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DYNACTOR SCRUBBER EVALUATION

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DYNACTOR SCRUBBER EVALUATION

by

D. W. Cooper and D. P. Anderson

GCA Corporation
GCA/Technology Division
Bedford, Massachusetts 01730

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EPA Project Officer: D. L. Harmon

Control Systems Laboratory
National Environmental Research Center
Research Triangle Park, North Carolina 27711

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ABSTRACT

A novel aspirative spray scrubber, the Dynactor (RP Industries, Hudson, Massachusetts), was tested for power consumption and collection efficiency at three flow rates, two temperatures, two dust loading levels, for two dusts. Total filter samplers and cascade impactors were used upstream and downstream from the collector. Power was determined from voltage, current, and phase angle measurements. A factorial design series of tests at two levels of flow, concentration, temperature, and dust type gave these average mass efficiencies: 99.0 percent for 4.0-5.6 μm aerodynamic diameter, 98.4 percent for 2.5-4.0 μm, 93.0 percent for 1.3-2.5 μm, 75.4 percent for 0.8-1.3 μm, 27.4 percent for 0.54-0.80 μm, and 47.4 percent for < 0.54 μm. Higher efficiency was fostered by: lower flow rate, lower inlet temperature, higher mass loading. Power consumption was about one-third of that expected from a venturi scrubber operated at a pressure drop (1.0×10^4 N/m^2 = 40 inches H_2O) giving equivalent collection efficiency. Collection efficiency for both the Dynactor and the venturi scrubber decreases dramatically for fine particles smaller than 1 μm.

This report was submitted in fulfillment of Task Order No. 6 under Contract No. 78-02-1316 by GCA/Technology Division under the sponsorship of the Environmental Protection Agency. Work was completed as of July 26, 1974.

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ACKNOWLEDGMENTS

Information and support supplied by Stanley Rich, Vice President and Technical Director of R P Industries, and by Dale Harmon, of Control Systems, Environmental Protection Agency, are acknowledged and were appreciated.

SECTION I
CONCLUSIONS

This evaluation was one of a series of such evaluations being conducted by the Environmental Protection Agency to identify novel devices which are capable of high efficiency collection of fine particulates. The Model DY-12-F2 Dynactor Scrubber of R P Industries (Hudson, Massachusetts) which was tested had substantially less than 99% collection efficiency on fine particulates, those smaller than 2 μm in diameter, and thus did not satisfy this objective.

The following average mass efficiencies were observed at the nominal rated flow (0.47 m^3/s, 1000 cfm) and at half its rated flow:

Size fraction (aerosol aerodynamic diameter)	Efficiency 0.47 m^3/s (1000 cfm)	0.24 m^3/s (500 cfm)
4.0-5.6 μm	98.8	99.2
2.5-4.0 μm	98.0	98.8
1.3-2.5 μm	91.2	94.8
0.8-1.3 μm	67.4	83.4
0.54-0.8 μm	28.1	26.7
$\leq$ 0.54 μm	45.5	49.3

These efficiencies are similar to those expected from a venturi scrubber with a pressure drop of 1.0 x 10^4 N/m^2 (40 inch H_2O). The Dynactor operates on about one-third the power of such a venturi. A comparison of costs for a venturi scrubber and a Dynactor scrubber for a 19 m^3/s (40,000 cfm) application indicated that the major difference between the two would be about \$40,000 to \$50,000 per year savings in electrical power costs (at \$0.025/kWhr) for those using a Dynactor scrubber.

The following factors improved spray scrubber collection efficiency: lower inlet temperature, lower air flow, higher particle mass concentration, higher nozzle pressure, surfactant addition.

SECTION II

RECOMMENDATIONS

Although the Dynactor does not give high efficiency collection for particles smaller than one micron diameter, in those applications for which a venturi scrubber might be suitable, the use of a Dynactor scrubber should be considered as one alternative. If collection efficiency requirements and other considerations would require a venturi scrubber with a pressure drop on the order of 1.0×10^4 N/m^2 (40 inch H_2O), a Dynactor scrubber could be substituted with a significant savings in power consumption and a comparable cost for equipment and installation.

