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ABSTRACT

The differences which exist between fine (<2.5 μm) and coarse (>2.5 μm) airborne particles with respect to their origin, chemical properties and environmental impact, call for their separate collection and analysis. An automated dichotomous sampler (ADS), equipped with a high efficiency single-stage virtual impactor and a microprocessor based controller to self-correct fault conditions including filter overload, has been developed as a model for commercial production.

INTRODUCTION

The differences which exist between fine (<2.5 μm) and coarse (>2.5 μm) airborne particles with respect to their origin, chemical properties and environmental impact, call for their separate collection and analysis. Automated dichotomous samplers (ADS), equipped with virtual impactors, have been developed for collecting size segregated ambient aerosol samples for large-scale monitoring

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applications.[1] They have been shown to be the most precise instruments of several tested in an intercomparison of sampling and analysis techniques for ambient aerosols.[2] Ten of these samplers were deployed in the St. Louis Regional Air Pollution Study monitoring stations, and from 1975 through 1977, 35,000 samples have been collected and analyzed.[3] To suit the need for a low-cost commercial dichotomous sampler, we have designed an improved and simplified virtual impactor for a second generation ADS. Additional features have been added based on the field experience with the earlier ADS. The operation of the sampler is controlled by a microprocessor-based electronics system.

VIRTUAL IMPACTOR DESIGN

The virtual impactor is an inertial particle size separator. Since a virtual impactor does not collect the particles, but merely redirects them in an airstream, it is free from problems of particle bounce and reentrainment often found in other inertial size separating devices. The new virtual impactor was designed specifically for the ADS and exhibits sharp particle-cut characteristics and low particle loss. Additional design objectives were simplicity, reliability and compatibility with analysis instruments. The resulting single stage virtual impactor design is shown in Figure 1. A total flow of $Q_0 = 1.0\ m^3/hr.$ is drawn from the inlet tube (with 2.86 cm ID) through the orifice ($D_0 = 0.305$ cm) in the acceleration nozzle. Particles greater than 2.5 μm aerodynamic size are focused and impacted across a gap (spacing S = 0.318 cm)

