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ON-LINE PARTICULATE ANALYSIS ON A FLUIDIZED-BED COMBUSTOR

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ABSTRACT

An on-line particulate analysis instrument has been developed by Leeds and Northrup Company under ERDA sponsorship for monitoring particle loadings in the gas clean up stages of advanced combustion systems. This instrument utilizes low angle forward scattering of optically illuminated particles by across-the-duct measurements to determine their size and concentration.

A prototype instrument has been designed and constructed to evaluate this means of measuring particles on fluidized bed combustion systems and field tests have been completed on this unit at the Argonne National Laboratory. This report presents a brief description of the instrument and discusses results obtained from the Argonne tests.

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ON-LINE PARTICULATE ANALYSIS
ON A FLUIDIZED-BED COMBUSTOR

SECTION 1

INTRODUCTION

An on-line particulate analysis instrument has been developed by Leeds & Northrup Company under ERDA sponsorship for in situ measurement of particle loading and size in the product gas streams of advanced combustion systems. A prototype instrument has been designed and constructed to evaluate this means of measuring particles on fluidized bed combustion systems and field tests have been completed on this unit at the Argonne National Laboratory. This paper presents a brief description of the instrument and discusses results obtained from the Argonne tests.

This particulate instrumentation is based on Leeds & Northrup's prior research in low-angle forward scattering of light by micron size particles suspended in fluid streams. When such particles are optically illuminated, the scattered light intensity at any given angle is a function of the size, shape and index of refraction of the particles. In the case where the wavelength is small in comparison to the size of the particles, the spatial distribution of the scattered light in the far field is dominated by the volume and size characteristics of the particles. The design of the ERDA instrument is based on utilization of simple diffraction theory to convert measurements of the composite Fraunhofer diffraction pattern for a large number of particles into meaningful particle data which characterizes the size distribution and concentration.

This type of instrumentation will be used later to evaluate the performance of secondary particle clean up and to measure the size distribution and concentration of particles at the inlet to gas turbines in direct combustion coal-fired systems. The latter application requires instrumentation amenable to measurement of particles in high temperature (1500-2000F) pressurized (up to 10 atmospheres) gas streams and be adaptable to rather large diameter gas ducts. The prototype instrument will accommodate gas ducts up to one foot internal diameter.

Field tests were completed at ANL on August 19, 1977 and the prototype instrument is now at Leeds & Northrup Company for calibration recheck. It will be delivered to Curtiss Wright Corporation soon where it will be installed on the Small Gas Turbine fluidized bed combustion system. This installation will enable testing the instrument performance for in situ measurements at seven atmospheres pressure and 1600F range.

I will first describe the particulate analysis instrument and then present some of the results from the tests at Argonne National Laboratory.

SECTION 2

INSTRUMENT DESCRIPTION

A schematic diagram of the optical train of the ERDA instrument is shown in Figure 1. This instrument consists of optical elements mounted to an optical bench which extends under a horizontal run of the combustion system duct. (The duct is not shown in the schematic, only its vertical center line). The illumination source is a helium cadmium laser mounted to the underside of the optical bench. Folding optics, attached to the left end of the optical bench, direct the laser beam across the duct where particles in the gas stream, which are illuminated by the beam, scatter the light. The scattered flux is collected by a lens and focused on a set of function masks. The portions of flux, which are transmitted through the function masks, are focused by a second lens on to the photomultiplier detector.

The output power of the laser is measured by a silicon photodiode which detects radiation from the rear Brewster window of the laser. This signal is displayed on a meter for ease of adjusting the laser alignment to maintain peak power output (10 to 20 mW).

A photograph of the prototype instrument is shown in Figure 2. This instrument consists of the optical subsystem assembly, an electronics package, laser power supply, and a digital line printer. All units, except the printer, are contained in NEMA 12 class enclosures to meet industrial environmental requirements. The laser and receiving optics units contain thermostat controlled heaters so that the optical subsystem may be installed on a gas duct which is located outside of a building.

