a linear transformation using the identity equations (Multiply the first equation by cos $\theta\nu$ and the second by sin $\theta\nu$ then add the two equations.)

$$I(\nu) = I_R(\nu)\ \cos\ \theta_\nu + I_I(\nu)\ \sin\theta\nu$$

In this way $I(\nu)$ can be calculated from the measured interferogram $i(\delta)$. Figure 5 is a typical spectral result of this calculation.

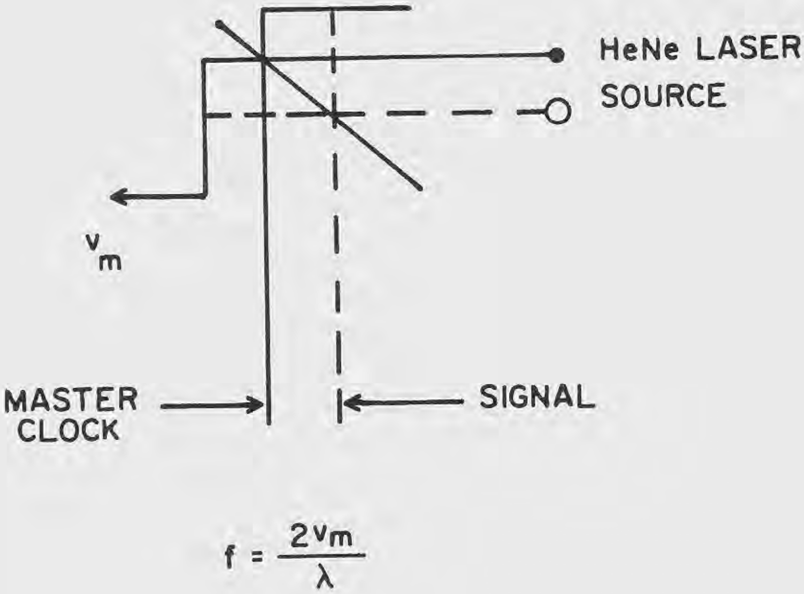
In the above derivations the interferogram has been assumed infinite in extent. However, in reality the moving mirror can only sweep out a finite optical path difference (X). The effect of finite mirror travel can be understood intuitively by considering a spectrum consisting of two closely separated spectral lines ν_1 and ν_2. The interferogram consists of the sum of two cosines of nearly equal frequency. As the retardation is increased ultimately the two cosines get out of phase and "beat" is observed. The observation of this beat is sufficient and necessary to distinguish between the two frequencies and therefore resolve the two spectral lines. The beat frequency is the difference of the two frequencies $(\nu_2 - \nu_1)$ and thus the period (or retardation) for the beat is $(\nu_2-\nu_1)^1$. Therefore the resolution of a Michelson interferometer $\Delta\nu$ is given by

$$X = \Delta\nu^{-1} \text{ or } \Delta\nu = \frac{1}{X}$$



This is an average of interferograms 2 and 3 from input tape labeled spectra

Figure 3. Typical interferogram.



RESULT

0.01 cm^{-1} WAVELENGTH STABILITY

Figure 4. Wavelength accuracy.

Wavelength Calibration

- Knowledge HeNe wavelength
- Mirror velocity
- Angle through interferometer

If mirror velocity changes

- Master clock tells computer
- Thus, at all times, the frequencies calculated by system are referenced to HeNe laser, which is simultaneously measured with each spectrum

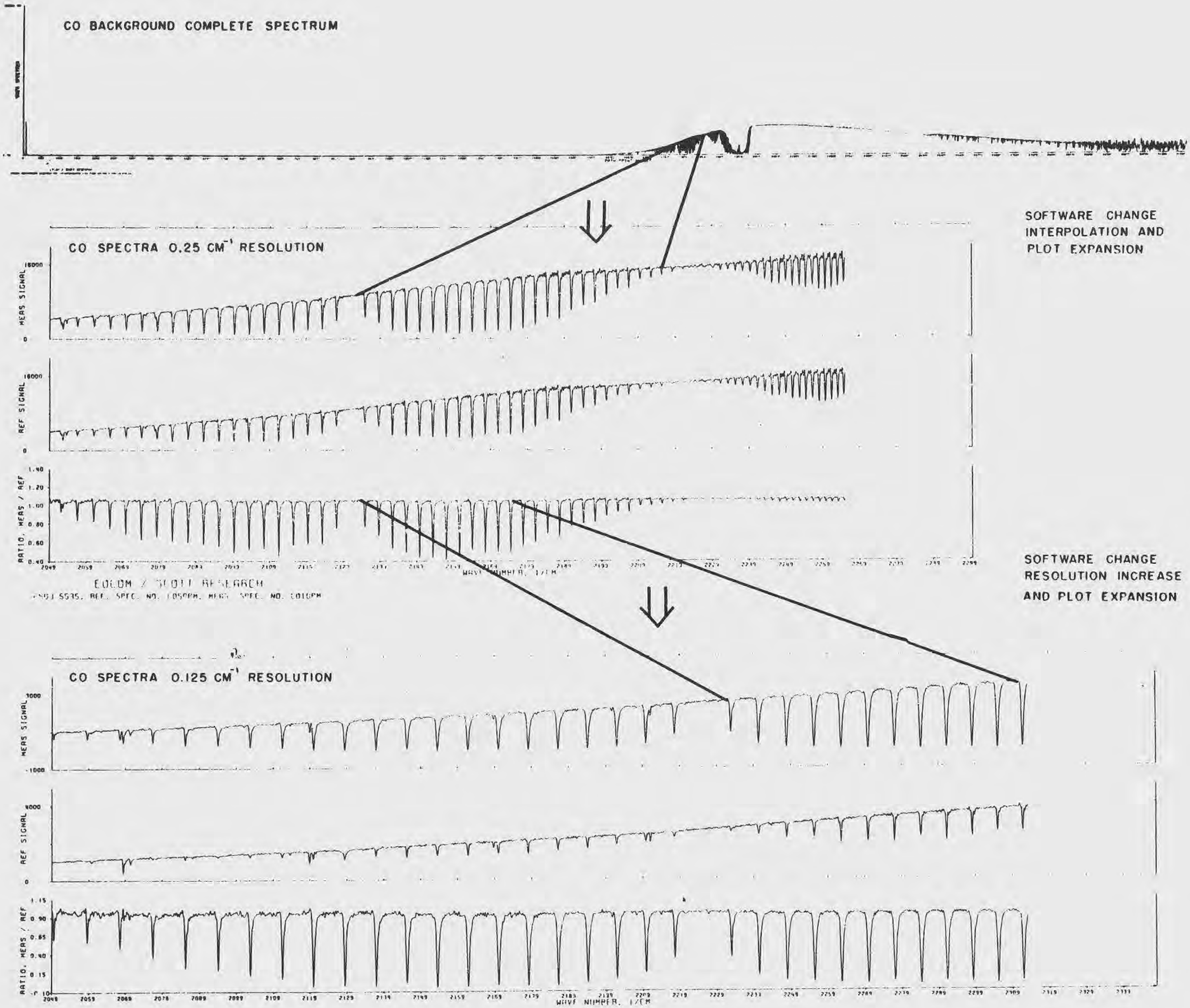


Figure 5. CO Spectra.