SECTION III

INTRODUCTION

This work was done to evaluate the Dynactor scrubber with respect to its mass collection efficiency as a function of particle size, the effect of several parameters on this efficiency, the air-moving capability and power consumption of the device, and its cost.

The Dynactor uses a proprietary nozzle design to produce a water spray which serves as an air eductor and as a scrubber, thus cleaning and propelling the gas simultaneously. A description of the Dynactor, written by its manufacturer (RP Industries, Hudson, Massachusetts), is in Appendix A. We tested one of the smaller units of its type, a two-stage device with a nominal rating of 1000 cfm (0.472 m^3/s), Model DY 12 F2. The Dynactor was installed in a test setup at GCA/Technology Division and the following measurements were made:

- Air flow and pressure gain versus spray nozzle pressure
- Electrical power consumption versus spray nozzle pressure
- Mass collection efficiency as a function of particle aerodynamic diameter at two levels of flow, temperature, and concentration, for two different dusts, in a balanced test matrix
- Mass collection efficiency as a function of particle size for several additional sets of conditions
- Total mass collection efficiency at the conditions noted above

The dust was generated by a dust feeder - air ejector combination. Its concentration was determined by gravimetric analysis of filter samples obtained by isokinetic sampling upstream and downstream from the Dynactor. The concentrations in a set of aerodynamic size intervals were obtained from gravimetric analysis of samples obtained by identical impactors, one placed upstream and the other downstream from the Dynactor, from which data the mass collection efficiency as a function of particle size was obtained. These data were analyzed using an F-test analysis of variance to determine which factors had significant influence on collection efficiency in the various aerodynamic size fractions and to estimate experimental uncertainty. Flow was measured using pitot tube traverses and pressure gain was measured using Magnehelic pressure gauges. Electrical power consumption was measured using an induction coil ammeter and an oscilloscope, from which current, voltage, and phase angle could be obtained.

The work also included some cost estimates, from which certain comparisons can be made with other control devices. Comparisons with other experimental results for spray scrubbers have also been made, especially with regard to which factors can enhance collection efficiency.

SECTION IV

TEST EQUIPMENT

Most of the experimental work was done with the equipment shown in Figures 1 and 2. This equipment allowed us to measure collection efficiency as a function of particle size as well as the conditions of flow, concentration, temperature, pressure drop, etc. which prevailed during the efficiency tests.

Figure 1 gives the overall picture of the test setup. Dust from a screw feed was picked up by an air ejector/aspirator and blown into ducting leading to the Dynactor. The flow in the ducting was produced by the Dynactor and the relatively weak fan of the heater/blower, sometimes in conjunction with the fan shown at the very end of the flow train. Upstream, the turbulent mixture was sampled five or more duct diameters from the dust feed by an Andersen Model III cascade impactor, usually run with isokinetic flow, and by a filter assembly (glass fiber absolute filter, 47-mm diameter) which always was operated isokinetically. An identical sampling combination was used downstream, as described more fully in Figure 2. The temperature and pressure of the mixture entering the Dynactor was measured as was, sometimes, the temperature of the mixture leaving the Dynactor. The pressure drop or gain across the device was measured. Each of the major components of the test equipment will be described in greater detail next.