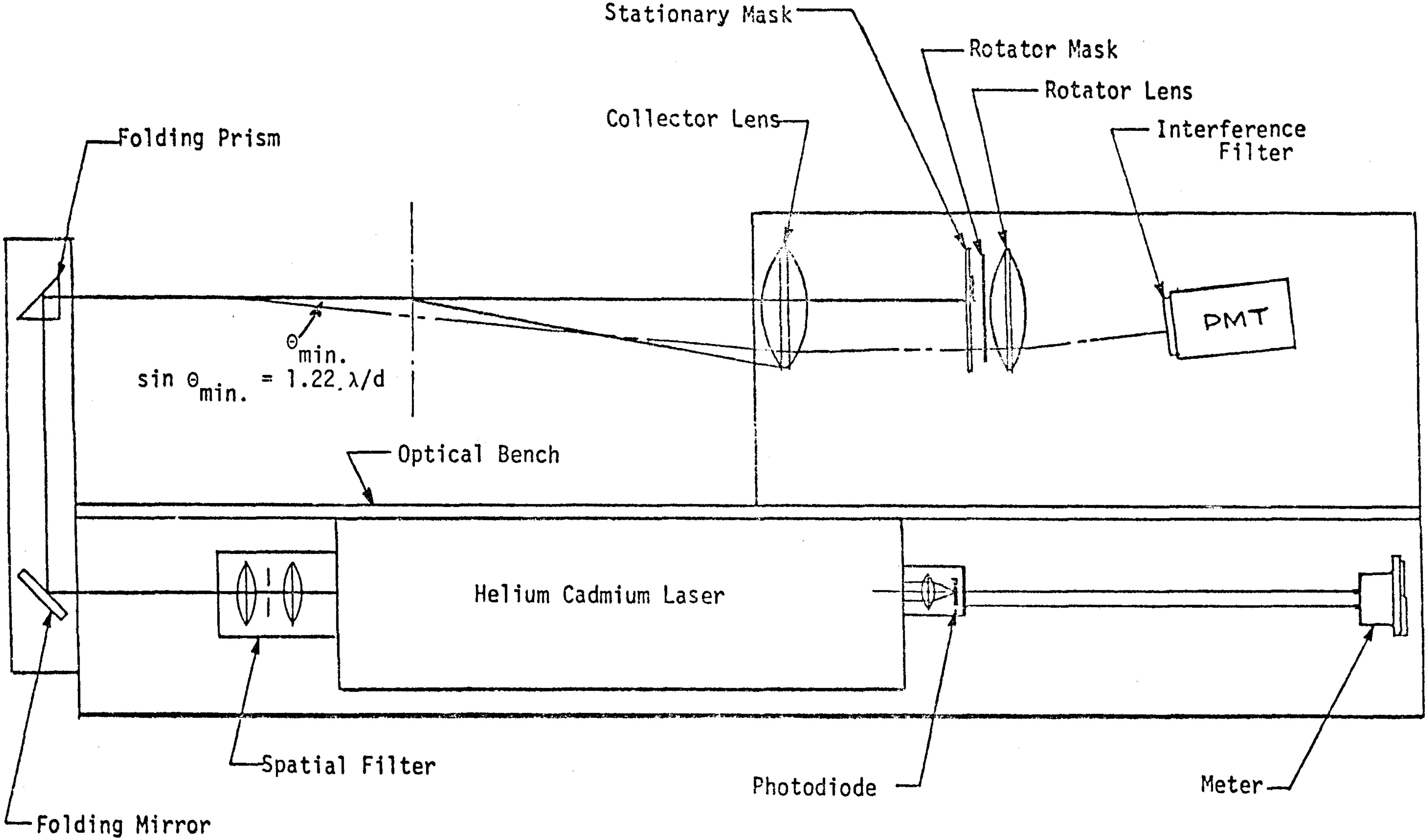


Figure 1: Particulate Instrument Schematic

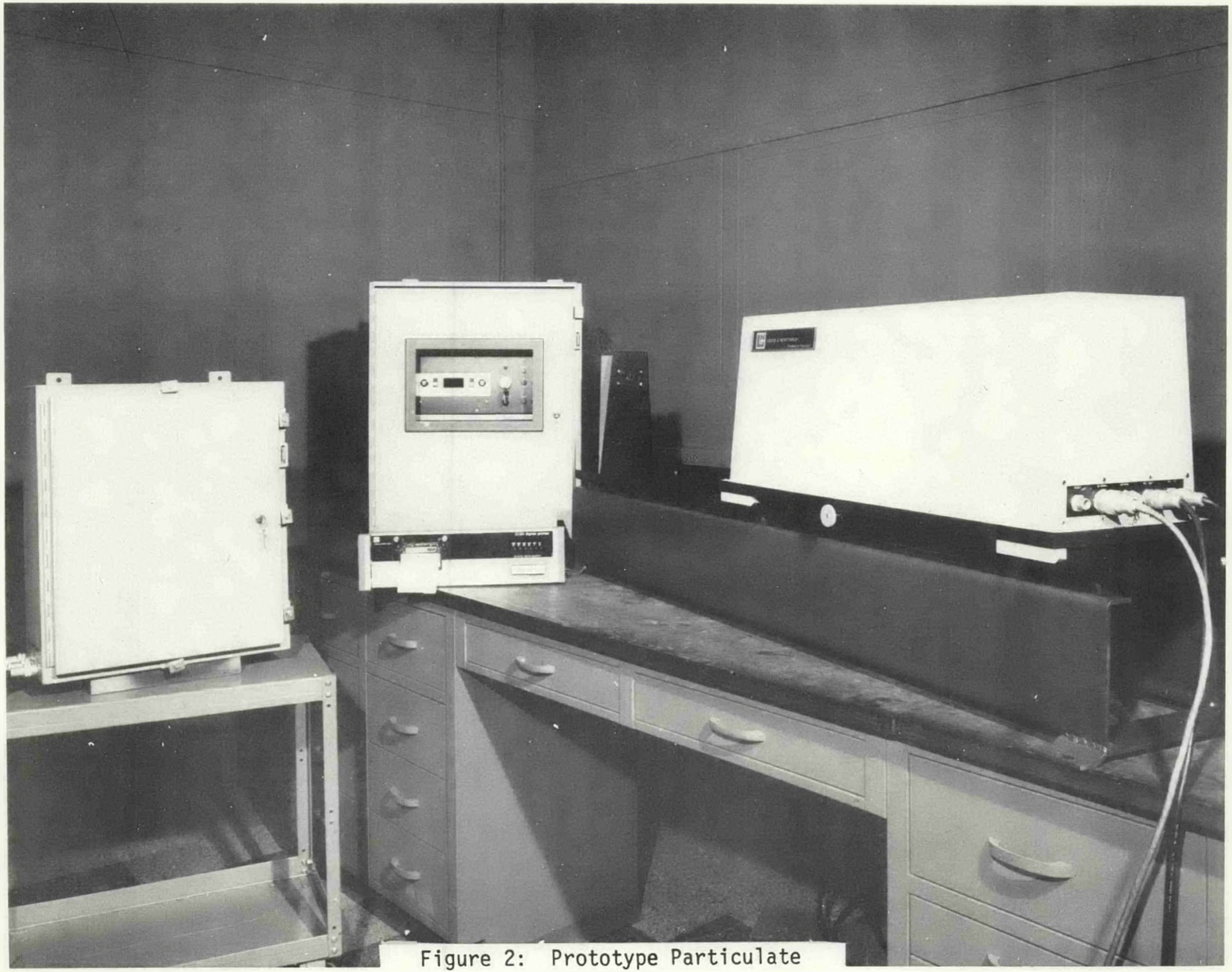


Figure 2: Prototype Particulate Instrument

The electronics package includes a microcomputer, visual display and all the operating controls. This unit can be located up to 200 feet from the optical subsystem. The digital data printer is used to log the output measurements and can be located remotely from the electronics package, if desired.

The opening on the optical subassembly from the folding optics on the left to the collection lens bezel is 30 inches. The vertical clearance above the optical bench to the laser beam center line is 9-1/2 inches. These dimensions were chosen to accommodate a 12-inch I.D. duct with a tee section viewing port extending on each side of the duct.

Mechanical adjustments are provided on the folding optics for alignment of the optical train to the duct windows after the instrument is installed. The instrument can be mechanically mounted to the duct through the load carrying base structure.

Without going into detail on the theory of optically scattering measurements, I will describe the basic fundamentals to enable those who may not be familiar with our instrument to understand the nature of its data outputs.