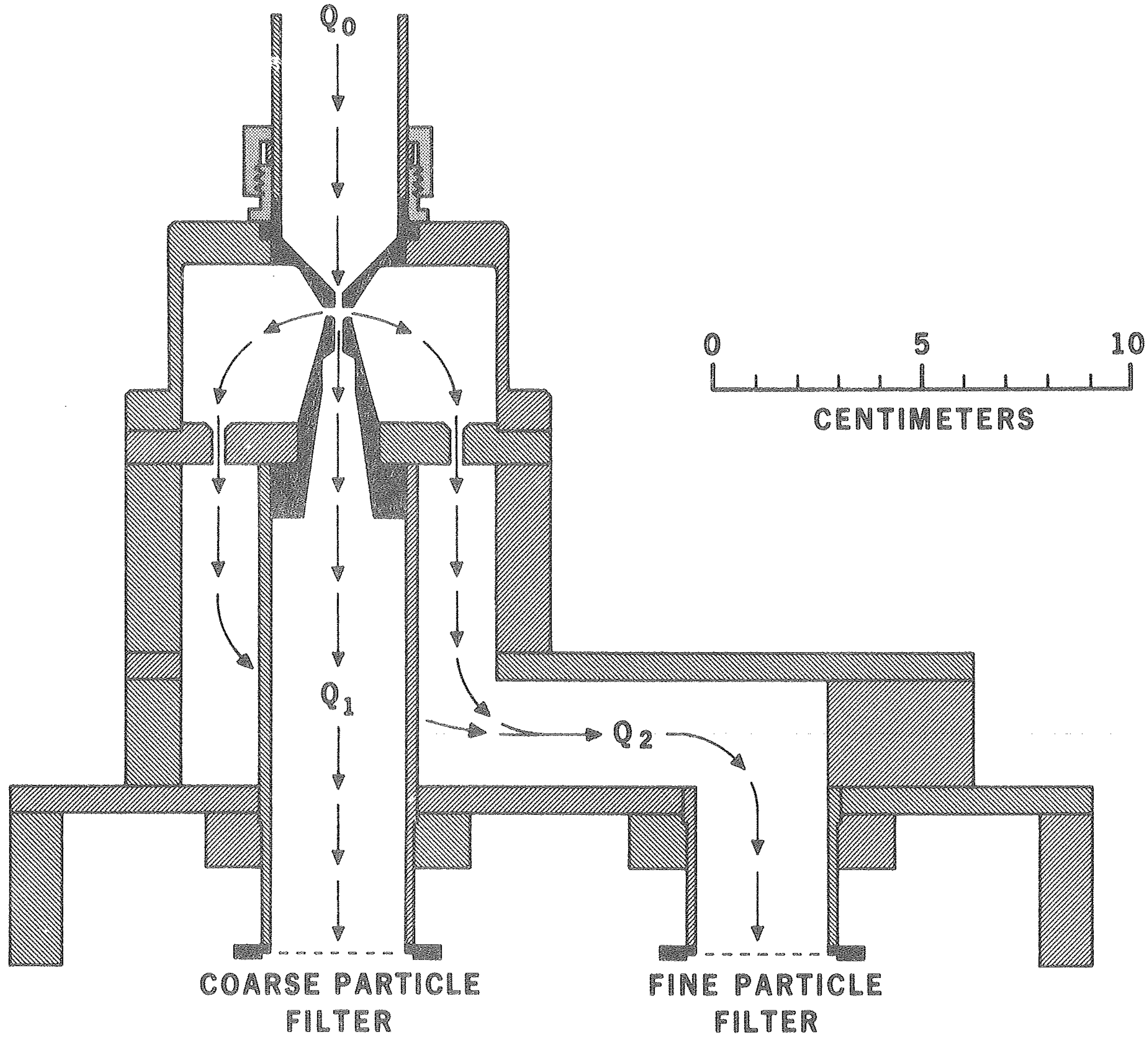

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Fig. 1. A cross-sectional view of the single-stage virtual impactor.

into the opening (D_1 = 0.422 cm) in the collection probe. These coarse particles are then carried by a flow of Q_1 = 0.1 m^3/hr. into the central drift tube where they are dispersed and collected uniformly on the coarse particle filter. The fine particles will be directed outward in a radial direction by the major flow Q_2 = 0.9 m^3/hr. They are then pumped through a set of eight holes (each with D_2 = 0.318 cm) in the flow distribution plate, recombined in the outer cylinder, and eventually deposited on the fine particle filter.

The dichotomous sampler is intended for sampling inhalable particles (i.e., those particles smaller than 15 μm), and is therefore equipped with an inlet device which excludes all particles above 15 μm. The virtual impactor is therefore designed to handle all particles up to 20 μm with minimal losses. The particle losses of the virtual impactor tend to consist of two components: a loss peak near the cutpoint where particles may collide with the physical surfaces which divide the major and minor flows, and an increase in losses for the massive particles which must navigate through the apparatus.

A theoretical study of virtual impactors has accurately accounted for the particle separation characteristics but has been found to be less useful in predicting losses for design purposes.[4] We have therefore resorted to an empirical approach. By focusing the particles in the acceleration region, paying proper attention to maintaining flow symmetry, and by the optimization of a number of geometrical parameters, we have been able to reduce the losses for liquid particles to less than 1% for all particle sizes up to 20 μm. Sample mass measurement by beta-ray attenuation and elemental composition determination by x-ray fluorescence requires good uniformity of particle deposition on filters. This has been achieved for all particles up to 20 μm. A more detailed account of the virtual impactor design is given in a separate report.[5]

SAMPLER DESCRIPTION

Aerosols are to be collected uniformly on 37 mm diameter membrane filters mounted in 5.1 x 5.1 cm plastic frames. The 32 mm opening in the frame defines the active deposition area. In order to avoid the problem of sulfur migration into the filter matrix as has occasionally occurred with the Millipore[†] cellulose ester filters,[6] Teflon[†] filters with 1.0 μm pore size are used (supplied by Ghia Corporation[†], Pleasanton, CA 94566). These thin filters (typically 1 mg/cm^2), being non-hygroscopic and having low impurity contents, are ideally suited for beta gauge and x-ray fluorescence measurements. They are held in commercial slide trays (36 samples) and can be cycled through all sampling and analysis instruments without being handled individually.

The ADS is designed to sample at a constant rate of 1.0 m^3/hr. A schematic diagram of the flow system is shown in Figure 2. The flow division between the coarse and fine particle filters is 1:9 (Q_1/Q_0 = 10%). A pneumatic feedback controller (Modified Bellofram Model No. 745 from Sierra Instruments, Inc.[†]) maintains a constant pressure differential

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[†]References to a company or product name does not imply approval or recommendation of the product by the University of California or the United States Department of Energy to the exclusion of others that may be suitable.