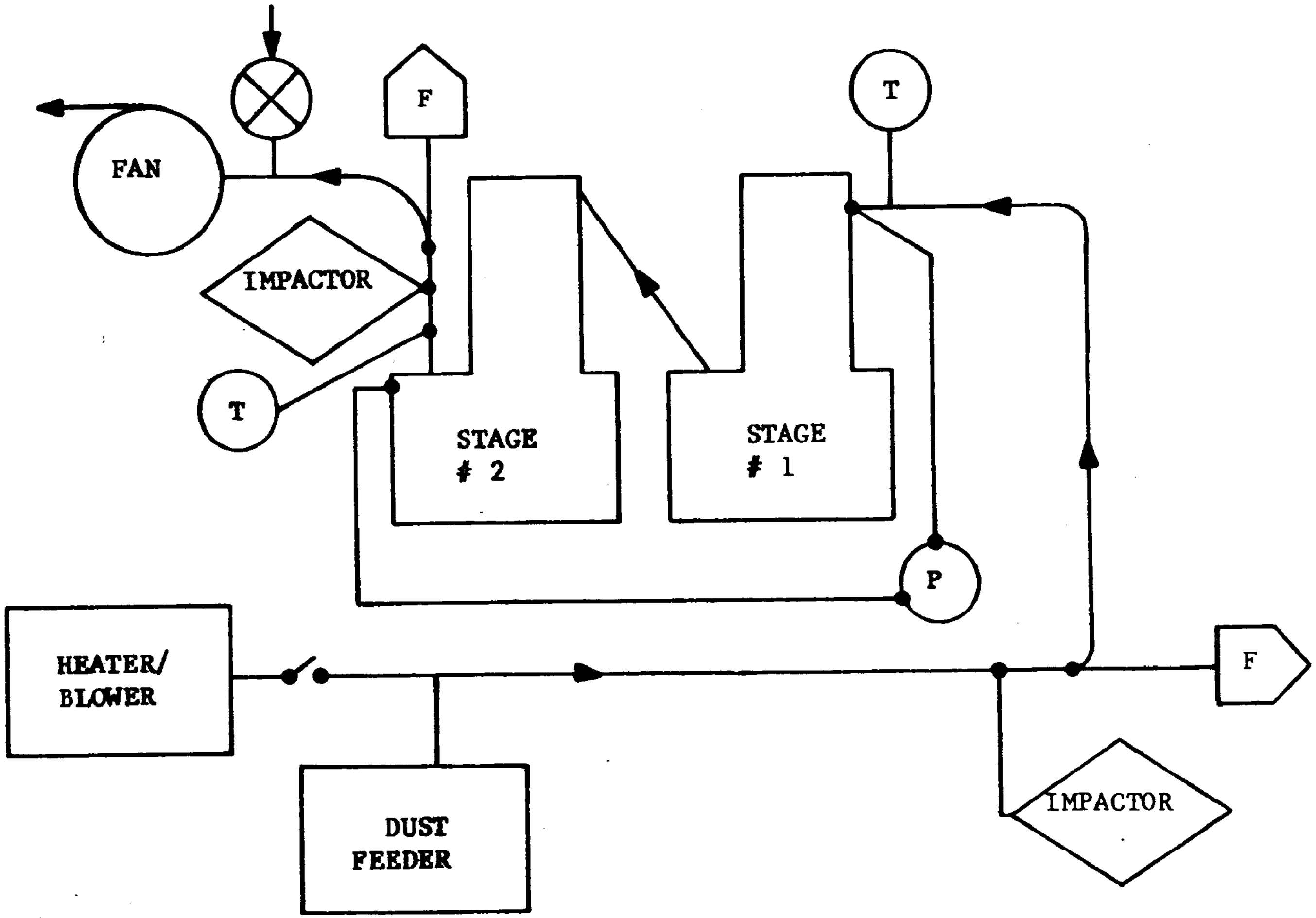


Figure 1. Test system for Dynactor two-stage scrubber evaluation, including filter samplers (F), thermometers (T), and pressure gauge (P)