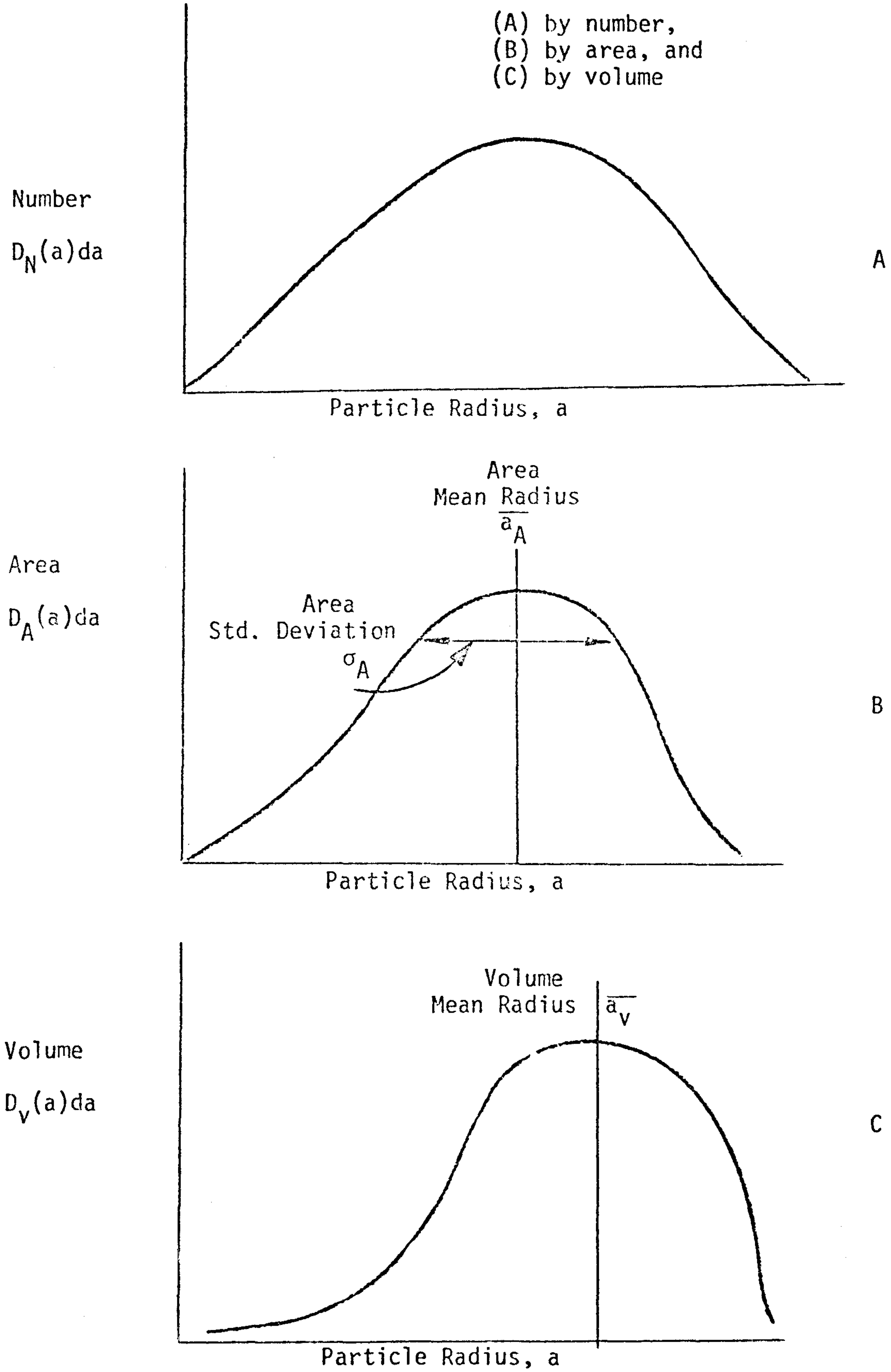
All particles illuminated by the collimated laser beam as it traverses across the gas duct scatter flux off the beam axis. For particles in the size range 1-100 microns most of the scattered flux is in the near forward direction. We collect that flux and through an optical process convert that data into information concerning the particle size distribution and the particle loading. The particle loading output is calibrated to be direct reading in parts per million by volume, i.e., ratio of total volume of particles per unit volume of gas.

A common means of presenting size distribution is to plot the population of particles as a function of their size as shown in Figure 3A. In order to obtain data more useful for control purposes, it is possible to describe size distributions in ways other than number density. Three means of presenting the same particle distribution are shown in Figure 3. The area distribution $D_A(a)da$ is the fraction of the total surface area of the particles within the range a to a + da. This is shown in Figure 3B. Similarly, Figure 3C shows the distribution by volume of particles. This cubic

Figure 3

Three Methods of Defining a Particle Distribution

(A) by number,
(B) by area, and
(C) by volume



response biases the distribution towards the larger size particles. Thus, the mean volume size $\overline{a_V}$ is always larger than $\overline{a_A}$ and it can be shown that the width of the area distribution is:

$$\sigma_A = [\overline{a_A}(\overline{a_V} - \overline{a_A})]^{1/2} \qquad (1)$$

The Leeds & Northrup particle instrument provides the following data outputs:

dV = volume of particles in ppm
MV = mean volume diameter in microns ($2\overline{a_V}$)
MA = mean area diameter in microns ($2\overline{a_A}$)
WA = width of area distribution in microns (2σ)

SECTION 3

PARTICLE INSTRUMENT TESTS AT ANL

Photographs of the prototype instrument installed on a one inch i.d. pipe at the Argonne facility are shown in Figures 4-6. Figure 4 shows the optical assembly mounted to the gas duct sample cell. After initial alignment, the laser beam is enclosed with a rubber boot from the instrument to the ports. There is no laser radiation danger to personnel as long as the equipment is maintained in this buttoned up state. No realignment of the optics was required during the two month test period.

The data processor and control console are located in the enclosure shown in Figure 5. The data logging printer is shown on the shelf above the enclosure. There were no electronic malfunctions during the course of the tests. The only problem encountered was an unexpected reduction in laser power. However, this didn't inhibit operation of the instrument even though the power dropped over a period of a few weeks from 20 to 8 mW.

A close-up of the ANL sample cell is shown in Figure 6. Two sets of air purge lines were provided by ANL to generate air curtains across each of the viewing port quartz windows. These optical quality windows were coated to eliminate reflection at the laser wavelength (442 nm). The windows were cleaned weekly but daily background measurements with clean air flowing in the duct show insignificant particle deposits between cleanings.