Figure 6 gives the equation for the resolution as defined at the half-power points.

Resolution of an interferometer spectrometer is also a function of the uniqueness of the OPD across the moving mirror. If a significant portion of the extended IR beam traverses a different OPD from that of another portion of the IR beam, then the resolution will be degraded. If this error distance δ_e is of the order 1/2 of a wavelength, then the interferometer will not produce a useable interferogram for that wavelength. This criteria places upper bounds on the flatness of all the optical components of an interferometer and also on the properties of the scanning system (i.e., allowable tilt). This also places a restriction on the divergence half angle, α of the incident optical radiation, δ_e for the extreme ray will reach $\frac{1}{2}\lambda_{min.}$ at an OPD of $1/\Delta\nu$. Therefore, the maximum divergence half angle tha can be allowed for a resolution at a frequency ν_{max} is given by:

$$a = \sqrt{\frac{\Delta\nu}{\nu_{max.}}}$$

FMS[R] 7200 Analytical Method

The FMS 7200 analytical technique used in the Monitoring Mode (gaseous compound concentration measurements) is based on the attenuation of IR radiation at the characteristic absorption frequencies of the particular toxic gas of interest. The basis of the technique is illustrated in Figure 7. As shown, the toxic gas has characteristic absorption at several frequencies (cm^{-1}). There are also regions in the spectrum where the gas does not absorb. The amount of absorption is given by the following relationship:

$$I\nu/I\nu_0 = e^{-\alpha_\nu cl} \qquad (1)$$

where $\alpha\nu \simeq$ absorption coefficient

$c \simeq$ concentration

$L \simeq$ absorption path length

$I\nu \simeq$ Intensity at the absorption frequency

$I\nu_0 \simeq$ avg. of reference Intensities

The reference frequency intensities allow determination of $I_0\nu$ which is the intensity value at the absorption frequency if no gas were present. I_ν and $I_{\nu 0}$ are constantly measured values for each individual

SPECTRAL RESOLUTION: LINE WIDTH AT HALF MAXIMUM OF INTENSITY

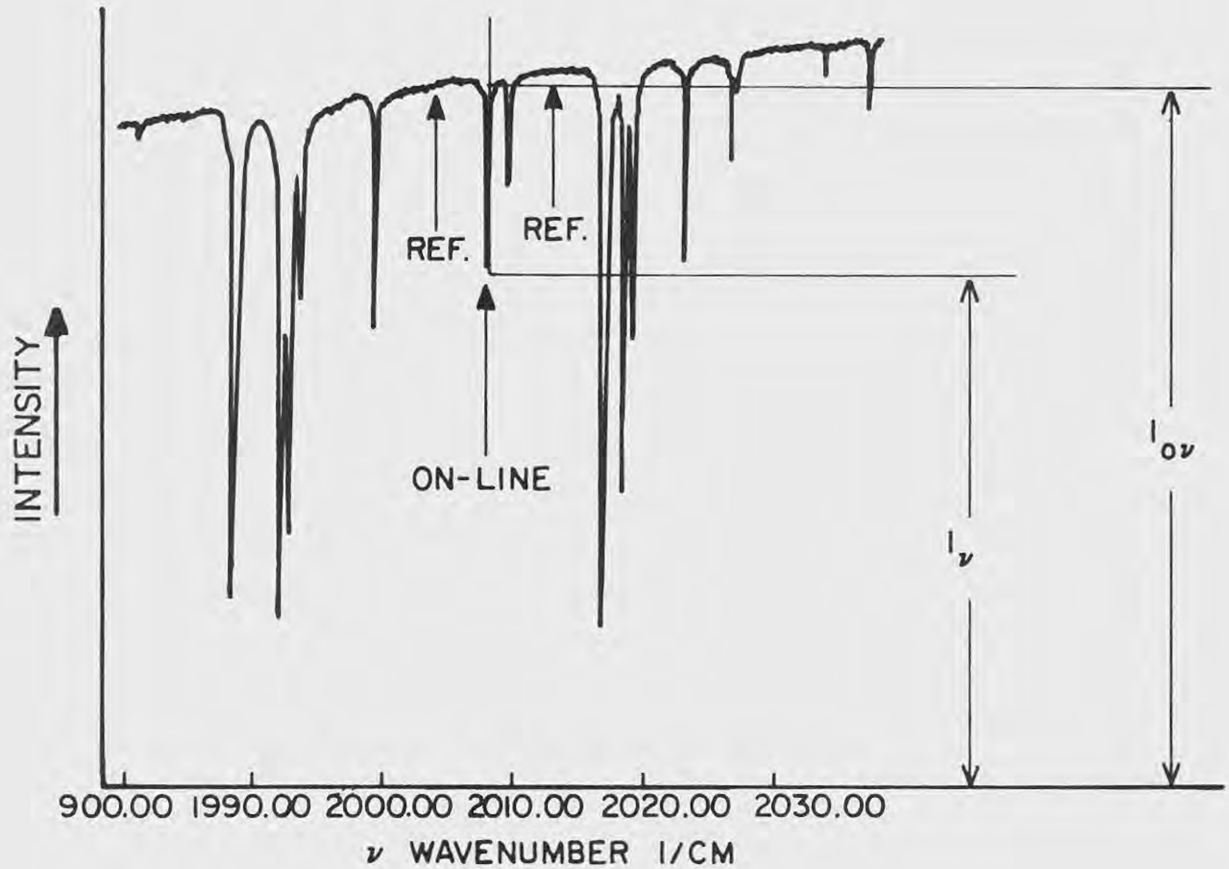
RELATIONSHIP FOR INTERFEROMETER: $\Delta \nu_{\frac{1}{2}} = \frac{1.22}{2\ L}$

L = Optical path difference in the two arms of the interferometer

ATMOSPHERIC LINE WIDTHS: $\sim 0.1 - 0.5\ CM^{-1}$

Figure 6. Resolution Criteria for Fourier transform spectrometers.

INFRARED ABSORPTION APPROACH



$$I_\nu / I_{o\nu} = e^{-a_\nu pcL}$$

$$c = \frac{1}{a_\nu pL} \ln\left(\frac{I_{o\nu}}{I_\nu}\right)$$

$I_{o\nu}$ Avg: $(I_{ref.})$

a_ν = absorption co-efficient

p = pressure

c = concentration

L = path length

Figure 7.

sample measurement.