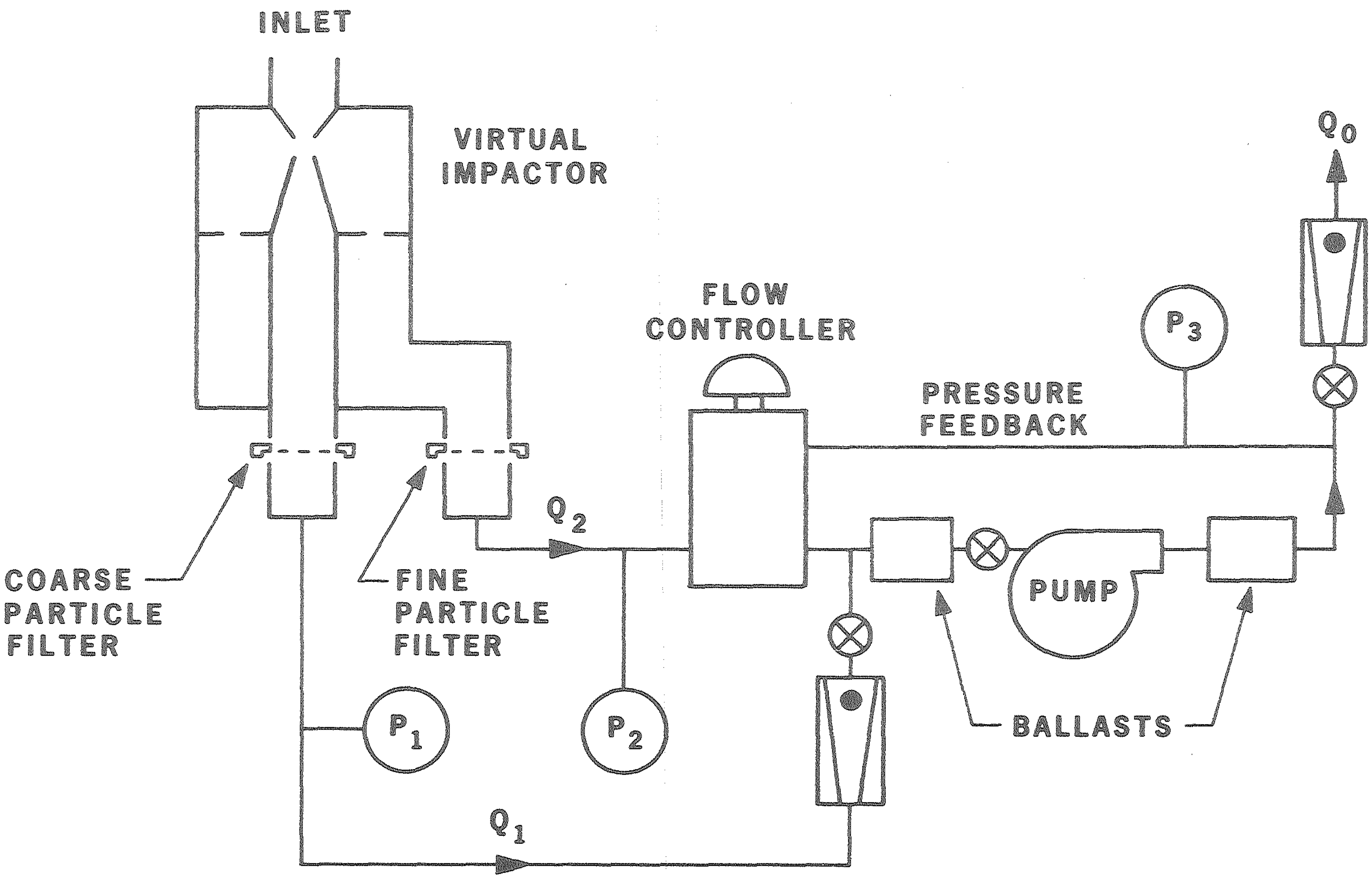

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Fig. 2. A schematic diagram of the ADS Flow System

of P_3 (10 cm Hg) across the exit orifice. Two ballast cylinders of about 1 ℓ each are used to damp the pulsations from the diaphram pump (Model Number 2917CE18, Thomas Industries, Inc.†, Sheboyan, Wisconsin 53081).

The pressures P_1 and P_2, behind the coarse and fine particle filters respectively, are monitored by pressure switches (Dwyer†, Model Numbers 1823-2 and 1823-20) for fault conditions. A lower than normal pressure differential signifies either a broken filter or an improper seal. As the clean filters become loaded, P_2 in particular will increase significantly until the valve in the flow controller is fully open. At this point, the flow controller has reached its limit of regulation and any further filter loading will result in a decrease of Q_0. This filter overload is detected by a second pressure switch (ASCO Tripoint† SB30A) which is set to trip when P_2 reaches 36 cm Hg below ambient, a condition corresponding to a 3% reduction in Q_0.

The sampler changer consists of an "elevator" which holds the twin slide trays and a horizontal shuttle which transports the selected pair of filters from their nested location in the slide trays to the sampling position. A template with binary coded decimal hole patterns is fastened to the elevator so that its absolute level location (from 1 to 36) can be sensed with a photo diode and displayed. A motor driven clamping device completes the sealing of the sample slide frames before the solenoid valve ahead of the vacuum pump is opened.

Figure 3 shows the top view of the ADS with the lockable top cover in the lifted position. The controller is located towards the front with the output printer and aerosol inlet to the rear. The electronic controller includes a number-oriented microprocessor (National Semiconductor† MM57109), and a digital watch and calendar circuit (Fairchild Semiconductor† FWA 6004), along with other logical circuitry. It can provide three modes of operation, namely, fully automatic, remote control via a computer link or manual execution of each functional step.