The Leeds & Northrup instrument was operated solo by ANL personnel for the evaluation tests after a one week break-in and training period.

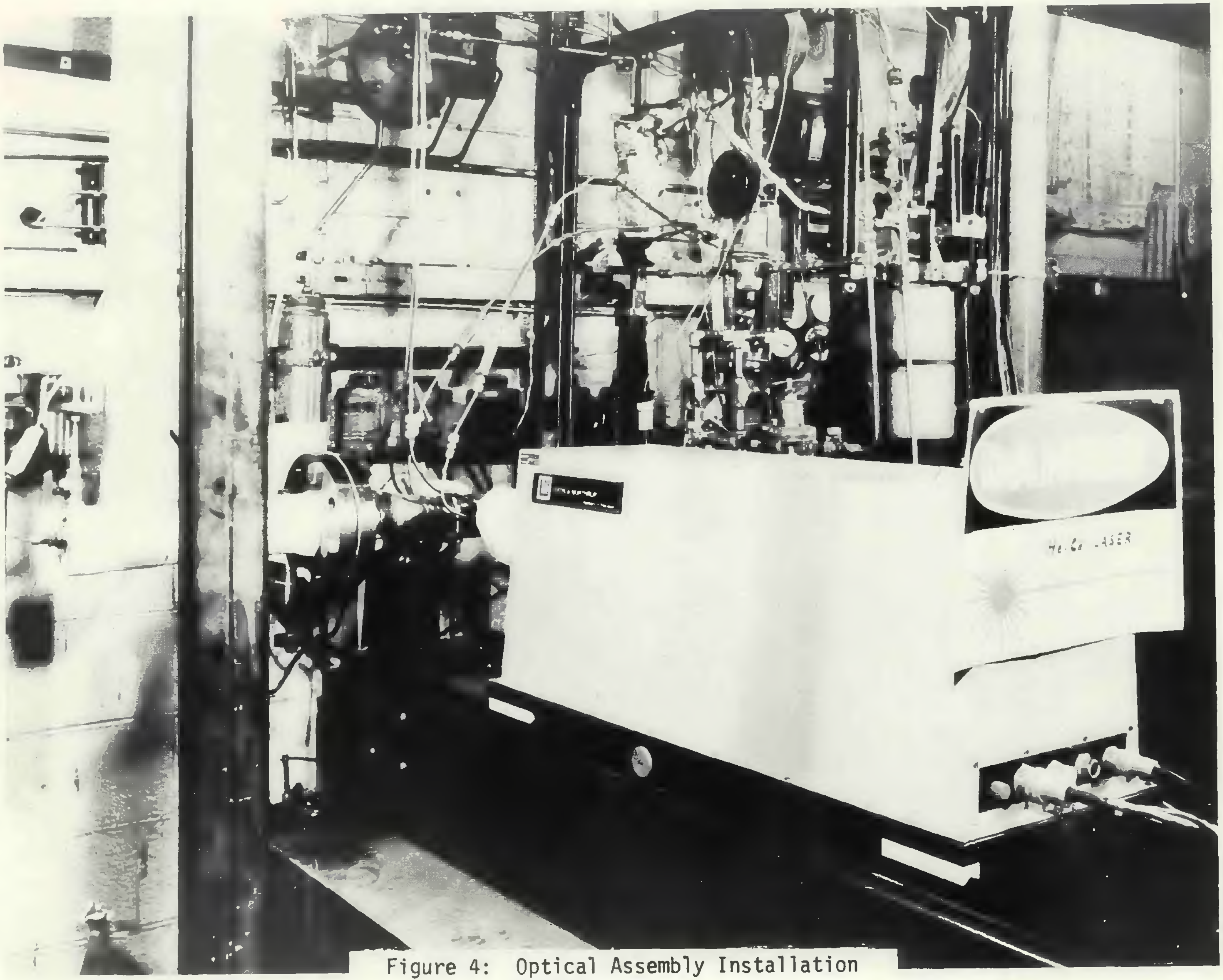


Figure 4: Optical Assembly Installation at ANL

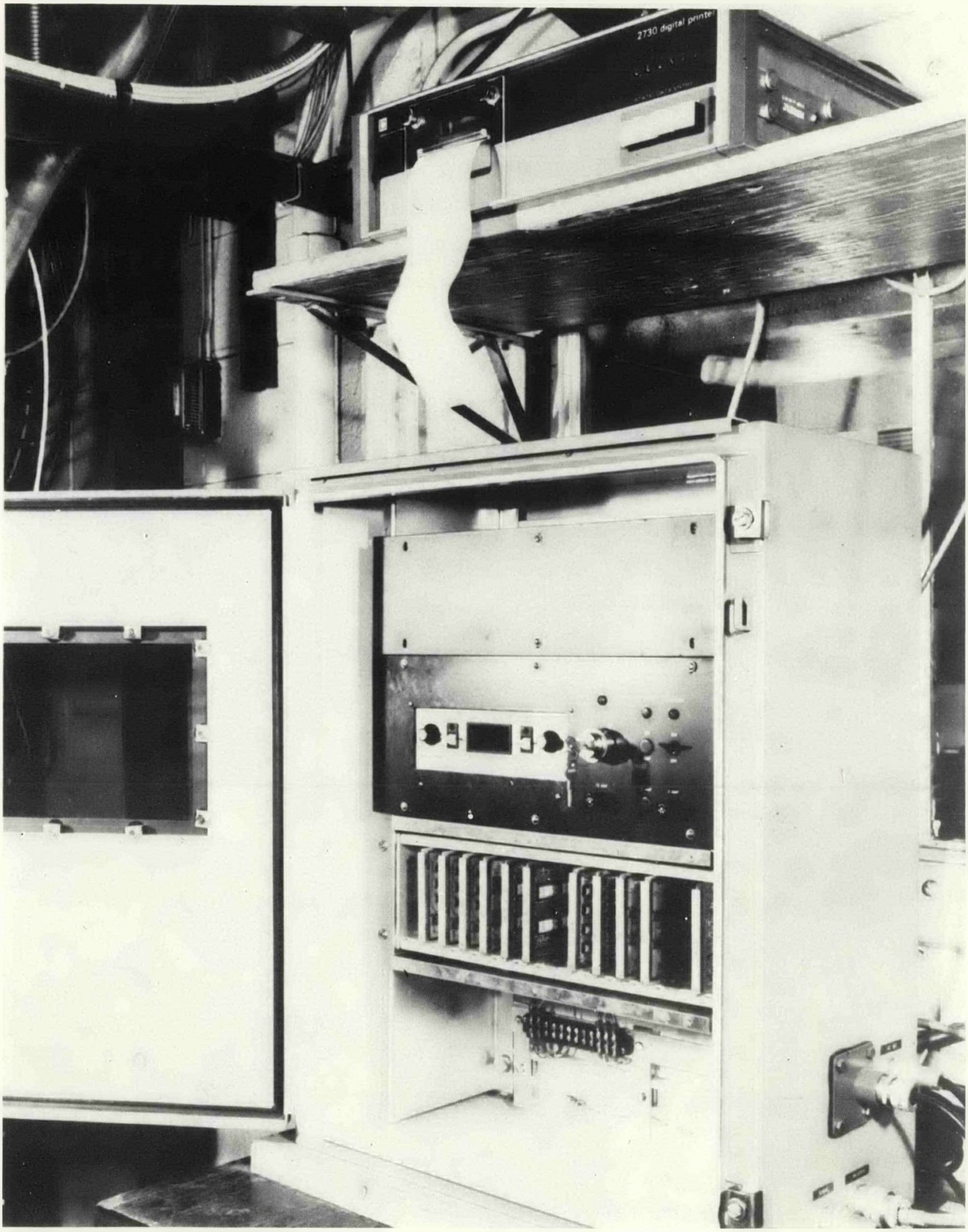


Figure 5: Electronics Unit Installation at ANL

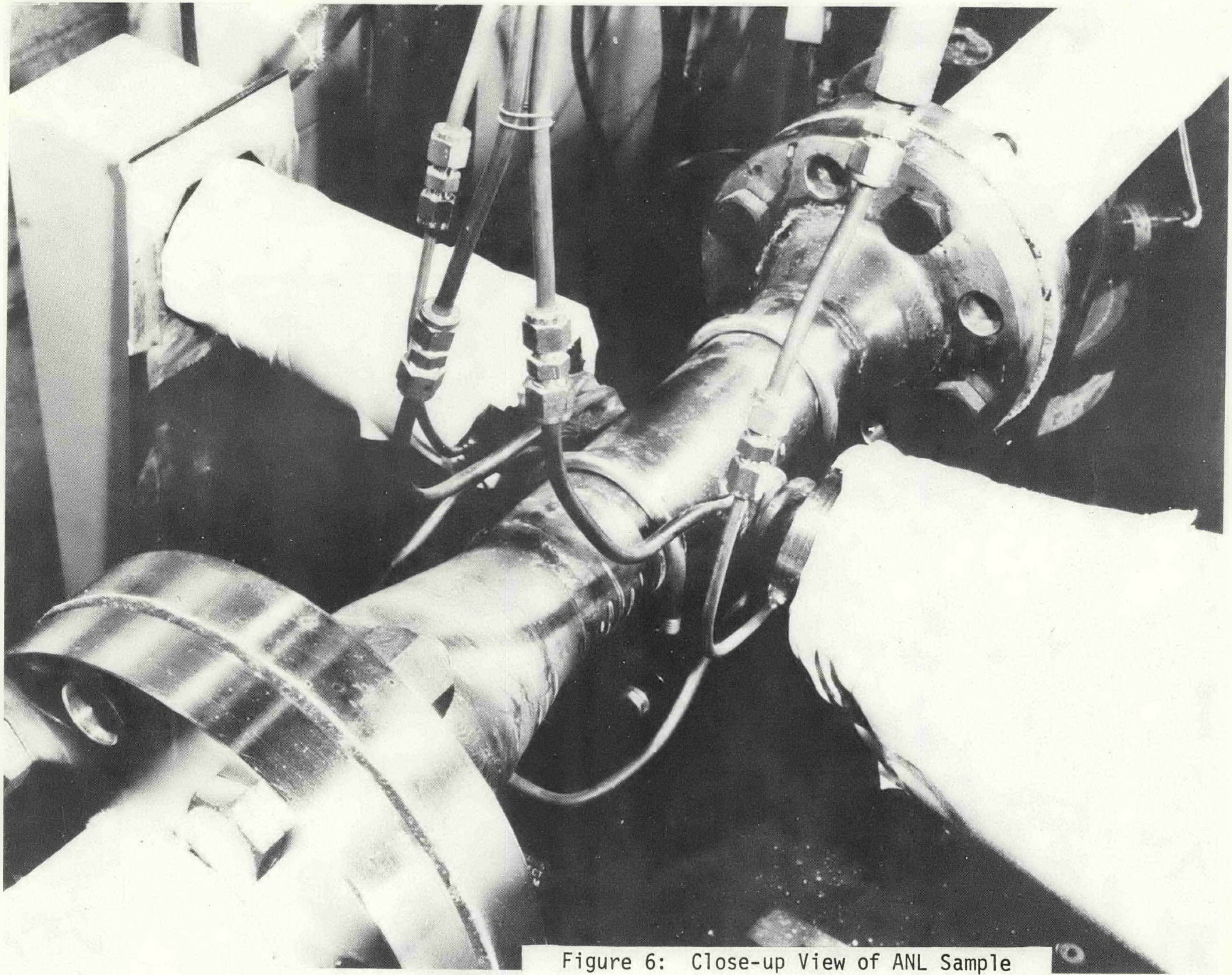


Figure 6: Close-up View of ANL Sample Cell

The piping arrangement at Argonne permitted measurement of particles after the secondary cyclone and after the metal filter which is downstream from the cyclones. Flue gas flow was directed to the particle instrumentation by valves to enable measurement of particles at either the input to or output from the metal filter.

Argonne provided an extractive port upstream of the optical windows that allowed particle size analysis on sampled material with cascade impactors. In addition, steady state grab particle samples were obtained with membrane filters.

The results of three combustion test runs utilizing Sewickley coal and Greer limestone are presented in Table I and Figures 7-9. Table I gives a comparison of size measurements made with the Leeds & Northrup instrument, called MICROTRAC, with the reduced data from the Anderson Cascade Impactor samples.

