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DEVELOPMENT OF A REAL-TIME

STACK PARTICULATE MASS MONITOR

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Abstract

Presently, particulate emissions from stacks are measured by sample and weigh methodology, which despite their status as 'reference methods' are often slow and sometimes not very repeatable. These methods use comparisons of before and after filter weighing to yield an average particulate concentration for a given sample period. The procedures require a great deal of care to give repeatable results because of the many inherent sources of error such as filter handling, transport, conditioning and weighing. Another disadvantage of gravimetric methods is that useful time history information, describing transients and stack stratification, is not possible.

Virtually all existing continuous stack particulate monitors (opacity, triboelectric, acoustical, and beta attenuation) suffer from potential inaccuracy in that they do not directly weigh particulate and must be periodically calibrated using the above reference methods. An easier, faster, more repeatable 'reference' technique would allow for more accurate and frequent calibrations of the present continuous monitors.

Rupprecht and Patashnick Co., Inc. (R&P) has developed a new instrument based on its TEOM® tapered element oscillating microbalance technology that accurately weighs the particulate mass in real-time. It consists of an inertial mass detector supported at the end of a sampling boom that is placed in the stack, and a control unit remotely located. An umbilical cable interfaces the mass detector with the control unit. The instrument features online direct mass concentration measurement in the stack, and eliminates the need for pre-test and post-test laboratory work. This reduces many of the error sources associated with manual sampling, providing a less labour intensive technique and more representative data. It also enables decisions relating to efficiency of abatement techniques to be taken 'on the spot' allowing optimisation in real time.

Introduction

Because of the increasing emphasis of particulate matter on health issues, and the impending legislation from the European Union, R&P believes that there is a need for an improved monitoring protocol for particulate mass emissions from industrial sources. In answer to this need we have applied our well proven TEOM inertial mass measurement technology, resulting in an instrument that directly measures source particulate mass concentrations in real time. The instrument may be used to perform tests equivalent to many of the current reference standards, as well as short term continuous tests. In addition, because it resolves mass in real time, it provides useful plant process information such as transient particulate mass concentrations during ramped loading, stratification in ducts and control device efficiencies. Another valuable use of the instrument is to calibrate existing continuous monitors such as opacity, triboelectric, acoustic and beta attenuation that, unlike the TEOM system, do not possess a direct relationship with particulate mass.

Continuous emissions monitoring accuracy and frequency of calibration are very important because regulatory action against power plants is often based on continuous emission particulate data. Even a relatively high compliance rate, can result in significant fines to some industries because of potentially high mass emissions represented by being out of compliance for only a small fraction of the time. It is important that the monitoring protocol be accurate, repeatable and inexpensive to ease the burden of demonstration and provide industry with watertight results.

Background

Many of the error sources inherent with the gravimetric methods have been eliminated in the TEOM mass detector. These include errors associated with pre and post weighing of the filter media such as conditioning, handling and weighing. Because the TEOM mass detector weighs the filter continuously there is no need to pre weigh filters. For example, a typical test would consist of installing a filter, stabilising the system in the stack, taring and initiating sample collection. At the end of the test the total mass added to the filter since the tare is equal to the total mass collected. This result is directly available at the site, eliminating the need to transport the sample to the lab for conditioning and post weighing. Inlet losses have also been significantly reduced and because the TEOM system is a mass detector, these losses can be quantified immediately at the site. The TEOM mass detector uses a short straight inlet tube to ensure isokinetic sampling of the flue gas and transport it to the filter. Directly following the traverse, the system is removed from the stack or duct, stabilised, and with flow through the system the inlet tube is brushed down with a stainless steel brush. All particulate matter collected on the inlet wall during the traverse is loosened and collected on the filter and immediately weighed, resulting in a high level of confidence that ALL material sampled is included in the determined mass. The microprocessor-guided operation of the instrument reduces testing errors and provides an accurate and repeatable test protocol.

TEOM Series 700 Source Particulate Monitor

The Series 700 Source Particulate Monitor, based on R&P's TEOM technology, is an in-situ instrument. It draws flue gas through a filter while maintaining isokinetic sampling and continuously weighs the filter, resulting in a measurement of real-time particulate mass concentrations. It can be used to measure total particulate mass levels or in conjunction with a cyclone to measure PM_{10} or $PM_{2.5}$ particulate mass levels.