After loading two trays of filters into the elevator, a typical operating sequence involves selection of the hour of the day for the sampling to begin, of the sampling period in hours, and the assignment of a tray number. These parameters are set by thumb switches on the controller panel. Pressing the "AUTO" button then initiates the sampling cycle. The elevator lowers itself to the first slide position and waits for the time to begin sampling. At this time, the shuttle transports the first pair of slides from the trays to their sampling positions under the virtual impactor. Following the filter clamping, the solenoid valve at the vacuum pump is activated for sampling. Following a 10-second pause for the flow conditions to be fully established, the pressure sensing switches (P_1 and P_2) are then examined. If either the P_1 or P_2 conditions are not satisfied, the slides will be withdrawn, a new pair of slides will be inserted, and an error message will be printed. If the P_2 condition is violated at any time after 20 seconds of sampling, then it is interpreted as a filter overload. In such cases, a fresh pair of samples will

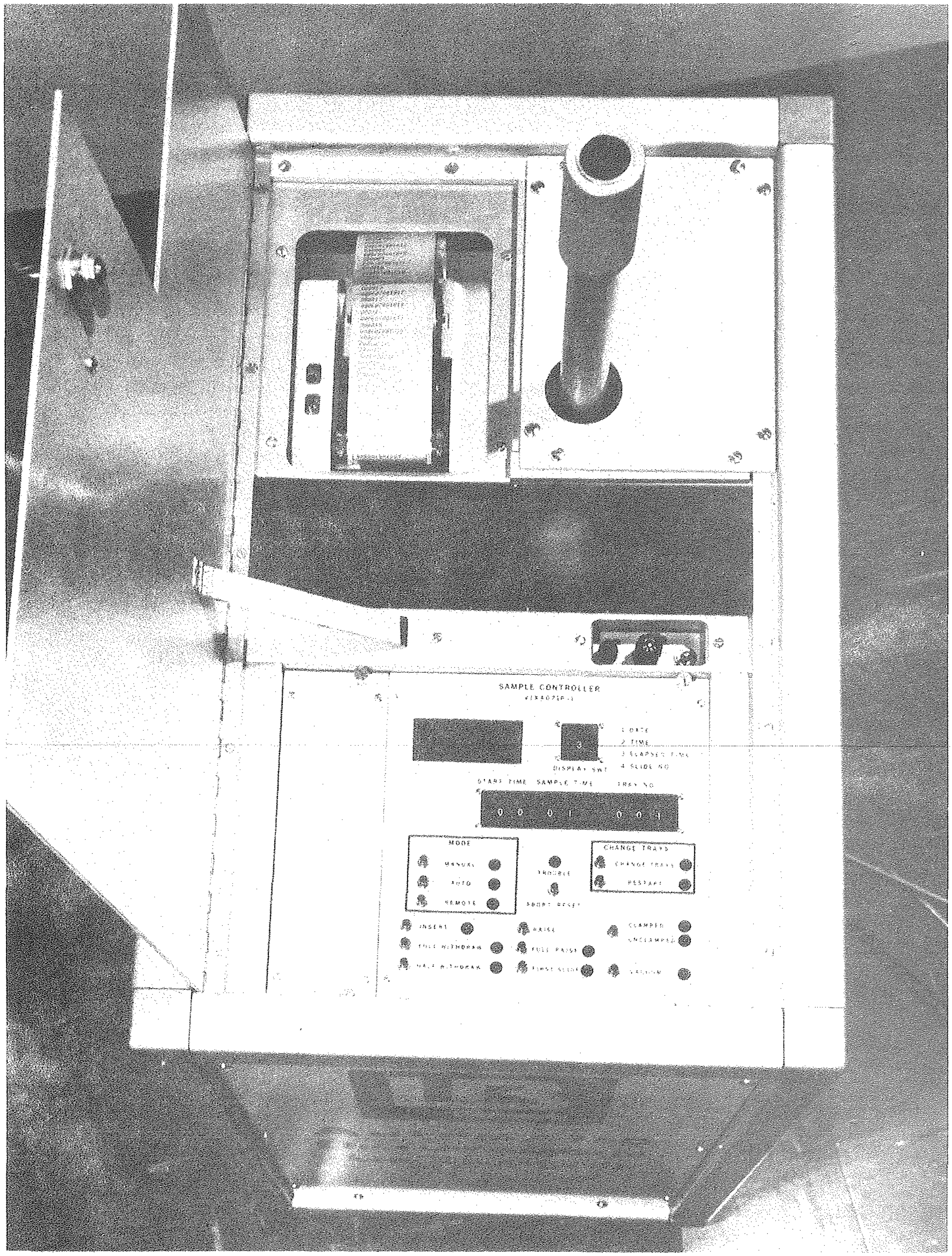

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Fig. 3. A top view of the Automated Dichotomous Sampler

be inserted, a message is printed, and sampling will continue for the balance of the preset sampling period. The phase of the regular sampling periods is therefore maintained and all samplers in a network remain synchronized.