The average mean volume diameters, $\overline{MV}$, for the impactor samples were calculated from truncated log normal distributions obtained via the Anderson Impactor. Since the MICROTRAC has a linear size response for particles one micron in diameter and larger, and a highly attenuated response to submicron size particles, the lowest channel (submicron region) data points from the impactor were not used. This provides directly comparable data over the size range 1-20 microns. The average mean area diameters, $\overline{MA}$, were similarly calculated from the Anderson Impactor data. The differences between the direct reading, on-line observations via MICROTRAC and the impactor data are tabulated.

The median diameter, 50th percentile for log normal distributions can be expressed as Median Diameter = $\sqrt{MV \times MA}$. The results of this computation are shown in the bottom three rows of Table I.

These results indicate good agreement between optical scattering and cascade impactor methods for particle sizing. In all but one case, the difference is less than one micron.

Two interesting characteristics are observed, however. The MICROTRAC size measurement tends to indicate slightly smaller size for the median

TABLE I: Particle Sizing in Microns

Measurement	In	Out	In	Out	In	Out
Calculated $\overline{MV}$ Anderson Impactor Sample	5.77	4.64	5.39	7.44	5.33	4.74
MICROTRAC $\overline{MV}$	2.92	5.13	3.91	5.45	3.62	4.39
Difference $\Delta\overline{MV}$	+2.85	-0.49	+1.48	+1.99	+1.71	+0.35
Calculated $\overline{MA}$ Anderson Impactor Sample	2.98	2.34	2.08	3.04	2.20	2.58
MICROTRAC $\overline{MA}$	2.15	2.39	2.26	2.64	2.19	2.71
Difference $\Delta\overline{MA}$	+0.83	-0.05	-0.18	+0.40	+0.01	-0.13
50 Percentile Anderson Impactor Sample	4.15	3.29	3.35	4.75	3.42	3.50
50 Percentile MICROTRAC	2.50	3.50	2.97	3.79	2.82	3.45
Difference	+1.65	-0.21	+0.38	+0.96	+0.60	+0.05

diameter and the MICROTRAC consistently shows the size of particles coming out of the final filter to be larger than at the input. In one of the three tests, the impactor data also shows the output particle size to be greater than the input. Further studies are needed to determine whether these are real characteristics of the particle dynamics, characteristics of the experimental method or a function of the instrument. It will be interesting to make similar measurements on a broader distribution of particle sizes and on a different type of particle separator to ascertain whether these observations are unique to the Argonne tests.

The loading data as functions of time are shown in Figures 7-9 for the three operating tests. The in situ volumetric loadings, as outputted by the MICROTRAC instrument, are converted to standard pressure/temperature conditions by the following equation:

$$I\ (\text{Grains/scf}) = \frac{D(1 + 0.00367T)dV}{2.29P} \tag{2}$$

where D = density of particulate (gm/cc)

T = gas temperature, nominally 160C

P = gas pressure, nominally 3 atms.

dV = instrument output in ppm.

The density of the material samples in these tests was 1.2 gm/cc.

The data from MICROTRAC are shown as dots for unit intervals of time. The loading is always high at the beginning of each run due to material loosened in setting the duct valves. It takes about 15 to 20 minutes for this to be purged out and reach a steady state.

The MICROTRAC data shows a slow oscillatory characteristic. Its means of measuring particle size is independent of laser power whereas the indicated loading is directly proportional to laser beam intensity. Similar variations in the dV output were observed when clean air was directed through the gas duct -- when a steady state zero was expected. Therefore, it is most likely that the oscillations were caused by laser instability. This condition is now being investigated by us to identify cause and determine means of eliminating this condition.