Figure 1 is a schematic diagram showing the flow through the system.

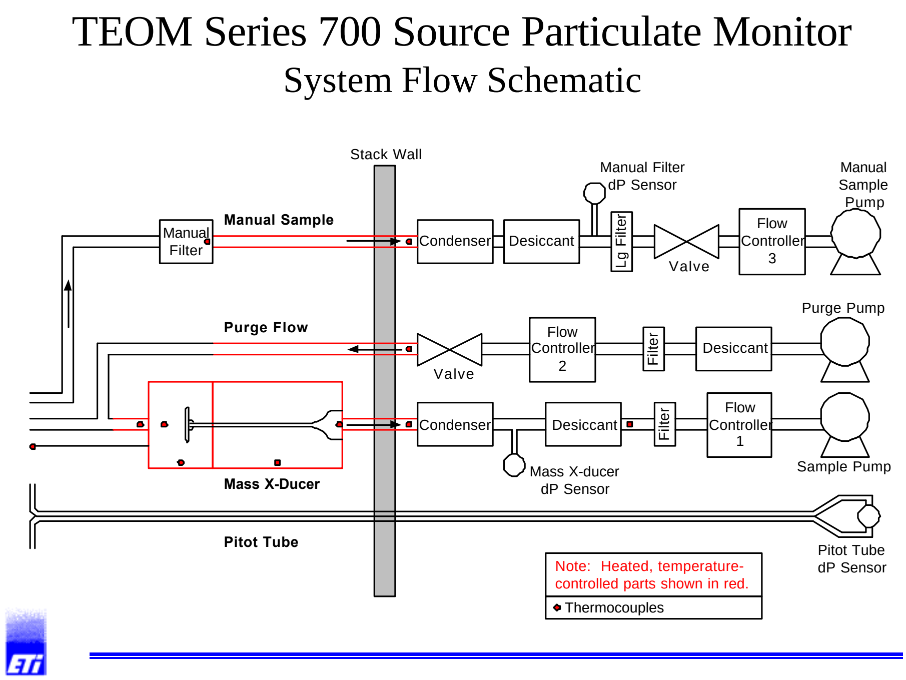


Figure 1

Flue gas enters the sample nozzle under isokinetic conditions and passes directly through a straight inlet tube to the filter mounted on the oscillating element where all particulate mass is collected at stack temperature. The filtered gas proceeds through heated lines in the structural boom to a condenser located on the platform outside the stack or duct where the gas is thoroughly dried before passing through the mass flow controller before being exhausted through the vacuum pump.

Many gravimetric reference methods require the removal of uncombined water from the sample. The TEOM mass detector achieves this by the use of a back flow system that is used to dry the sample immediately after filter loading. The use of this back flow prior to and following a static test or traverse will yield results directly comparable to the reference methods.

The mass detector and structural boom have an outside diameter of 2.75 inches allowing them to fit into a standard 3 or 4 inch pipe. The structural boom is collapsible to adapt to various field conditions and for ease of transport. It is supplied in 5 foot sections with a maximum length of 25 feet. Traversing is accomplished by sliding the dimensioned boom through a flange with a quick release clamp. The mass transducer currently operates in sources up to 200 °C and it is envisaged that a high temperature version will be offered shortly. An exchangeable inlet tube kit containing various inlet assemblies of different diameters allow sampling of sources with a wide variety of gas velocities.

Mass Transducer Operation

The mass transducer is a hollow tube, clamped at one end and free to vibrate at the other. An exchangeable filter cartridge is placed over the tip of the free end. This “tapered element” vibrates at its natural resonant frequency. An electronic control circuit senses its vibration and, through positive feedback, adds sufficient energy to the system to overcome losses. An automatic gain control circuit maintains the vibration at constant amplitude. A precise electronic counter measures the frequency, which has a direct relationship with mass.