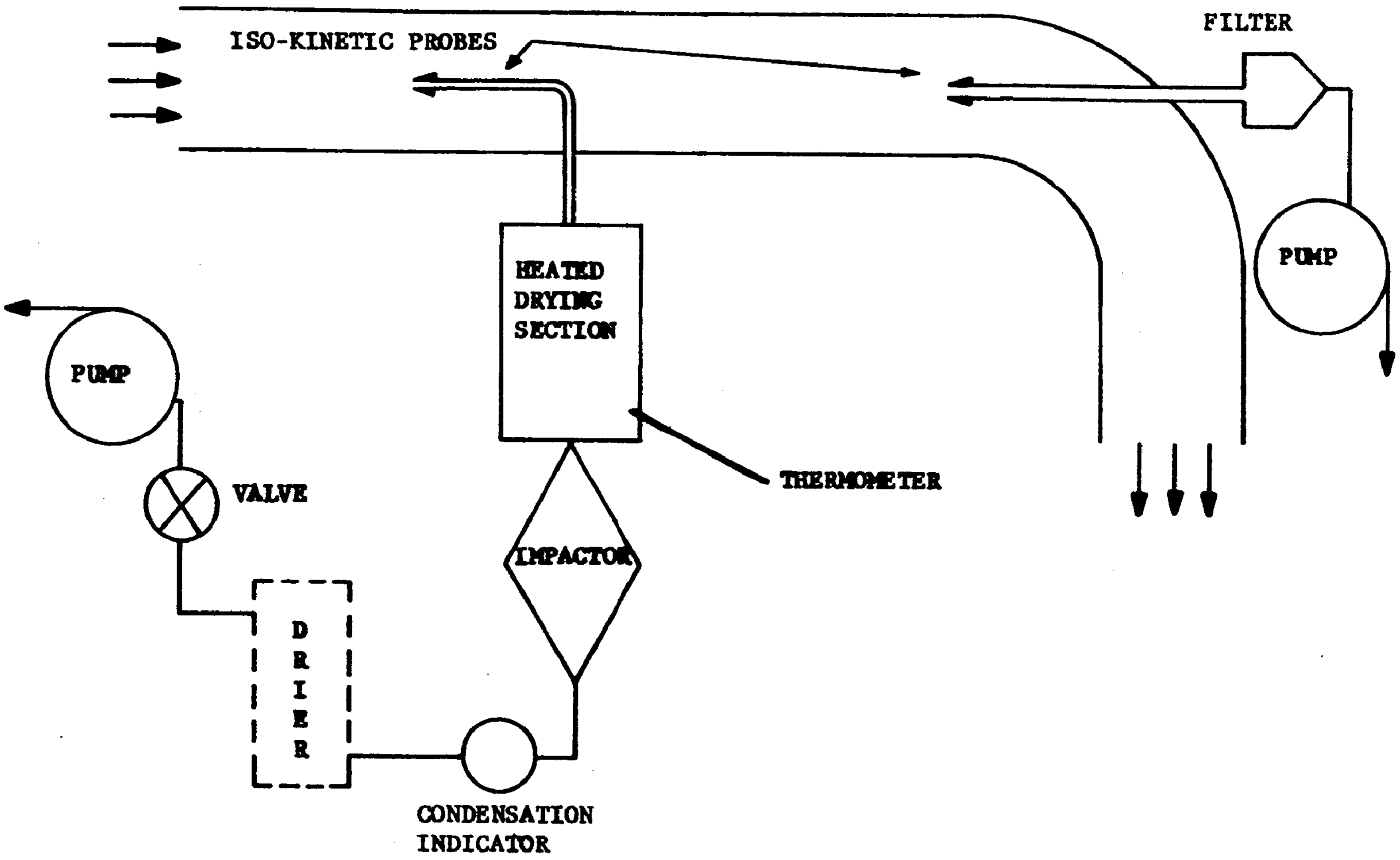


Figure 2. Details of aerosol concentration and size distribution measurement sections

HEATER/BLOWER

The heater burned propane supplied continuously from a pressurized tank. Propane was selected because its combustion products are almost exclusively carbon dioxide and water, with a negligible production of carbon aerosol. The heater was rated at a maximum of 350 x 10^3 Btu/hr (1.03 x 10^5 joule/s). Its blower could provide 1400 cfm (0.66 m^3/s) maximum flow.