The absorption coefficient ($\alpha\nu$) is a characteristic constant of the toxic gas to be measured and L the pathlength is fixed for any given measurement. Therefore, everything is known in Equation (1) and therefore can be rearranged to yield concentration which is given in Equation (2).

$$C = \frac{1}{\alpha\nu \ L} \ln \left(\frac{I_\nu}{I_{0\nu}} \right) = \quad (2)$$

The process of the FMS 7200 analytical method is to measure I_ν and $I_{0\nu}$ which requires a three frequency measurement per gas and from these determine concentration. This measurement is then repeated in sequence for the required number of sampled points. Similar type calculations are performed for other gases either simultaneously or in sequence depending on the sensitivity and time requirements. This technique has many inherent advantages derived from the interferometer Fournier Multiplexed Instrument. The system provides a multitude of spectral frequencies for performing the analysis in addition to the sensitivity and specificity advantage of an interferometer type system.

This analytical technique provides internal spectral intensity stability. As shown in Figure 8 . The signals S1 and S2, the reference line signals from which S3 is determined, have a lever arm effect which reduces the effect of small changes in S1 and S2. Therefore, any of the sources of drift such as electronics, source temperature, detector or wavelength are self-compensating.

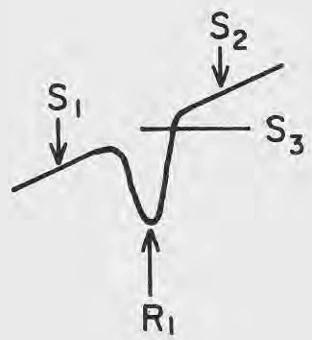
System Specificity

By selecting lines properly there are several ways to avoid interferences. The first is with the spectral resolution capability of the system; a region is selected for the spectral line measurements which is clear of any interferences. This is generally the case because of the large number of spectral elements provided by the interferometer system (high resolution capability).

Another approach is to use line selection and redundancy in the "subtract interference" mode, as shown in Figure 9 . This technique is measuring both the interfering gas and the gas of interest and subtracting out the effect of the interferent. There are, in general, two types of situations for interfering gases. The first, which is illustrated in Figure 9a, in which the gas of interest is partially overlapped by the interfering gas. In this case,only a fourth measurement frequency need be included in order to determine the concentations of the two (2) different gas species.

The second case is illustrated in Figure 9b , where the interfering gas completely overlaps the gas of interest. In this case, two additional measurement frequencies from which to measure the concentration of the toxic

NOTE: Lever arm effect reduces effect of small changes in S_1, or S_2 on S_3.



- o S_1 and S_2 used to determine S_3

- o System drifts

  - o Electronic
    Effect S_1, S_2, and R_1
  - o Source temperature
    Can change by 300°C with less than a 10% effect on the calibration at the sensitivity of the system
  - o Detector
    Effect S_1, S_2, and R_1 same
  - o Wavelength
    Does not drift within accuracy of measurement

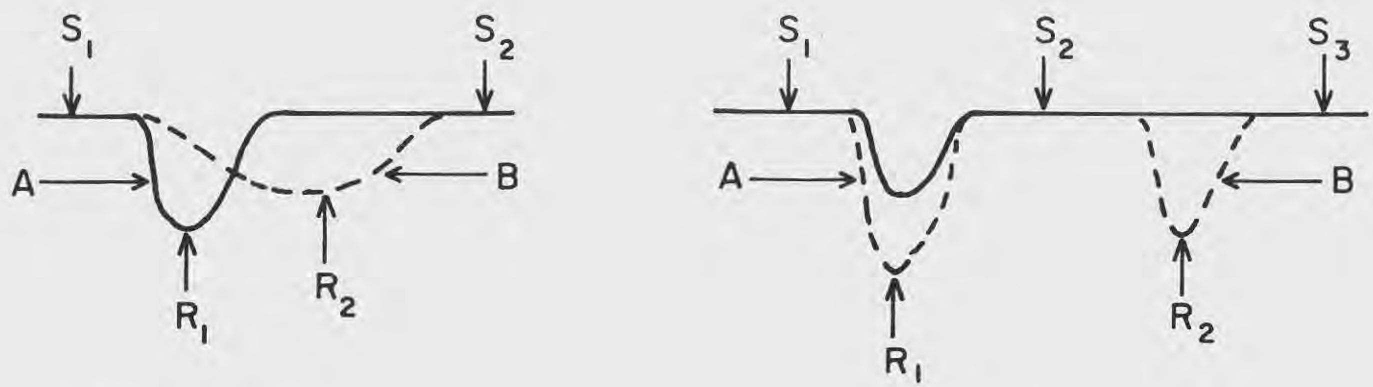
Figure 8. Internal stability.

a

Subcontract Interference Mode

b

Substract Interference Mode



(a)

o Concentration

$S_1 \cdot R_1 \cdot S_2 : C_{A + B}$
$S_1 \cdot R_2 \cdot S_2 : C_B$
$C_{A + B} - C_b = C_A$

o Check

S_1, S_2

(b)

o Concentration

$S_1 \cdot R_1 \cdot S_2 : C_{A + B}$
$S_2 \cdot R_2 \cdot S_3 : C_B$
$C_{A + B} - C_B = C_A$

o Check

S_1, S_2
S_1, S_3
S_2, S_3

Figure 9. Line selection and redundancy.

gas. In both cases the reference lines are used as internal reference checks for insuring proper and stable operation of the analytical method.

A third method to avoid interference problems utilizes spectral features. In this case, the spectral feature of the gas of interest must be sharper than the interfering gas. As indicated, the reference lines are set at equal absorption coefficient values of the interfering gas and the concentration determined in the normal fashion.

These same techniques may be applied to liquid and solid samples for analytical determination of concentration of known samples. The only difference will be that the spectral features of these type samples are much broader in nature and therefore can be determined with lower spectral resolution than is required for gas phase work. Also, the sample handling and transmission cells will be different based upon the particular measurement requirements.

The analytical technique described above requires a prior knowledge of the spectral characteristics of the sample and interferences for any given measurement requirement. Therefore a spectra must be generated of the sample and interferences in order to properly select the spectral frequencies to apply the analytical technique. The user may acquire this data or EOCOM Corporation will provide this analytical service.

EOCOM's analytical laboratories in Irvine provide this fulll spectral capability. The broad spectral variations may be obtained on the samples of pure gas, of suspected interferences and samples of the work atmosphere. This spectra are stored on disk and readily available for analysis. The capabilities of EOCOM's full spectral data system with the advanced software and scope display allow rapid data acquisition, rapid Fourier transformation, and easy spectral analysis to arrive very rapidly at the proper set of conditions to apply the analytical method.