To facilitate record keeping by the operator, pertinent information is automatically recorded on the printer. This includes the assigned sample tray number, preset sampling period, listing of the start and termination times in month, day, hour and minute for each sample together with any error code. In order to allow the operator to change slide trays at any time without interrupting the sampling cycle, an automatic change tray feature has been incorporated. When this function switch is activated, the sample shuttle will withdraw partially without disturbing the samples being collected while allowing the elevator to be raised to the top. An empty slot is always reserved in the first slide position of the new trays where the current samples will be stored upon the completion of their regular cycle.

Figure 4 shows the front view of the sampler with the side and rear panels removed. Referring to the side view of the sampler in Figure 5, the elevator appears to be situated at the center. The vacuum pump is hidden in the soundproof enclosure at the lower left while the virtual impactor is at the upper right in front of the printer. The two flow meters shown near the lower right-hand corner are supplied by the Porter Instrument Company[†] and are custom calibrated to ± 2% accuracy. The special calibration marks of 1.67 ℓ/m and 16.7 ℓ/m corresponds to the designed flows for Q_1 and Q_0 respectively.

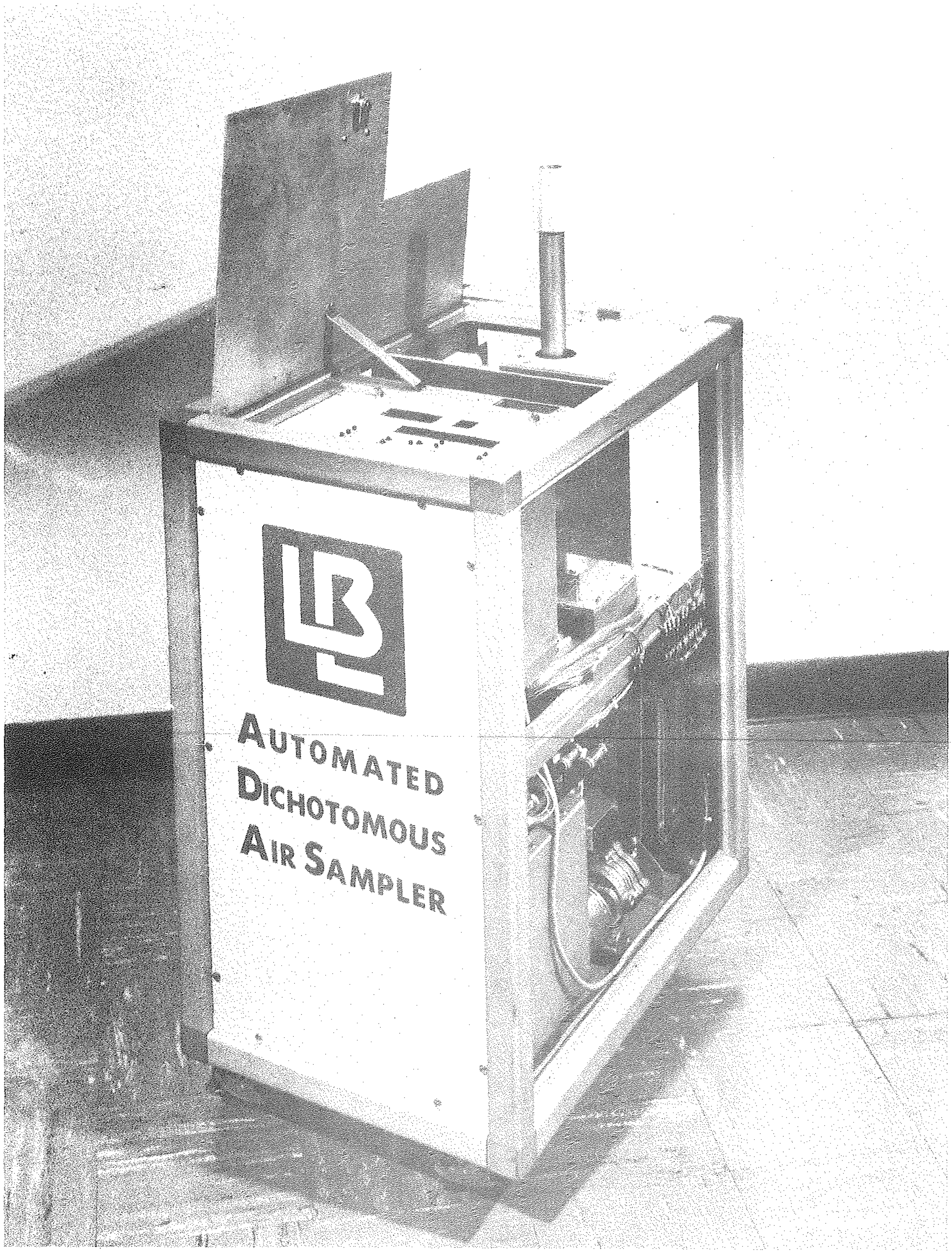

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Fig. 4. An oblique view of the ADS with side panels removed.