DUST FEEDER AND ASPIRATOR

The dust feeder (Acrison, Inc. Model 120) operated with a vibrating hopper that channeled the dust into a cavity from which a screw feeder directed an adjustable constant volume flow to the aspirator. The aspirator was powered with pressurized air at 80 psig (5.5 x 10^5 N/m^2 above atmosphere) and blew the dust into the main ductwork while deagglomerating the aerosol material.

IMPACTORS

Upstream and downstream from the Dynactor, we used the Andersen Model III in-stack impactor to size-fractionate the aerosol. Except for early tests which were run at 28 ℓpm (1 cfm or 4.7 x 10^{-4} m^3/s), the impactors were operated at 14 ℓpm to lessen the likelihood of particle rebound, as advised by its manufacturer. The impactors were used with the glass fiber media impaction substrates designed for them. Later in this report is a description of some tests done to ascertain weight changes in the impactor substrates due to causes other than the accumulation of particulate material. The temperature of the impactor at the Dynactor outlet and its drying section (Figure 2) was kept about 20°C above the temperature of the Dynactor exhaust stream to produce drying of the droplets present in the exhaust. The drying section volume was 2.4 x 10^{-3} m^3 (75 cm long by 6.4-cm diameter), which yielded a residence time of 10 seconds.

Preliminary tests showed that the concentrations downstream from the Dynactor scrubber were much lower than those upstream. To obtain enough material on the downstream impactor for weighing and yet not too much material on the upstream impactor (to prevent rebound and reentrainment), it was necessary to run these impactors for different total durations, the downstream impactor sampling for about 10 times as long as the upstream impactor. The total downstream sampling time was subdivided into intervals, and the upstream samples were run briefly at the time mid-points of these intervals, essentially the analogue of a midpoint quadrature. The total filter samples had the same durations as their impactor counterparts. To prevent material from being captured by the probes upstream when a sample was not being taken, these probes were blocked with removable baffles.

Consideration was given to correcting the data obtained with the upstream impactor for the volume of air that was in the drying chamber at the beginning of each sample, approximately 2.4 liters of air, relatively free of aerosol due to sedimentation, etc., between samples. Generally each upstream sample was for a minute or two, thus 14 to 28 liters (0.5 to 1.0 ft^3), so that the relatively clean air would be from about 8 to 16 percent of the total sample. When we checked the flow rate of the upstream impactor at the end of the test series, we found that it had drifted from 14 ℓpm (0.5 cfm) to 17 ℓpm (0.6 cfm), whereas the downstream impactor had not drifted from 14 ℓpm. The average contribution of this drift would be to make the concentrations upstream seem 10 percent higher than they were, but the contribution from the relatively clean air would have made the concentrations seem 8 to 16 percent too low, so these effects nearly cancelled each other. The net effect on flow and the 5-percent change in aerodynamic cutoff diameter in the upstream impactor were treated as negligible. The downstream impactor sampled for 10 minutes or so generally and the 2 percent (2.4/140) effect on total volume sampled was also ignored.

METTLER BALANCE (H15) AND WEIGHING ERRORS

The concentrations were determined from weight changes in the filters and impaction substrates. To ascertain the reproducibility of our weighing measurements, we made 18 weighings each of two weights, 10 g and 100 mg, over 8 days. We obtained 16 readings of 9.9994 and two of 9.9993 g, and 14 readings of 0.1000 and four of 0.1001 g, from which we concluded our reproducibility was better than 0.1 mg.

To check whether or not dessication made a substantial difference in the impactor substrate material, we made 24 weighings before and after dessicating the substrates for a day's duration. The mean change in weight was 0.15 mg loss (for substrates averaging 0.20 g) and 11 of the 24 changes were 0.1 mg. From this we decided to dessicate the substrate material before making the tare weighing as well as before making the weighing with the captured particulate material.