Determining the Plant Environment and Employee Exposures

During an eighteen (18) month period, EOCOM Corporation, in conjunction with the Pantasote Company of New York, has very carefully studied the concept of area monitors in conjunction with the following objectives:

- Fast Excursion Detection
- Accurate Employee TWA's
- Eliminate Requirements for Personal Sampling
- Management Information System to Aid in Achieving OSHA "Performance" Standards

After a thorough study, it was decided to embark on a measurement program to find out the in-plant variables involved in trying to achieve the objectives. In order to do this we then proceeded to:

- Quantify the Nature of Gases in the Work Environment
- Determine Appropriate Sampling Sequence for an Area Monitoring System
- Relate the Employees to the Results of the Area Monitor and Determine Their Exposure

Nature of Gas in the Work Environment

In order to understand the work environment and how this relates to employee exposure, we have taken literally millions of sample point data from our various field installations and analyzed the data for the statistical nature of the gases in the breathing zone. The purpose of this effort was to establish the distribution of the gas concentration levels. This obviously is affected by the air flow, molecular weight of the gas, reactivity of the gas in the atmosphere, type of source of the gas, etc. However, from these studies we have sufficient data to say that a "log Normal" distribution is sufficient to represent the distribution of the gases studied in the various plants studied. To our knowledge this is the first in-plant data to confirm the NIOSH report of April, 1975, entitled "Statistical Methods for the Determination of Non-compliance with Occupational Health Standards", by Nelson A. Leidel and Kenneth H. Busch, HEW Publication No. (NIOSH) 75-159 (Reference 1). In this report they use air pollution data to support their "log normal" distribution methods. Now with our confirmation of this data (to be published in the latter half of 1975) (Reference 2), it is possible to use many of their analytical techniques and statistics. These can be used to analyze data from an area monitor to determine compliance (at various confidence levels), to predict plant performance based on the "log normal" statistical model and to easily analyze current plant performance against past plant performance for detection of significant trends.

More specifically the attached Figure 10 shows the difference between the "log normal" distribution and the more commonly used normal distribution. To define the "log normal" distribution it is necessary to determine the Geometric Mean (GM) and the Geometric Standard Deviation (GSD) (similar to the Arithmetic Mean (μ) and Standard Deviation (ε) for the normal distribution).

$$GM = \mu / \sqrt{\frac{h\,\sigma}{\varepsilon\,\ln \mu} + 1}$$

$$GSD = \varepsilon^{\sqrt{\ell n \left[\varepsilon^{\frac{\ln \sigma}{\ln \mu}} + 1\right]}}$$

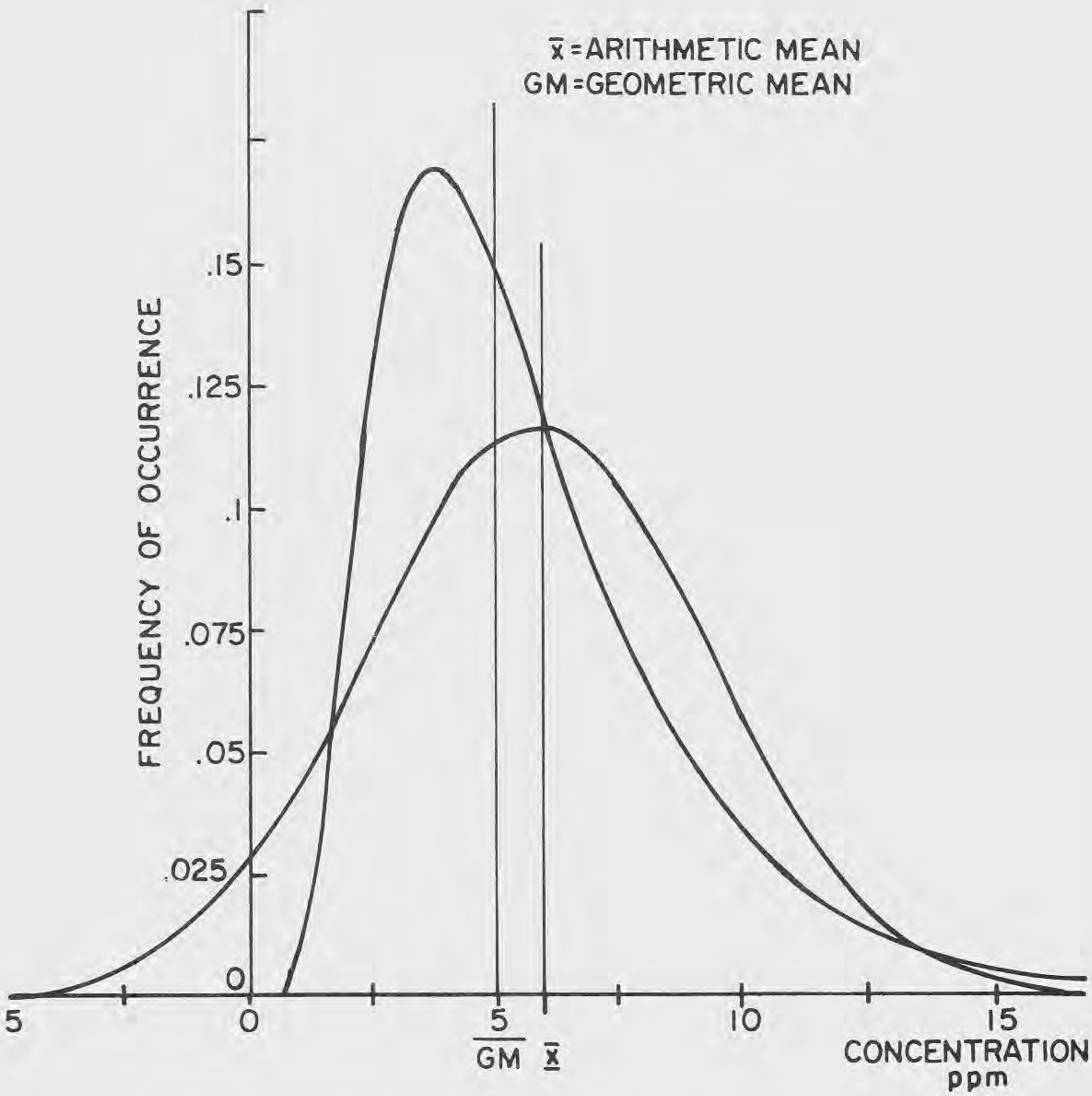


Figure 10 - Log normal and normal distributions with the same arithmetic mean and standard deviations.