The tapered element is a mechanical oscillator with a high quality factor whose frequency can be described with two parameters, the restoring force constant, K, and the mass, m, consisting of the mass of the filter, m_f, the effective mass of the tapered element, m_0, and the filter loading Δm.

$$m = m_f + m_0 + \Delta m \qquad (1)$$

The relationship between these quantities is given by the simple harmonic oscillator equation:

$$4\pi^2 f^2 = K / m \qquad (2)$$

or

$$f^2 = K_0 / m \quad \text{with } K_0 = K / 4\pi^2. \qquad (3)$$

Calibration Process

If a known mass, Δm (determined gravimetrically) is placed on the filter, K_0 can be determined from the frequencies f_1 and f_2 where f_1 is the frequency without Δm, and f_2 is the frequency after loading with Δm.

$$f_1^2 = K_0 / (m_f + m_0) \qquad (4)$$

$$f_2^2 = K_0 / (m_f + m_0 + \Delta m) \qquad (5)$$

From these two equations K_0 can be calculated for a particular device:

$$K_0 = \Delta m / (1/f_2^2 - 1/f_1^2) \qquad (6)$$

The tapered element is made of non-fatiquing inert material and retains its calibration indefinitely.

Mass Measurements

Once K_0 is determined for a particular tapered element, it can be used for mass measurements.

If the element is oscillating at the frequency of f_a and exhibits the frequency f_b after an unknown mass uptake $\Delta m'$ can be obtained as a function of f_a, f_b and K_0. It is:

$$f_a^2 = K_0 / m \qquad (7)$$

$$f_b^2 = K_0 / (m + \Delta m') \qquad (8)$$

where m is the total mass of the system before the mass uptake. Elimination of m yields the fundamental equation for mass uptake.

$$\Delta m' = K_0 (1/f_b^2 - 1/f_a^2) \qquad (9)$$

Note that the starting frequency, f_a, can be defined at any arbitrary time, and a mass measurement does not depend on the knowledge of the previous loading of the filter. Tracking frequency with time yields the mass rate, and when combined with the flow rate through the filter produces the mass concentration.

Modes of operation

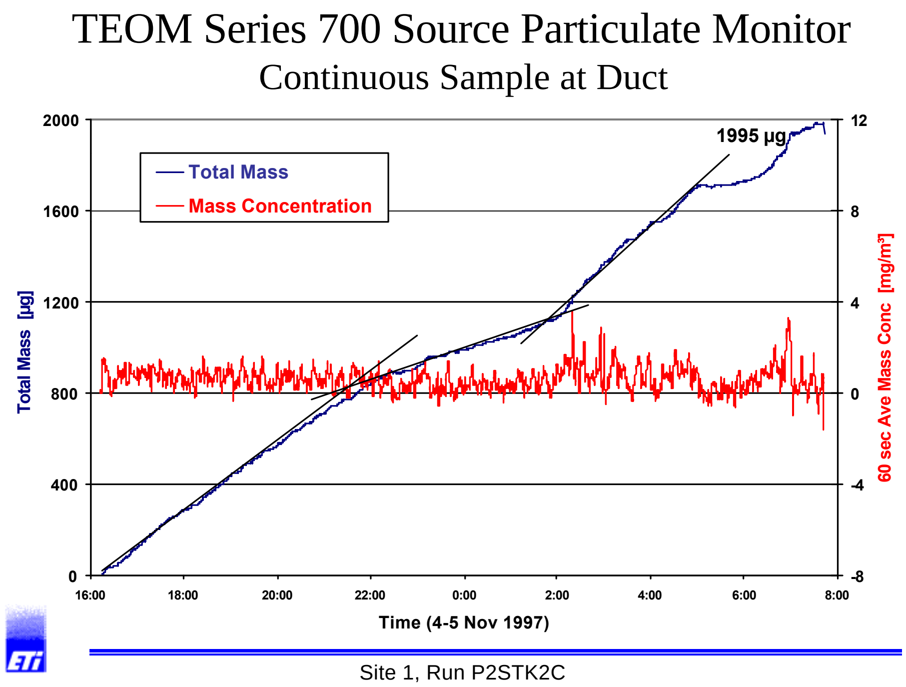
The TEOM 700 may be operated in two modes: continuous sampling and time proportioned sampling. Continuous uninterrupted sampling is used for relatively short duration tests, on the order of a few hours, similar to most reference methods. Because filter life is a function of the type of particulate matter as well as the concentration, test duration on the order of days are possible.

Sampling for only a portion of the total time can extend filter life. This “time proportioned sampling” technique lengthens the time between filter changes, and can be used to calibrate present continuous monitors on a regular basis. For example, a scheme where the TEOM mass detector is operated for a short time each hour and compared with opacity readings during the same period would allow the constant updating of the continuous monitor calibration.