Precautions were taken to enhance weighing accuracy for all efficiency tests. The substrates were dessicated at least 12 hours. A static charge eliminator was used in the Mettler analytical balance. The substrates were weighed singly and the weights of groups of four were compared with the sum of the four individual weights. To lessen the likelihood of the wrong substrate being ascribed to a given impaction stage, the substrates were numbered so that their last digit was the same as the stage with which they were to be used.

COMPARISON OF ANDERSEN MARK III IN-STACK CASCADE IMPACTORS

In a comparison test done before the Dynactor efficiency tests, the two identical impactors were used to sample the same aerosol, iron oxide powder generated from a Wright dust feeder into a wind tunnel. Each impactor drew 28 ℓpm (1 cfm) from a Y-connection that was connected to a single sampling probe. The results of this test are given in Tables 1 and 2 and in Figure 3. The "reclaimed" media were rinsed in methanol

Table 1. DATA FROM TWO ANDERSEN MARK III CASCADE IMPACTORS SAMPLING SAME IRON OXIDE AEROSOL (MAPICO BLACK) AT 28 ℓpm ON NEW MEDIA

Impactor Stage	Mass collected		Percentage of total mass		Cumulative mass percentage		Effective Diameter (μm) D_{50}
	Impactor #4601	Impactor #4602	Impactor #4601	Impactor #4602	Impactor #4601	Impactor #4602	
1	0.4	0.2	2	1	2	1	9.6
2	0.3	0.2	2	1	4	2	6.0
3	0.6	0.4	3	2	7	4	4.0
4	0.8	0.7	5	4	12	8	2.75
5	2.0	1.9	11	11	23	19	1.75
6	9.6	9.7	54	55	77	74	0.9
7	3.3	3.8	19	22	96	96	0.54
8	0.1	0.2	1	1	97	97	0.36
Filter	0.6	0.5	3	3	100	100	
Total Mass	17.7	17.6	100	100			

Correlation coefficient: 0.998

Table 2. DATA FROM TWO ANDERSEN MARK III CASCADE IMPACTORS SAMPLING SAME IRON OXIDE AEROSOL (MAPICO BLACK) AT 28 ℓpm ON RECLAIMED MEDIA (FINAL FLOW IN #4601 WAS ABOUT 5 PERCENT LESS THAN THAT OF #4602)

	Mass collected		Percentage of total mass		Cumulative mass percentage		Effective Diameter (µm) D_{50}
Impactor Stage	Impactor #4602	Impactor #4601	Impactor #4602	Impactor #4601	Impactor #4602	Impactor #4601	
1	0.1	0.1	1	1	1	1	9.6
2	0.1	0.1	1	1	2	2	6.0
3	0.4	0.3	2	2	4	4	4.0
4	0.7	0.6	3	3	7	7	2.75
5	2.2	1.8	12	10	19	17	1.75
6	11.3	10.6	59	59	78	76	0.9
7	3.5	3.6	18	19	96	95	0.54
8	0.1	0.4	1	2	97	97	0.36
Filter	0.6	0.6	3	3	100	100	< 0.36
Total Mass	19.0 g	18.1 g	100	100			