FROM: HEW Document No. (NIOSH) 75-159

"Statistical Methods for the Determination of Noncompliance Occupational Health Standards"

The GM and GSD (for any time period long with respect to plant variations), completely defines, from a statistical viewpoint, the "log normal" curve for the frequency of concentration of various levels of the gas being monitored.

That is to say that you now have a definition of your plant environment that allows projection of the probabilities of various ocurrences in the plant as well as to determine compliance with various OSHA "Performance" Standards. Thus, the EOCOM data system, as appropriate, calculated these parameters as well as TWA's.

Sampling Algorithm

Given that the EOCOM data system keeps track of the GM and GSD of each breathing zone sensor probe* (of the area monitor), it is then possible to evolve a sampling algorithm that will have:

- Higher Probability of Excursion Detection
- Turn Warning Systems Off in the Shortest Time to Minimize the Use of Masks
- Isolate the Actual Probe Nearest the Cause for the Excursion

A. Probe Data

First using just the sample probe data (employee time/motion studies will be considered later), management selects a parameter(s) (P [M]) of the gas that is key to their plant operation under the OSHA Standard. For instance in the case of the VCM Standard, management might select individual probe readings of greater than 25ppm until April 1 ,1976, and 5ppm after that time with the objective of having the correct mask on at all the required times. On the other hand, depending on the general levels of VCM in the plant, management might select eight (8) hour averages of the probes that are higher than 0.5ppm and 1.0ppm as two (2) parameters to determine the sampling algorithm. Another parameter that could be selected is the GSD of a probe. In any case, the selection of the desired parameter (one or more) is made by management as a function of plant conditions relative to the standard as well as any other requirements they may have.

*NOTE: For this discussion, no consideration is given to the number of samples from a probe that yield a useful GM and GSD. Also the effect of high instrument noise (not "log normal" distributed) relative to the variations in plant levels is not considered in this discussion. Both these parameters are a function of the area monitor used with the data system and should be evaluated on an individual case basis and could affect the distribution or time intervals used with the statistics.

For instance, let's take the case of selecting the probability of the sample probe having a reading of 5ppm or greater P[≥ 5ppm/ reading]. Using the GM and GSD for each probe, the axis plural for the "log normal" distribution of Figure 10 is determined and a set of probabilities, one for each probe, is determined.

$P\ [M]\ ,\ P_2\ [M]\ ,\ldots\ldots P_n\ [M]$

These probabilities of probe readings at or above 5ppm are then used to determine those probes that should be sampled more often (i.e. higher P M) and from these probabilities is developed the sampling pattern where the sample probe selection is under the control of the EOCOM System, the result being that those points with most likelihood of a 5ppm excursion are monitored more often.

B. Employee Data

A second level of effort is to also include as part of the sampling probability model, the probability of any employee being at any one breathing zone probe. This data is derived from time/motion studies of the involved employees (or job categories).

From the time/motion study, one obtains the probability of each employee (category) with respect to probes.

$P\ [T_{A_1}],\ P\ [T_{A_2}]\ldots\ldots P\ [T_{A_n}]$

$P\ [T_{Z_1}],\ P\ [T_{Z_2}]\ldots\ldots P\ [T_{Z_n}]$

By combining the probabilites of all the employees (catagories) with the P M for each point, you then have the probability for that probe that any employee may be exposed at that probe.

$P\ [E_1],\ P[E_2]\ldots\ldots P\ [E_n]$

These probabilities are then used to generate a sampling distribution that is used in the sampling algorithm of the EOCOM System.

C. Search Sampling

In addition to the above statistically controlled sampling, the EOCOM System also goes into a search routine when an initial alarm or excursion occurs. This search is performed to be sure that the highest point of concentration is located so that effective corrective action can be taken as soon as possible. This search routine takes into account the wind direction (normally known because of forced ventilation) as well as the probabilities of the points around the initial excursion. After establishing all the alarm conditions in the area, EOCOM System then proceeds to monitor the rest of the system while establishing a higher priority for reading the alarmed area more often until the condition is corrected. Again all of the TWA (p)'s are calculated correctly by the trapezoidal integration.

D. Multi-Level Sampling

The EOCOM System also has the capability of multi-level sampling. The multi-level sampling concept is to monitor the mixture of several points simultaneously. That is to take for instance, 3 points and mix them in the gas manifold. Thus the measurement of the three (3) points would provide the average of the three (3) points (1, 2 and 3). In order to make a decision on a 5ppm alarm, the EOCOM System analyzed the data as shown in Figure

Multi-level sampling has the advantage of "sweeping" the plant at up to three (3) times faster than single point sampling. It has certain requirements to be effective and still not deteriorate the TWA and other calculations being performed by the EOCOM System.

1. In order to almost achieve the factor of 3 speed improvement the average levels in the plant (for the case of Figure 11) would have to be below 5/3 or 1.66ppm. In no case is the approach slower than single station sampling. The worst case is when all levels in the plant are 5ppm, then the system will measure R, R_1 and R_2, or three (3) such measurements. Most cases we have observed are such that almost the full factor of three (3) can be achieved.

2. One has to take care in selecting the points that are to be averaged so as not to affect the other calculations. We have shown that this is accomplished by selecting points with roughly equal P [E] and/or P [M].

3. Although the EOCOM System has the multi-level sampling capability, it may require different gas manifolding than presently in use.

In summary, the multi-level sampling capability does improve:

- Probability of Measuring Excursions
- Average Time To Survey the Plant

SITUATION

1. P [m] 5 ppm.
2. Simplified version of program.
   NOTE: Real program takes into account recent measurements of points and probability of most likely point of excursion.

Reading = R (Average of Points 1, 2, and 3)