Results

A prototype source particulate monitor was evaluated through field testing at a number of coal burning facilities a copper smelting facility and a cement kiln. Summaries of these tests follow.

The first test, shown in **Figure 2**, is an example of continuous monitoring in the stack of a coal burning plant . Very low emissions were experienced because of the presence of an oversized electrostatic precipitator control device. We are unable to



demonstrate the accuracy of this test because there was no corresponding gravimetric standard comparison test data available.

Figure 2

However, extensive testing at this facility indicates that the concentrations shown in figure 2 do represent typical particulate mass concentrations experienced at this site. The test shows the excellent mass resolution of the TEOM mass detector with its ability to resolve very low concentration levels. Resolving low concentrations is a key role for this new technology with the coming of the low-level particulate standards to be introduced in Europe.

The second test, shown in **Figure 3** is an example of continuous monitoring in the stack of a coal burning plant.

TEOM Series 700 Source Particulate Monitor
Mass Concentration and Opacity

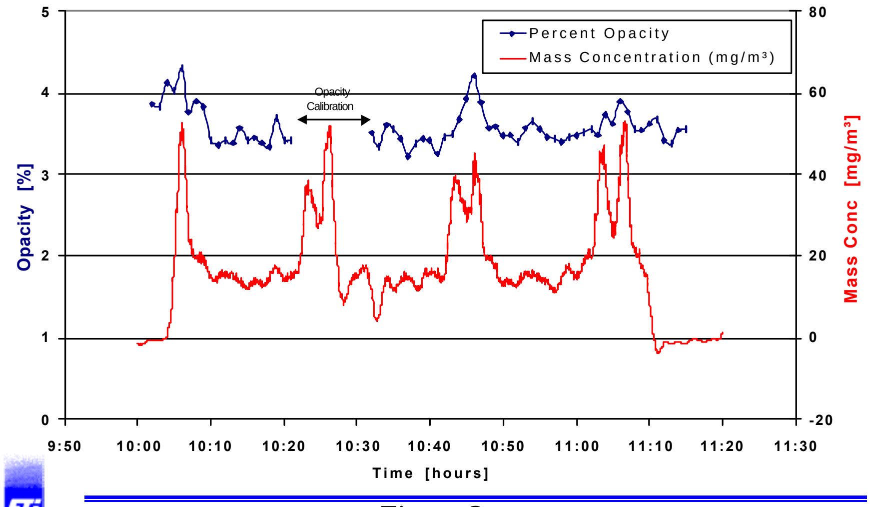


Figure 3

Moderate particulate mass concentrations were experienced during this test.. This facility uses an electrostatic precipitator as the control device. The TEOM mass detector was operated in its continuous mode for a test duration of 1 hour and 10 minutes... A demonstration of the usefulness of the time history of the test is shown when three sharp increases in particulate mass concentration were observed at 10:20,10:40 and 11:00 LST. On further investigation it was found that these increases are probably a result of the cleaning of the collection plates on the output stage of the electrostatic precipitator as shown by the opacity monitors at the site but with much less clarity. Additional data taken at this facility continue the trend, with sharp increases in concentration observed at ~20-minute intervals.

The third test shown in **Figure 4** is an example of time proportioned sampling in the stack of a coal burning plant .

TEOM Series 700 Source Particulate Monitor
Detail of Time Proportioned Sampling at Duct