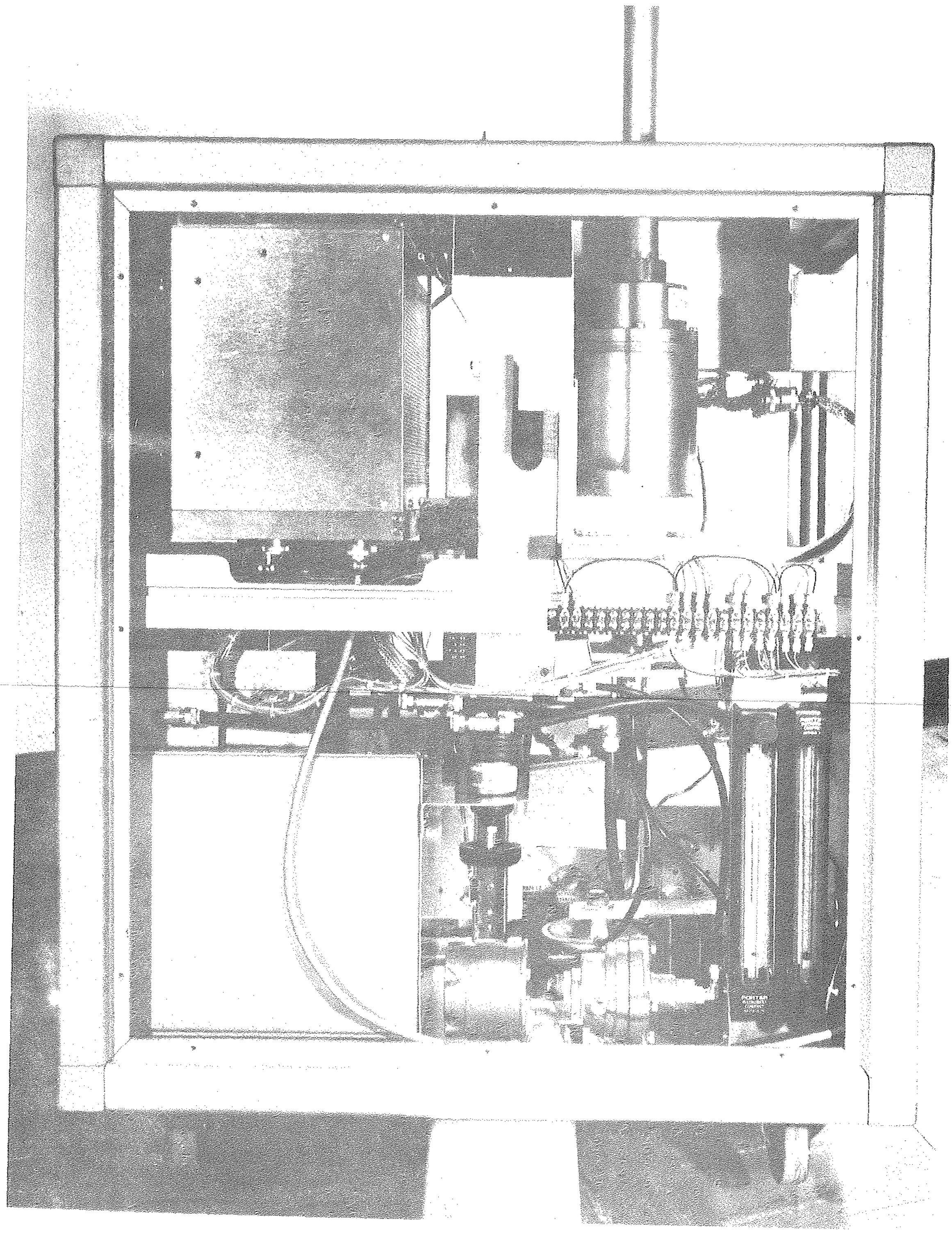

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Fig. 5. A side view of the Automated Dichotomous Sampler.

SAMPLER PERFORMANCE

The performance of the virtual impactor in terms of its particle-cut characteristics, wall loss and uniformity of deposition, has been evaluated using methods previously described.[7] Monodisperse DOP particles labeled with uranine dye are drawn from a Berglund-Liu[†] vibrating orifice generator into the sampler to be collected on the coarse particle filter (C) and fine particle filter (F). These samples and any particle loss within the virtual impactor are washed off for quantitative determination by UV fluorescence measurements. The run-time of each test is optimized such that the detection limit of any loss measurement is about 0.25%.