Smooth lines are drawn through the MICROTRAC data points to show the

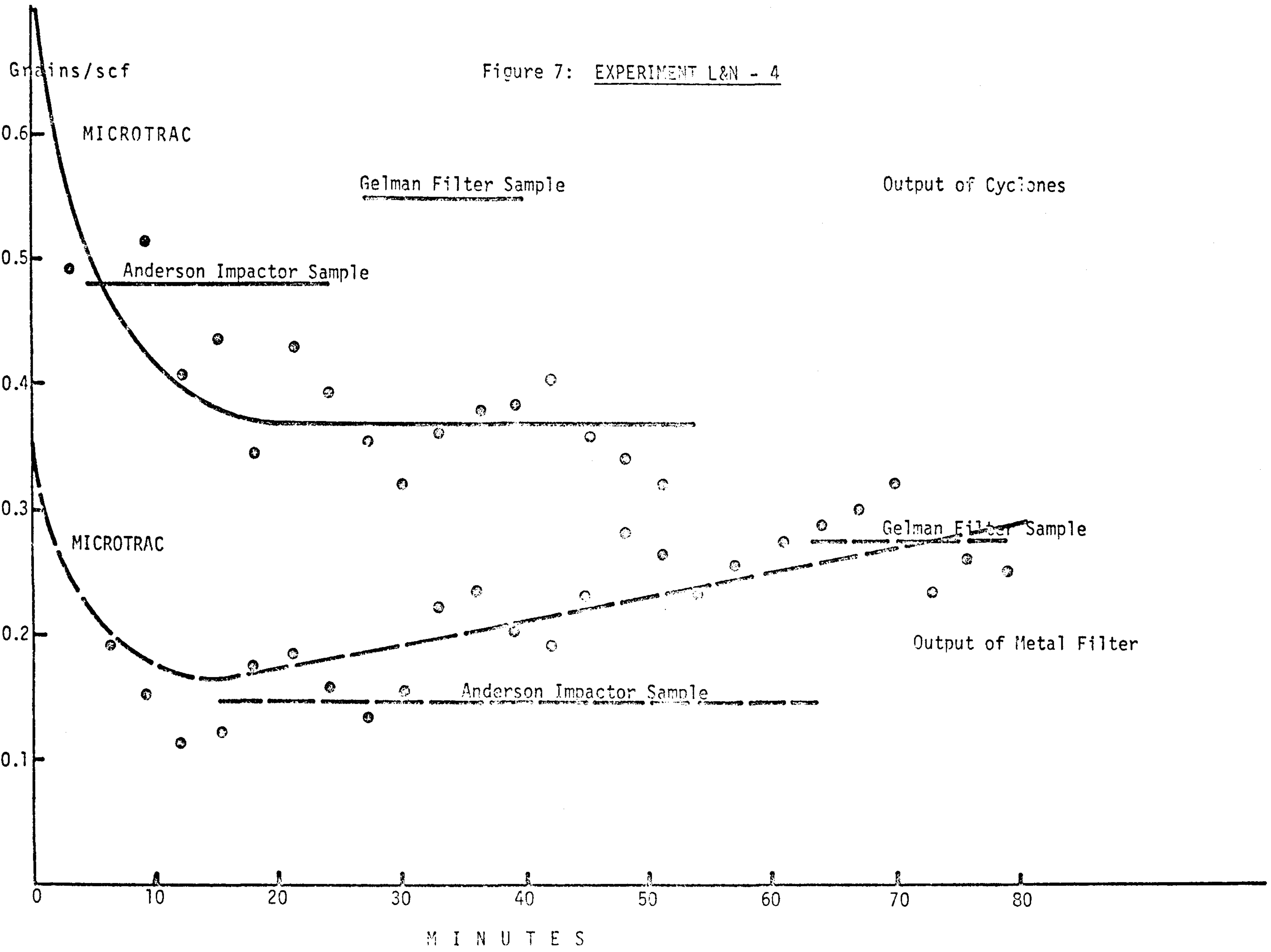


Figure 7: EXPERIMENT L&N - 4

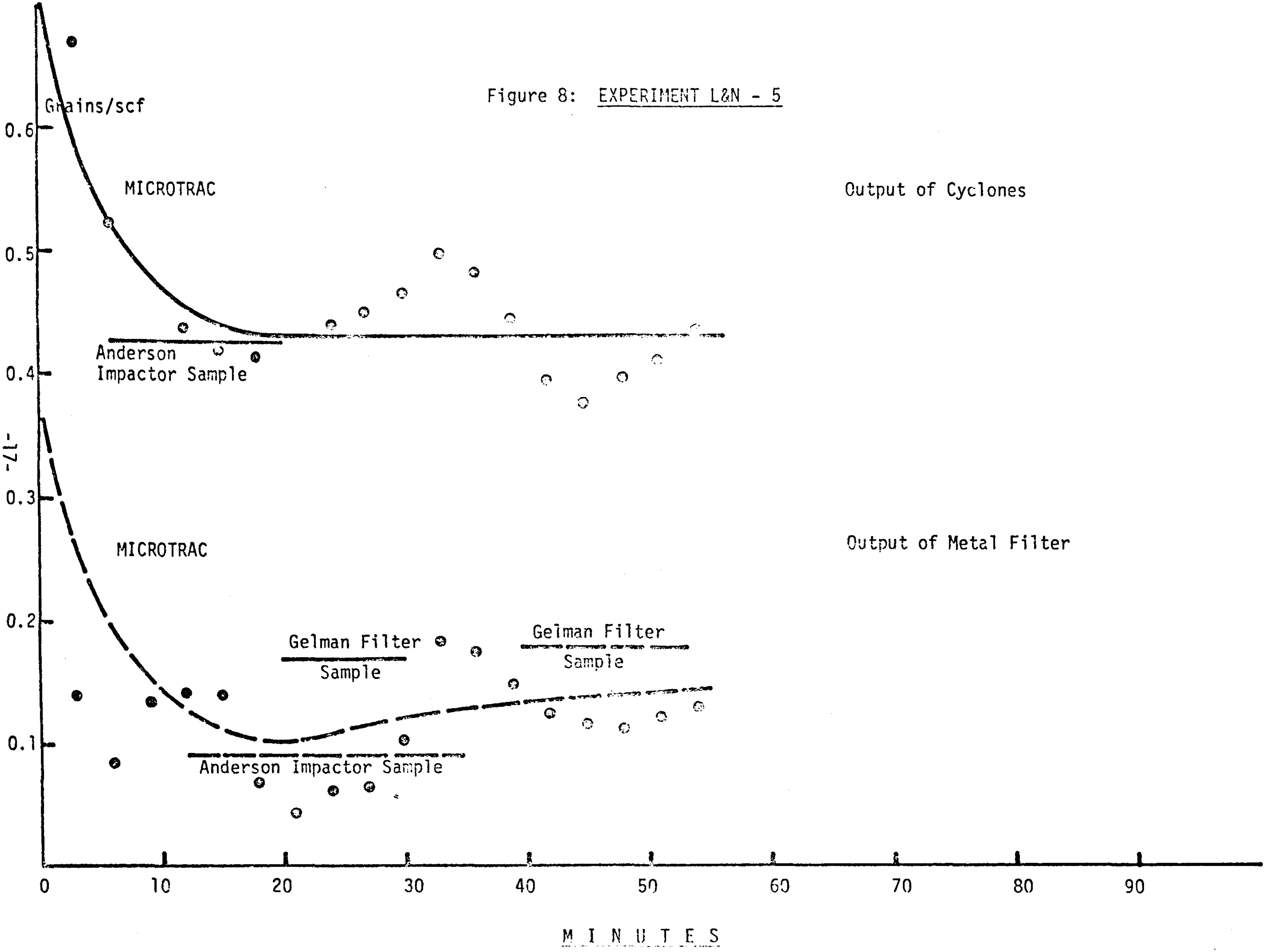
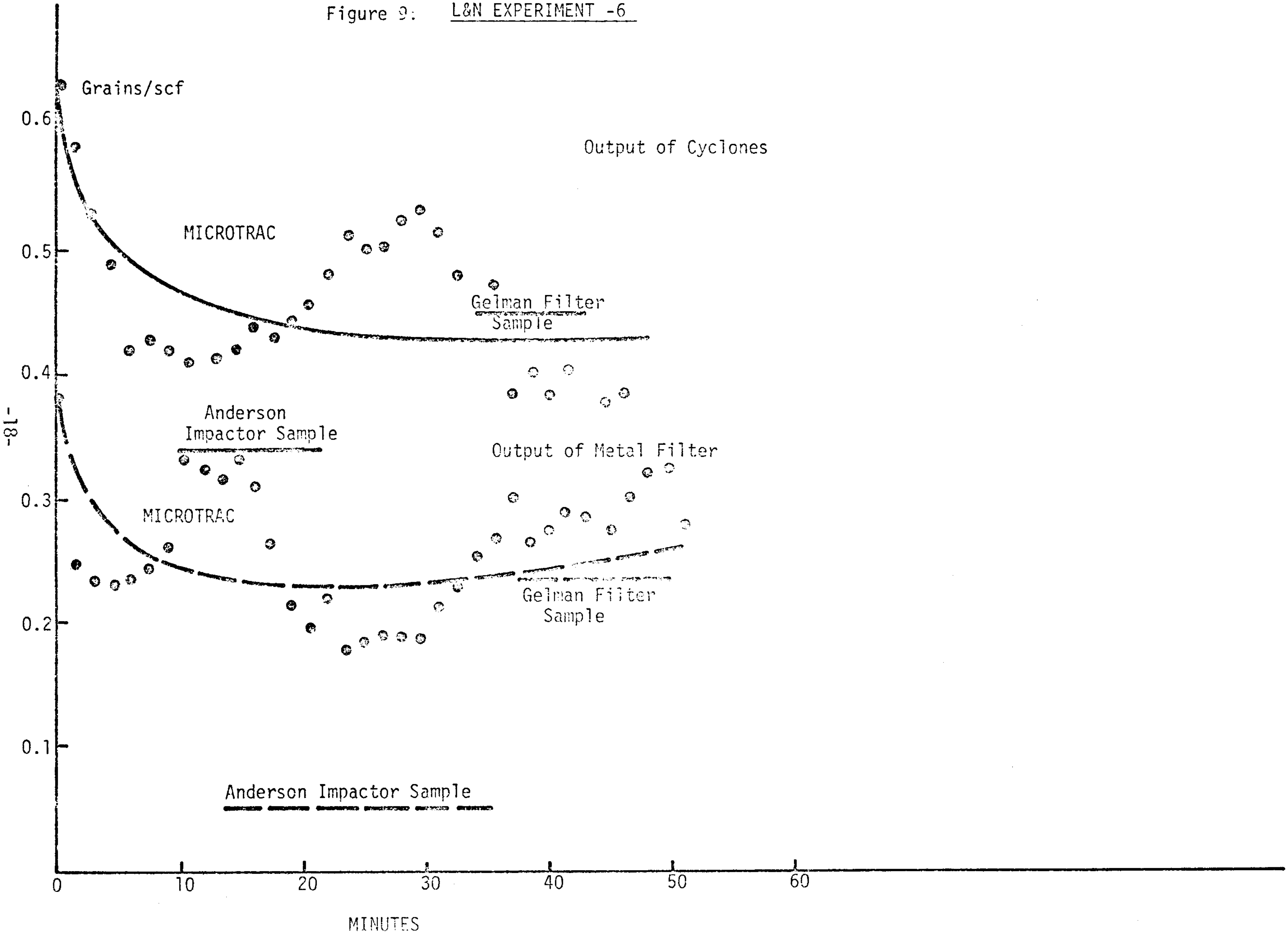