Correlation coefficient: 0.999

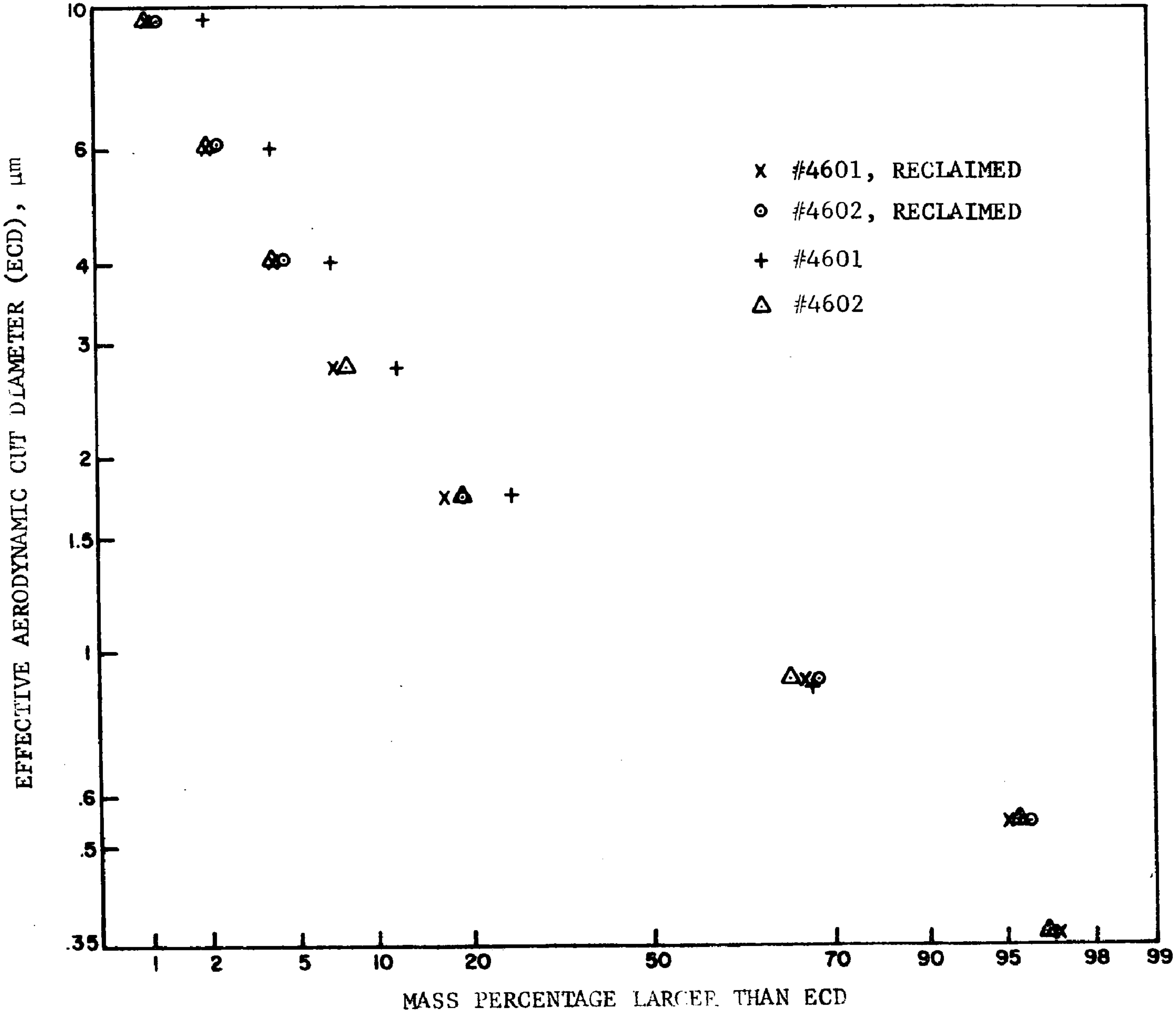


Figure 3. Cumulative mass size distribution of iron oxide pigment aerosol as determined by two impactors (#4601 and #4602) with original substrates and with reclaimed substrates. Aerosol generated by Wright dust feeder

and reused. The correlation coefficient for the mass captured on the corresponding stages of the impactors was 0.998, indicating very close matching. The data also indicate the impaction substrates can be reclaimed by rinsing with methanol, which is significant, as they cost nearly \$1.00 apiece.