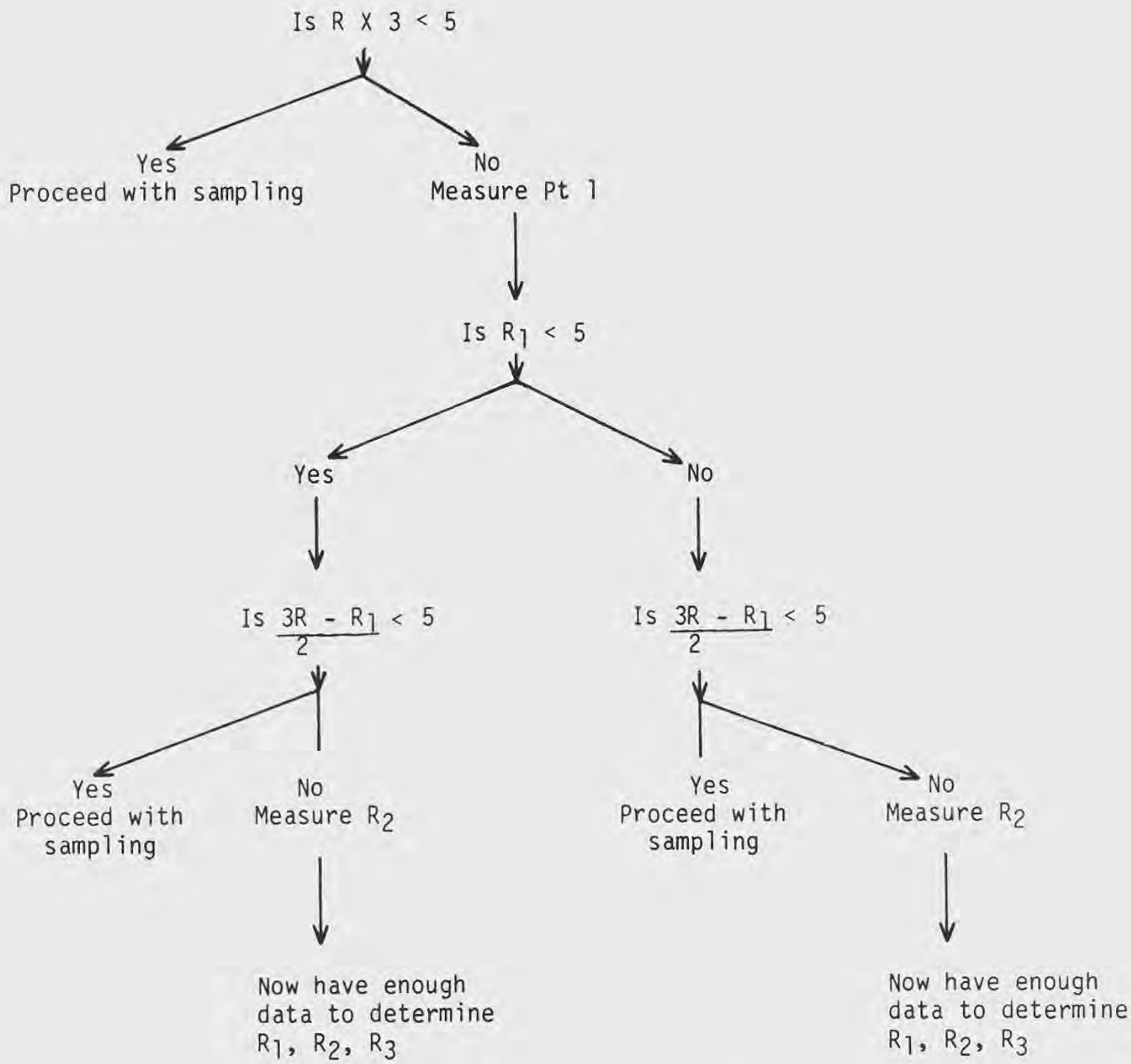


Figure 11. Multi-layer sampling.

Summary of Sampling

In summary, the sampling algorithm of the EOCOM System allows the user to:

- Have a system that responds to its environment. Each day the GM and GSD are updated and the sampling algorithm corrected for plant trends and variations.
- Sample the area monitor in an intelligent fashion based on the "living" statistical trends of the plant environment.
- Select the sampling decision paramenters that are deemed important to management.
- Enter new or changed time/motion studies.
- Get to excursions significantly faster than a sequential sample system.
- Correct excursions fast.

Basic Reporting of the EOCOM System on the Plant Environment

In order to provide management with significant information concerning the plant environment, its changes and the degree of complicance with a standard, the EOCOM System reports several parameters regarding the plant data measured by the probes. First, individual probe readings are available through the printer or by optional mass storage device. However, except for investigating specific events, it is felt that the following summary parameters are sufficient to fully define the environment for each probe.*

- TWA (P)
- Trend TWA: TWA (TP)
- GM (P)
- Trend GM: GM (TP)
- GSD (P)
- Trend GSD: GSD (TP)

The total plant (floor or area) environment is defined by the sum of the probe data for the plant (floor or area).

A) TWA (P): TWA (P) is calculated from the basic data points measured by the sensor probes. It is important to note that the non-uniform sampling (with time caused by the sampling algorithm in section above) requires careful attention to the means of calculating the TWA. The EOCOM System calculates the TWA with a trapezoidal integration of the individual readings, yielding the correct value for the area under the curve, which then for any

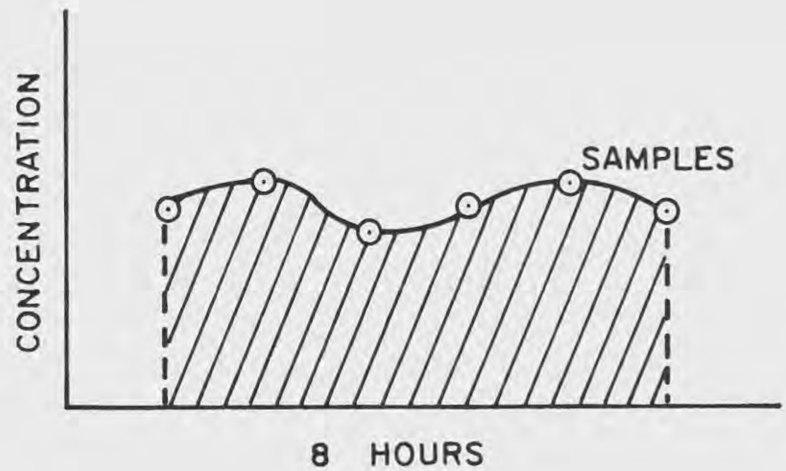
*NOTE: The EOCOM System calculates many other parameters as noted in its specific specification sheet. The parameters discussed here are those used to describe the plant environment and employee exposure.

given time period (15 minutes, 1 hour, 4 hours, 8 hours, etc.) provides the correct TWA (P).

The area under the curve is shown in Figure 12. It is this true area divided by the time that yields TWA values. It is interesting to note that most management selection criteria for P [M] will lead to an optimum sampling of the eight hour period. That is to say that most of the selection criteria used by management will lead the sampling algorithm to sample active exposure areas more often than less active exposure areas. This is shown by the following condition:

A) Small number of samples per 8 hours:

- Low P (M)
- Low P (E)
- Low GSD (EP)



B) Many samples per 8 hours

- High P (M)
- High P (E)
- High GSD (TP)

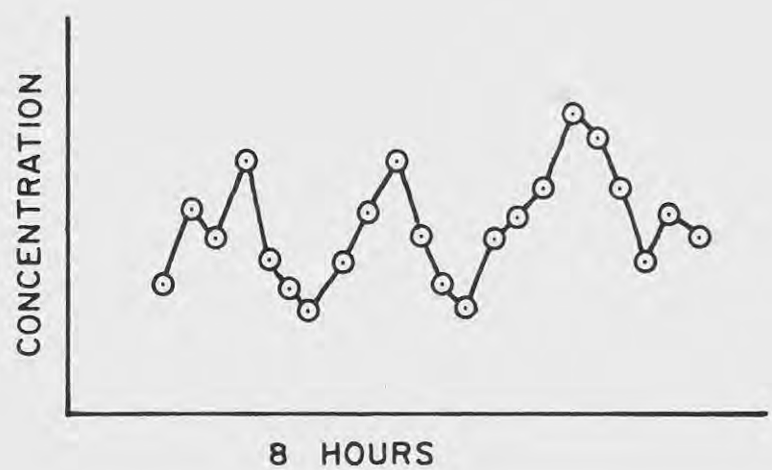


Figure 12

In both cases the system samples the data correctly to provide the correct time weight average (P).