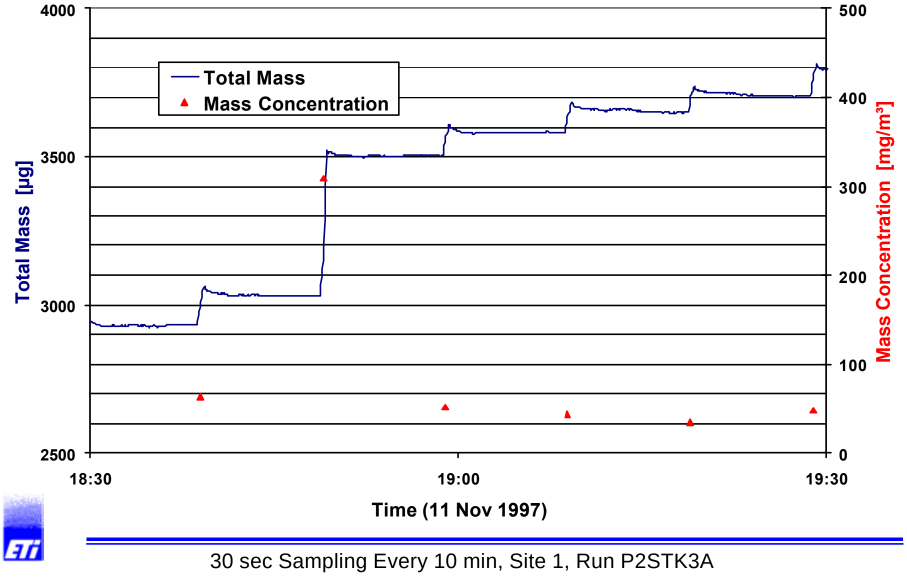


Figure 4

Wood was being used to supplement the coal for fuel, resulting in high concentration levels. Therefore, the time proportioning technique was used to prevent rapid clogging of the filter. The TEOM mass detector reported particulate mass 8.5% higher than the manual sample obtained directly following the test. The particulate collected in the inlet of the TEOM mass detector represented 12.2% of the total particulate mass collected on the TEOM mass detector filter. Particulate mass concentration was calculated using the change in mass between pauses in the time proportioned sampling scheme. This test demonstrates the instrument's ability to operate in high particulate concentration conditions. This data set shows the tremendous stability of the mass detector operating in the extremely harsh conditions typical of source testing. The in stack mass resolution during the pause cycle is a fraction of a microgram.

The fourth test shown in **Figure 5** is an example of long duration continuous testing at a European copper smelter with moderate particulate mass concentrations.

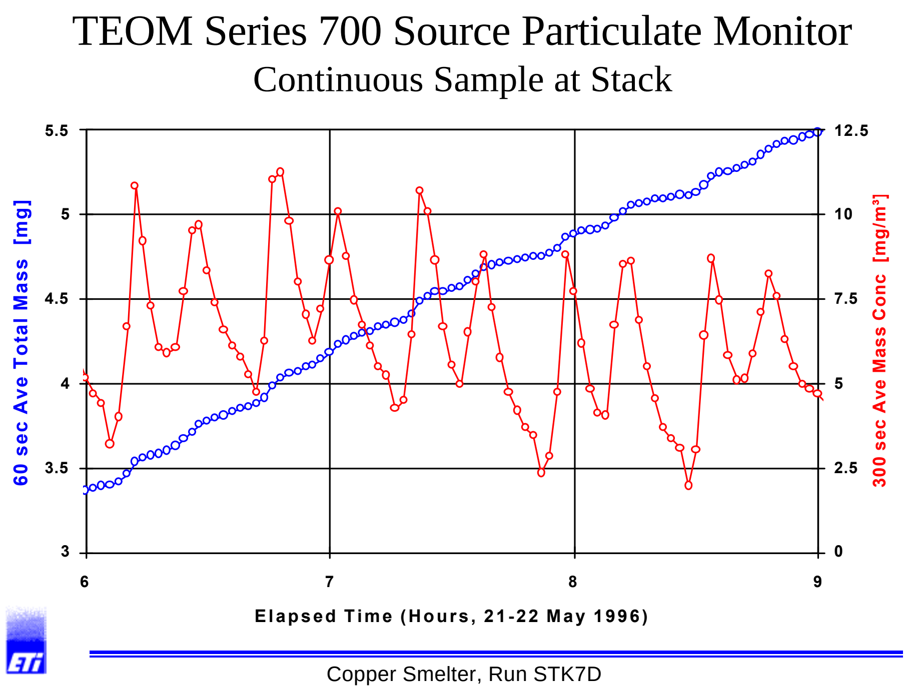


Figure 5

Due to prototype instrument memory constraints data was averaged and saved every 2 minutes instead of collecting every 2-seconds as in the previous tests. This does not allow us to see quick changes as clearly because they have been smoothed but still offers a valuable insight into the time cycle of the concentrations at the plant. Cycling of data between high and low particulate concentration as shown in figures 5 and 6 results from the 6-bank bag house going through its 36 minute cleaning cycle (One bag every 6 minutes). This cycle consists of closing 1 bank of bags for 6 minutes for back flushing. It is then opened and the next bank is closed and cleaned and so on. One of the banks had a faulty seal on the shutoff door and each time it was closed a stream of fresh air was allowed to mix with flue gas. This reduced the mass concentration (and the temperature) for the 6-minute cleaning of that bank.