The test results of the 2.5 μm cutpoint (when C/(C+F) = 0.55) virtual impactor is plotted in Figure 6. The maximum loss peak near the cutpoint is under 1% with the uncertainty indicated by the error bar. Through experimentation, we were able to eliminate particle losses in all other regions of the impactor except at the inner tip of the collection probe. No losses were found at sizes below the cutpoint. In the coarse particle range, we measured about a 1% loss at 20 μm. About 0.3% of the 20 μm particles were found on the inlet cone due to gravitational settling, the remaining were found as wall losses in the drift tube.

The virtual impactor design permits a different particle size cutpoint to be realized by the replacement of the acceleration nozzle and the collection probe. Figure 7 shows the similar results obtained for a 3.5 μm cutpoint version in which only the critical

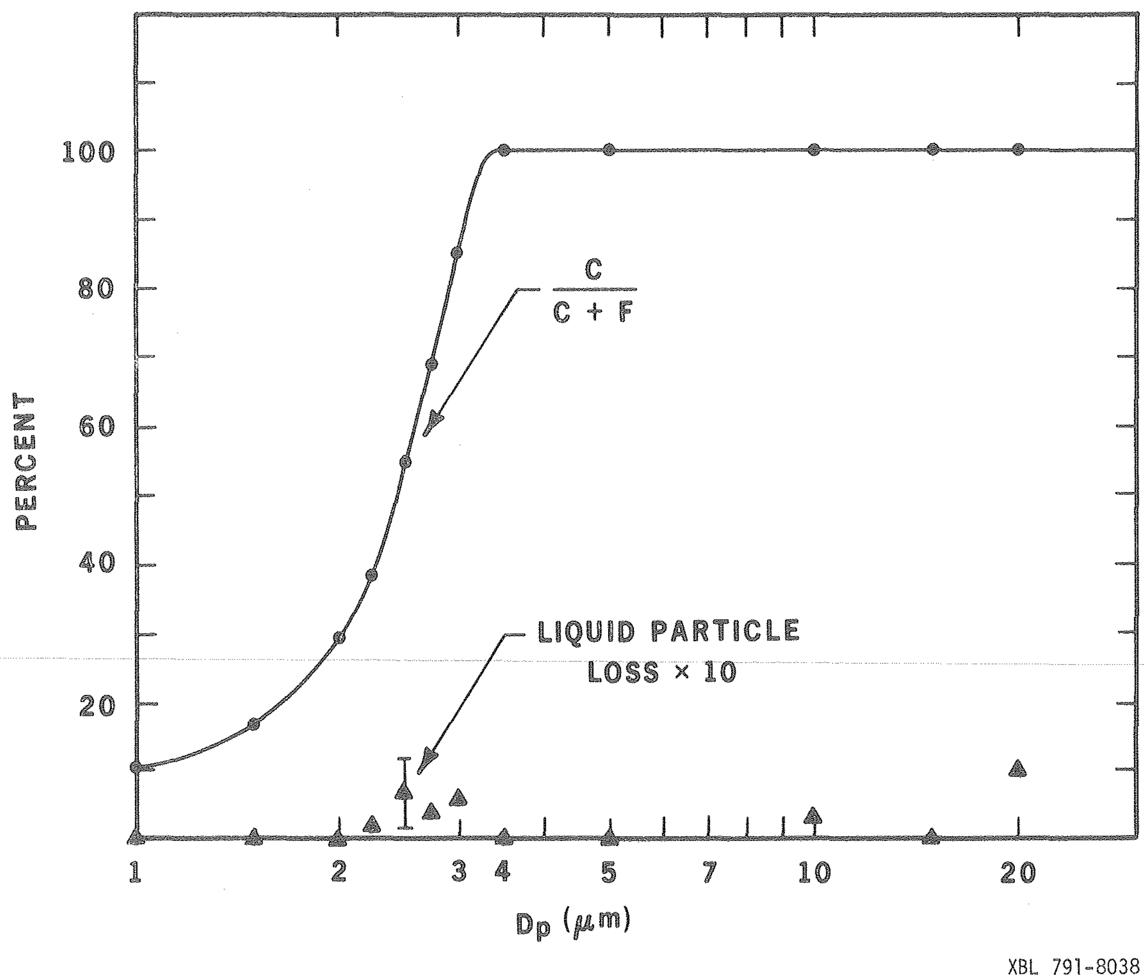

Fig. 6. The size separation characteristics and wall loss measurement of a 2.5 μm cutpoint virtual impactor as a function of particle size Dp. C and F represent particle collections on the coarse and fine filters respectively.