C) Trend Responsive TWA (TP): In order to compare today's performance with past performance, the EOCOM System outputs an exponential TWA which is:

$$TWA\ (P)_O = 0.X\ TWA\ (P)_O + (1 - 0.X)\ TWA\ (TP)_Y$$

Where the subscript O indicates today's data and the subscript Y indicates yesterday's data, the factor X determines the number of days that are used to determine the trend (TWA (TP). The factor X is selectable by the user and can be varied to give very long term trends or shorter term (such as a week) trends. The effect of setting X to a time constant of seven to ten days is to smooth out any abnormalities of a given day, while at the same time giving data on the most recent performance of the plant. This is depicted in the following figure:

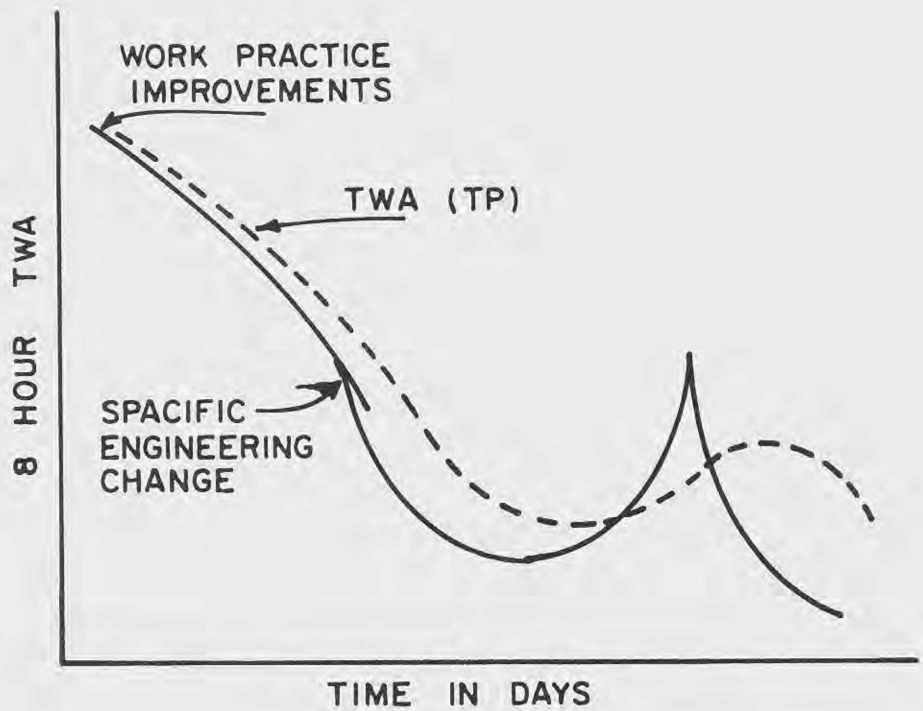


Figure 13

By this method you can readily compare today's performance TWA (TP) with the average of a previous (selectable) set of days and decide if today's performance is significantly different. An alternate path is to simply calculate the TWA for extended periods of time (rather than exponentially). This is possible with the system; however, it is our opinion that the most recent data contains more management significance. However, either is available from the EOCOM System.

D) GM and GSD:

The significance of GM and GSD is that they allow one to completely describe the plant in terms of statistical numbers. This uniquely defines the log normal curve in Figure 1 from HEW Document No. (NIOSH) 75-159, (Reference 1). Again it is significant to compare the present to the most recent plant data. By using this data, you can easily assess the plant performance for the day both in actual levels and in variations. Since it has been shown that the data is log-normal distributed, it is also possible to use the GSD and GM from a series of days to project the plant environment into the next shift or day with a confidence level attached to projected performance on a future shift or day. Again, the continuing GSD and GM are reported as trends also. Thus the system reports: GM (P), GM (TP), GSD (P) and GSD (TP) in the same fashion as the TWA (P) and TWA (TP) values.

Further, using the GM and GSD allows one to assess whether any given shift or period is within the previous experience and whether a combination of shifts represents a new trend. Depending on the process and results from the system, it may be more appropriate to keep separate records on the shifts in each day rather than running the average from shift to shift through the day into the next. In certain industrial cases, we have noted a substantial difference in the value of GM and GSD from shift to shift. In one case, the night shift runs significantly higher than the other two shifts.

It is worthwhile to comment on the effect of the sampling algorithm on the calculation of GM and GSD for the eight (8) hour periods. The actual log normal distributions are based on random samples. The samples taken (at least for a short period) cannot be considered random. However, our data to date does show a substantially log normal distribution for periods as short as one hour.

Employee or Job Category TWA

The EOCOM System calculates employee (or job category) exposure by using the measured TWA (P) for the time period of interest for each point and the time/motion study data (P $[T_{A_1}]$.........P $[T_{A_n}]$)

This approach leads to extremely good long term TWA of employees. Certainly it is based on more information than a 1 or 2 time/month personal sample. The time that the EOCOM System takes to converge on accurate TWA (when compared to charcoal tubes) is a function of many variables, such as:

- Conditional exposures
- Validity of time/motion study and its variability
- Placing of the sensors in the breathing zone
- Number of samples per measurement period provided by the area monitor
- Cyclic (or non-cyclic) nature of the process
  etc.

It has been our experience to date with an installed VCM monitor system that with the inclusion of the conditional exposure (man in reactor) that calculated TWA values converge to the measured TWA values in less than eight (8) hours.

For those situations where the employee may perform several job categories within a shift or from shift to shift, the job category concept should be used and the employee should log in on a per shift basis the time spent in each job category that is a regulated job category.

EPA Requirements

With the present proposed standards for EPA monitoring in plant effluents for substances such as VCM (EPA 40 CFR Part 61: National Emission Standards for Hazardous Air Pollutants Proposed Standard for Vinyl Chloride) EOCOM intends to offer an optional accessory to EOCOM System to perform either a mass calculation of VCM in the air in the plant and that VCM that escapes the plant into the environment or to accept data from an exhaust sensor (one or more) and provide the appropriate data analysis, such as 10ppm per hour limit. In view of the status of this proposed EPA VCM standard we have not chosen the final approach.