TEOM Series 700 Source Particulate Monitor
Flue Temperature and Mass Concentration Profile

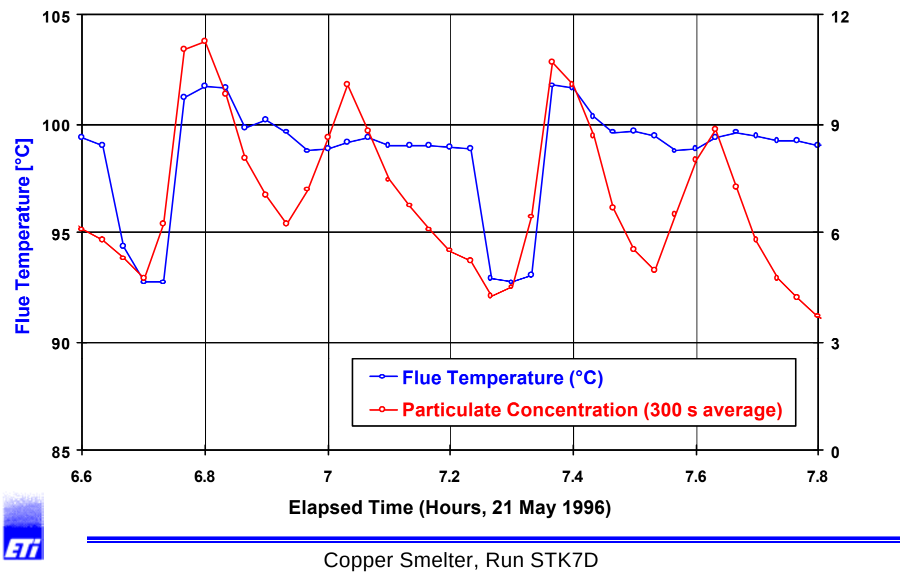


Figure 6

Increases in concentration may be explained by the differences in the efficiencies of each bank of bags. For example, a bank may have a torn bag allowing excess particulate mass to pass into the flue gas, or the opening of a door may re-entrain particulate from surfaces. This data set shows how useful the instrument is for studying control device parameters.

Conclusions

The application of R&P's well proven TEOM inertial weighing technology offers an improved stationary source particulate testing methodology. Variations in aerosol parameters resulting from process ramping show a need for continuous real time mass measurement without dependence on particle size or other particle attributes. Existing continuous monitors all possess such dependencies; however, inertial weighing has a direct physical relationship with mass. Applications for this instrument include gravimetric method equivalent testing, performing diagnostic studies on control device parameters, and calibration of existing continuous particulate monitors–opacity, triboelectric, acoustical and beta attenuation that do not enjoy a direct relationship with particulate mass.

The in-situ TEOM mass detector minimises typical inlet losses found in existing in-situ continuous monitors. Transport losses are minimised due to straight-line isokinetic sampling. There are no losses due to impaction in tubing bends or settling in long horizontal runs.

The prototypes of this instrument have been field tested to demonstrate performance under real conditions. A number of different industrial process sites both in the USA and in Europe have and are still being used to test in a variety of flue gas conditions, particulate concentrations and size distributions.

Typically the reference method results and the TEOM prototypes have differed by less than 10% as shown in **figure 7**.

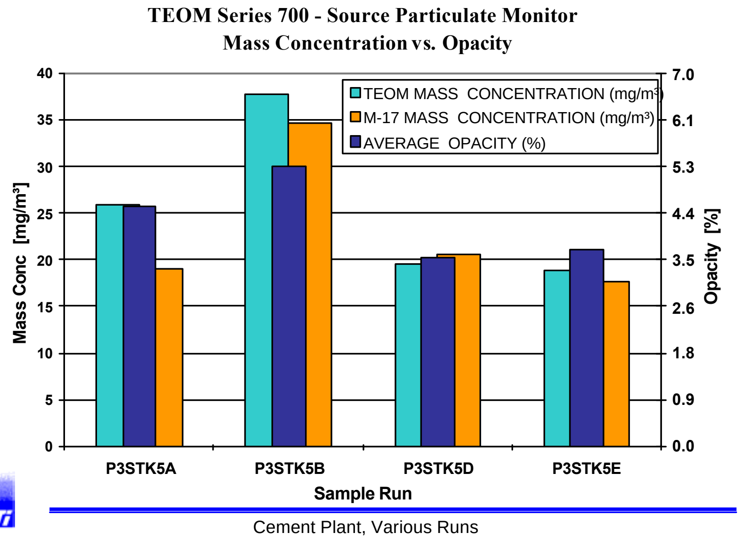


Figure 7

When it comes to precision the TEOM shows significantly better performance than the gravimetric systems **Figure 8** shows to agreement of two systems run in parallel to show the high level of precision achievable with this technology.