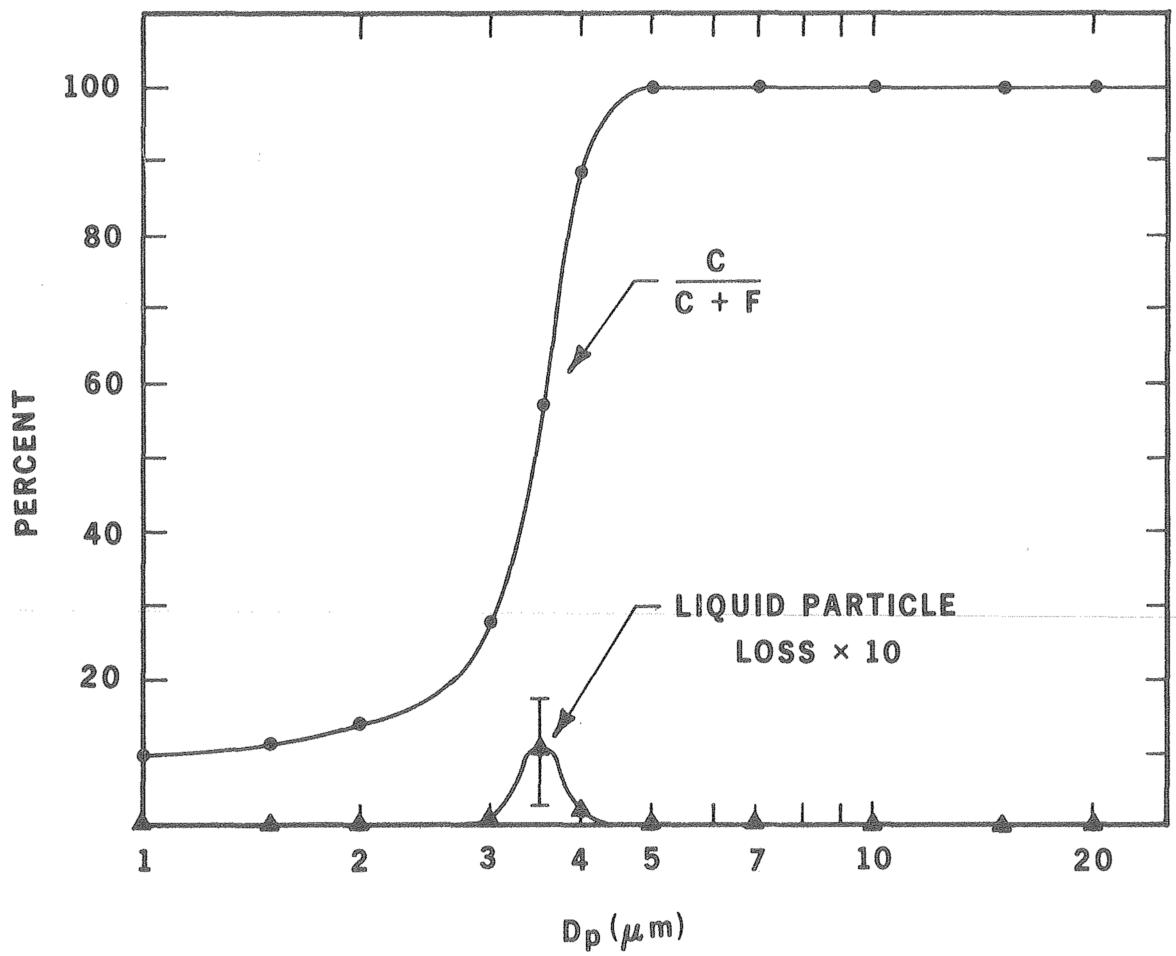

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Fig. 7. The size separation characteristics and wall loss measurement of a 3.5 μm cutpoint virtual impactor.

dimensions are changed, D_1 and D_2 being 0.391 cm and 0.541 cm respectively.

In terms of aerosol mass per unit filter area, fine particles are much more effective in clogging the filter than coarse particles. Results on filter loading test with smoke particles indicated that, for the 1 μm pore-size Teflon[†] filters used in the ADS, the maximum mass loading was 100 ± 10 μg/cm².

CONCLUSION

The recognized importance for an aerosol monitoring network to measure the proper aerosol parameters in terms of particle size and chemical composition has prompted the development of dichotomous samplers that are well characterized, highly efficient, and simple to produce. Automation not only reduces operating cost and human errors, it also insures the validity of samples taken in important incidents (during smog episodes and heavy aerosol loading conditions) by detecting the filter overload and changing samples. The second generation ADS has fulfilled its design objectives to provide better quality and standards in airborne particulate monitoring.

ACKNOWLEDGEMENTS

The design of the virtual impactor used here was supported by The Environmental Protection Agency under Interagency Agreement with the Office of Health and Environmental Research of the Department of Energy. The complete sampler system design as described here was supported by the Office of the Assistant Secretary for Conservation and Solar Applications of the Department of Energy under Contract W-7405-ENG-48.

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