Effect on Employees

A true interactive intelligent monitor, as installed in a VCM monitoring situation has been observed to have the following effects:

1. Excursions due to work practice have significantly decreased due to the speed of the monitor and its ability to capture 94% of the excursions. This has, without intervention of management, brought a force to bear on the employees which had the effect of dramatically reducing excursions due to work practices.

2. A previous monitor system was circumvented by the employees knowing the sequential nature of the sampling device. Knowing this they were able to perform critical operations that might cause excursions while the monitor was not sampling in the area. With installation of the new system and its sampling algorithm, this was no longer possible, and a significant change in work practices occurred which also improved productivity.

REFERENCES

1. HEW Publication No. (NIOSH) 75-159. Statistical Methods for the Determination of Noncompliance with Occupational Health Standards.

2. Coppola, J., D. Mattson, K. Lindelin and S. T. Dunn. The Use of Area Monitors for Determination of Compliance with OSHA Performance Standards. (To be published).

Nomenclature

GM	:	Geometric Mean
GSD	:	Geometric Standard Deviation
P [M]	:	Management Selected parameter for determining sampling algorithm (one or more can be selected)
P [T_{A_1}]	:	Probability of man A being at point 1, etc.
P [E]	:	Probability of exposing any employee at a sensor probe
TWA	:	Time weighted average as defined in 29 CFR 1910.93 (d) (1)
TWA (C)	:	Measured eight (8) hour time weighted average of an employee or job category
TWA (P)	:	Eight (8) hour time weighted average of a sensor probe
TWA (TP)	:	Exponential average of eight (8) hour time weighted average of a sensor probe
GM (P)	:	Eight (8) hour geometric mean of a sensor probe
GM (TP)	:	Exponential average of eight (8) hour geometric mean of a of a sensor probe
GSD (P)	:	Eight (8) hour GSD of a sensor probe
GSD (TP)	:	Exponential average of an eight (8) hour GSD of a sensor probe

Subscripts

1, 2, 3, n...: Probe numbers

A, B, C......: Employee or Job Category

GLOSSARY OF TERMS

ADAPTIVE SAMPLING

Adaptive sampling is the process by which those areas where a worker together with an excursion are more likely measured more often than those areas less likely. It is a combination of the probability of man, probability of excursion, data from ancillary inputs, data about transient workers and conditional exposure to determine in which order probe points are to be measured.

ANCILLARY INPUTS

The auxiliary data that record employee movement, wind direction, process conditions etc., used as parameters in the adaptive sampling algorithms.

BREATHING ZONE

Area containing the air being inhaled by a worker.

CONDITIONAL EXPOSURE

Those times during a normal cycle of production where a worker will automatically become exposed to an excursion based upon his deliberate action of performing a required task.

DATA CURRENT

Data that is $\leq$ 10 days old and $\geq$ 1 minute old.

DATA HISTORICAL

Data which is available for review from other analytical methods. i.e., Charcoal Tubes, Gas Chromatographs, Grab Bag, Hand Held Monitors etc., and is more than 10 days old.

DATA REAL TIME

Data that is < 1 minute old.

EMPLOYEE EXPOSURE

The amount of subject gas that comes within an employee's breathing zone. Usually expressed as a function of time such as a time weighed average (TWA).

FMS 7200/GC UP-GRADE

A technique where an EOCOM FMS 7200 system is integrated with an existing gas chromatography system.

EXCURSION

An increase in contaminant level that is greater than or equal to a predetermined standard.

GAS FUTURE

Those gases which may require monitoring by either the government or management at a later data.

GAS CHROMATOGRAPH DRIVER

An interface in a FMS 7200/GC Monitoring System which directs the sequence of the multi-streamer GC system.

GAS-SUBJECT/INTEREST

Gas that is being monitored.

INTERFERENCE PROTECTION

Monitoring the gas of interest in such a manner to determine the existence of interferences to the gas measurement.

INTERPOSING RELAYS

Electrical contacts that drive the sample collection system, field alarms, mimic panels and audio-visual enunciators.

MULTI COMPOUNDS

Measuring more than one gas of interest and comparing each to specific standards.

MULTI-PROBE SAMPLING

A measurement technique where more than one probe/point is sampled.

MIMIC PANEL

A collection of lights mounted on a panel within the outline of the regulated area that represents the sample probe or point locations, and is used to communicate the location of excursions.

PROBE/POINT

A stationary point where air samples are drawn.

PRIME SENSOR

The equipment that analyzes the sample for the subject gas.

PRINTER-ALARM

Dedicated to recording the sequential alarms in excess of the standard.

PRINTER-REPORT

Produces hard copy for management, EPA, OSHA and other special reports.

PROBABILITY OF EXCURSION

Probability of Excursion is the probability of an excursion greater than or equal to a predetermined level at any point or area.

PROBABILITY OF MAN

Probability of man is probability of a man or employee of a specified job classification will be found at a point or area.

PROBABILITY OF MAN MEETING AN EXCURSION

The probability of man or an employee of a specific job classification will be at a point or area when an excursion occurs.

REAL TIME

Data that is less than 1 minute old.

REAL WORLD MEASUREMENTS

The actual levels of subject gas at all points within a defined area at a specific time.

REGULATED AREA

That space that is controlled and monitored for excursions of a subject gas.

SAMPLE COLLECTION SYSTEM

The required equipment, vacuum pumps, manifolding, traps, lines and valves, etc., required to move the sample from the probe point to the prime sensor.

SPECIAL REPORTS

That which may be required by management but not necessarily OSHA or EPA.

VALIDATION PROGRAM

A plan of action to insure employee exposures are being computed accurately.

WORKER MOVEMENTS

The cyclic pattern of worker as he performs his daily job requirement. This is usually a job classification, and is used to predict the probability of a man being within a defined area.

WORKER-TRANSIENT

Those workers who do not normally perform in a cyclic manner within the regulated area, i.e., Maintenance people, Management Supervision, Outside Contractors, etc.

WORKER-TWA

The time weighed average of a workers' exposure defined by OSHA.

* * *

NIOSH

SYMPOSIUM PROCEEDINGS

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U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Centers for Disease Control
National Institute for Occupational Safety and Health

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Held at the
Atlanta Hilton Hotel
Atlanta, Georgia

February 27-28, 1979

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Centers for Disease Control
National Institute for Occupational Safety and Health
Division of Physical Sciences and Engineering
Cincinnati, Ohio 45226

January 1981

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402

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DHHS (NIOSH) Publication No. 81-107