Figure 8: EXPERIMENT L&N - 5

Figure 9: L&N EXPERIMENT -6



loading trends. In addition, the loading values obtained by the cascade impactor and the membrane filter samples are shown. The horizontal location and length of lines for the extracted sample loadings indicate approximate time and duration for collection of each of those samples. The vertical location of each line designates its loading measurement.

A significant part of the variance between MICROTRAC and extracted samples may be due to non-uniformity of loading across the pipe or, probably more likely, due to problems of achieving isokenetic sampling with the extractive probe. A particular advantage of the MICROTRAC type of instrument is that it measures all particles passing through the laser beam and the gas flow is not influenced in any way by this method of measurement.

For installations on larger ducts, such as on the 10 inch i.d. duct at Curtiss Wright, the scattered flux from some particles 1 to 3 microns in size will be vignetted due to the limited size of the collecting optics. The scatter angle Θ_{min} to the first minimum in the diffraction pattern is a function of wavelength (λ) and particle diameter (d) as shown in Figure 1. Thus, very small particles at long distance from the collector lens scatter flux outside this lens. To compensate for this factor (vignetting), we assume that the smallest particles are either uniformily distributed or distributed concentrically about the center of the line of the gas stream. The data processing routine provides a weighting factor for particles producing vignetting, to compensate for their lost flux.

In such installations, the MICROTRAC will detect and measure all particles traversing across the laser beam which are larger than a specified size (e.g., 3 microns). The amount of scatter flux collected from particles smaller than that size is determined by the distance of the collecting lens from the center line of the duct and the size and quantity of these particles. Thus, once the installation geometry is specified, the appropriate weighting factors are determined for compensating that flux which is lost. These constants are then inserted into the microcomputer program to correct the size distribution and loading data and provide a uniform response over the total range of particle size (1 to 20 microns).

SECTION 4

CONCLUSIONS AND FUTURE WORK

The results of these tests on the ANL fluidized-bed combustion system indicate that over the limited range of particle size and loadings encountered downstream of the cyclones, the MICROTRAC data output compares reasonably well with Anderson impactor measured samples. Furthermore, differences observed for these two types of measurements may be attributed to the means of extracting the particulate sample for the cascade impactor.

Three problems were observed with the MICROTRAC instrument and all three problems seem related to the laser:

(1) The laser output power decreased with time and exhibited a slow oscillation,
(2) The loading sensitivity (0.1 grains/scf on a 1 inch i.d. duct) is marginal for after final filtration measurements, and
(3) A significant part of the particulate loading is contributed by submicron size particles which are not measurable by the prototype instrument.

The latter problem was anticipated since the instrument response falls rapidly as the particle size (diameter) approaches the wavelength of the laser emission (0.442 μm). Some improvement in submicron response could be achieved when a reliable ultraviolet laser is commercially available.

The loading sensitivity observed at ANL is about three times less sensitive than predicted from our laboratory measurements. This is directly relatable to the instabilities of the laser output power. Loading sensitivity on the order of 0.001 grains/scf should be achievable on a 10 inch i.d. duct at 10 atms. with a laser operating at rated power.

The cause of laser instability in the prototype unit will be investigated and corrective action will be sought from its vendor. Then the volumetric calibration of the instrument will be reverified in our laboratory.

Finally, the prototype instrument will be delivered to Curtiss Wright Corporation where it will be installed between the final filter and the turbine inlet on the Small Gas Turbine system. The duct at that location is a 4-inch i.d. refractory lines spool piece. With this size duct and our capability to move the receiving optics on its optical bench, we can vary the distance from the gas stream to the collecting optics. This will enable us to determine the uniformity of loading across that duct and to verify the effectiveness of the compensation for vignetted flux in larger ducts.

This evaluation will complete our work on this contract and we will be ready to investigate its applicability to direct combustion demonstration-scale plants.

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