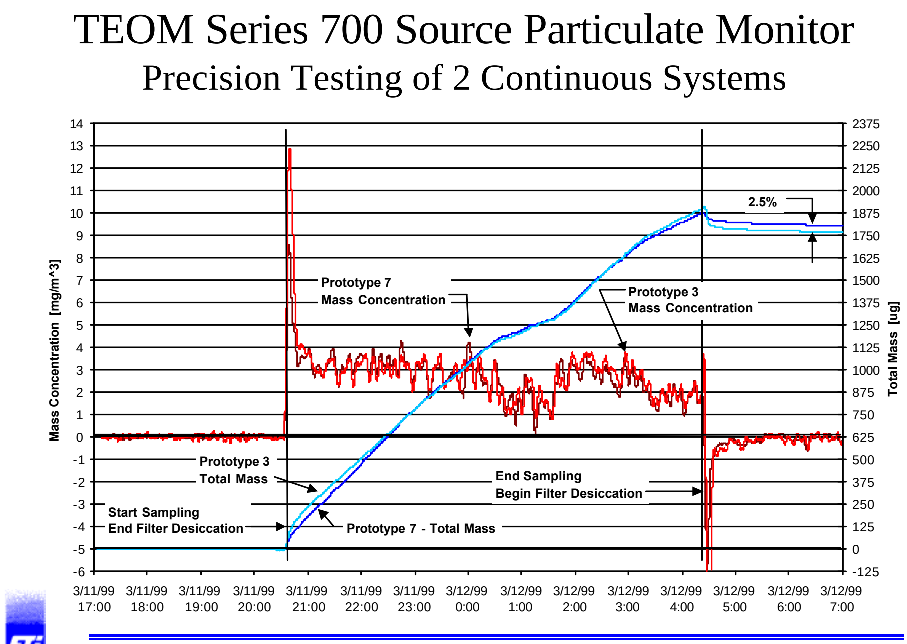


Figure 8

Current Status

The tests presently continue across Europe and the USA with a number of pre-production units for the remainder of 1999 with a commercial product becoming available early in 2000. Perhaps at the same time as the dawn of the new millennium we are about to witness the dawn of a new standard method of measuring the concentration of stack particulate.

Full details of the TEOM 700 stack particulate monitor will be available from the ETI Group booth in the CEM99 exhibition hall where a system will available for closer inspection.

Engineers and developers from both R&P and ETI will be delighted to discuss specific applications of the technology and to answer any questions delegates may wish to ask about the technology, hardware or software.

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Please note that the CEM 99 conference dinner in the theme of James Bond *007* is sponsored by the TEOM *700*

(Courtesy of ETI Group and Rupprecht & Patashnick)

SPECIFICATION SHEET

TEOM® SERIES 700
Stack Particulate Monitor

Features
- Easily Transported collapsible Structural boom
- Exchangeable inlet tube kit allowing isokinetic sampling
- Interfaces existing condensers, gas analysers, and typical source sampling peripheral equipment
- Results available immediately following test

Source parameters
• Port diameter:	3” Pipe minimum
• Maximum traverse distance:	24 feet
• Flue gas temperature:	200 °C Maximum
• Flue gas velocity:	Maximum
• Particulate Concentration:	Minimum; Maximum

Instrument Performance
- Resolution: tbd
- Accuracy: tbd
- Minimum detectable limit:
    mass: .1 µg
    mass concentration: 100 $\mu g/m^3$
- Precision: tbd

Operating range
- Main flow rate: 0.5 to 5 l/min
- Temperature of mass transducer: 5°C above flue gas temperature
- Inlet tube not heated
- Filter temperature will be slightly high than flue gas temperature.

Filter Media
- Pallflex TX40, 12mm effective diameter
- Glass fibre