The smallest weight change that could be read from the balance we used was 0.1 mg, so that the weights are precise to within about $\pm$ 0.05 mg, which is also an estimate of the accuracy of the difference between two weights which are nearly the same, the case that we had to deal with in the main. In the comparisons of the two impactors, the ratio of two weights for the same stages for the different impactors diverged from unity significantly as the weights approach 0.1 mg, as expected from the weighing precision.

These comparison tests show that the impactors are nearly identical in performance, which is what is required in the tests of the Dynactor collection efficiency.

LOSSES FROM IMPACTION SUBSTRATE MATERIAL

It has been reported by Bird, et al. (1973) that the substrate material used in the impactor, cut from glass fiber filters, had a tendency to lose weight in handling and use. At the beginning of our tests we weighed four such substrates before and after inserting them into and removing them from the impactor, and we found an average weight loss of 0.1 mg per substrate. Subsequent tests involving actually sampling aerosols produced some very lightly loaded substrates that showed weight losses $\gtrsim$ 0.1 mg. Blowing off the substrates before using them visibly removed some loose material. Rinsing the substrates in methanol before using them removed an average of 1 mg of loose solid material per substrate. There was noticed some losses in weight even with the procedure of rinsing with methanol, dessicating for 12 hours or more, weighing, using, dessicating again, weighing again. To estimate this loss we wanted to determine an average weight loss due to handling and sampling, so we sampled filtered air for 2 hours at 0.5 cfm. The average loss was 0.23 mg per substrate. All these loss tests are tabulated in Table 3.

The first column of Table 3 briefly describes how the impactor substrate material was treated before it was tested; either it was used as it came from the manufacturer (untreated) or it was washed in methanol and dried again. The second column tells how the substrate was used in the tests: either just loaded into the impactor and then unloaded immediately or loaded, used to sample a test aerosol as part of the efficiency tests, and unloaded or loaded, used to sample filtered air, and unloaded. The weight loss is the difference between the substrate weight before the test and the weight after the test; the losses listed for the substrates used to sample the aerosols are the losses for the substrates which showed any loss, 25 of the 176 substrates from a series of 11 efficiency tests, which substrates were invariably very lightly loaded (visual inspection). The fourth column gives the number of substrates having the indicated loss. These tests led to the following treatment of the data obtained with the cascade impactor:

1. Weight changes of 0.3 mg or less were taken to be 0.3 mg for calculation of efficiencies, which efficiencies are given as inequalities.

2. Weight changes of 0.4 mg or more were used without correction.

We decided not to add a "loss correction" to the data, although arguments can be made for doing so or not doing so. The usual total weight change was approximately 20 mg divided among the eight stages and final filter and a correction, if used, would have been approximately 0.2 mg per stage. Disadvantages to making such a

Table 3. ANDERSEN MODEL III IMPACTION SUBSTRATE LOSSES

Treatment	Test conditions	Weight loss (mg)	Number
Untreated	Load and unload (4)	-0.1	4
Most washed in methanol	Sample aerosols (176)	-0.1 -0.2 -0.3 -0.4 -0.5 -0.6 average loss: -0.26	8 9 2 2 0 4
Washed in methanol	Sample filtered air (8) for 2 hours, at ambient temperature	-0.1 -0.2 -0.3 -0.4 average loss: -0.23	2 3 2 1
Washed in methanol	Sample filtered air (8) for 15 minutes, ambient temperature	-0.1 -0.2 -0.3 average loss: -0.12	5 1 1

correction are that the uncertainty in the correction would add to uncertainty already present in the data and that the correction complicates going from the raw data to the derived quantities (concentrations, efficiencies) and vice-versa. This problem of impactor substrate losses is under further investigation by the Environmental Protection Agency (Control Systems).

DUCTING

For the tests conducted at flow rates of 500 cfm (0.24 m^3/s) and 1000 cfm (0.47 m^3/s) the sheet metal ducting upstream from the Dynactor was 8 inches in diameter by about 12 feet long (0.20 m diameter by 4 m long) connected to an expander to take it from 8-inch diameter to 16-inch diameter (0.20 m to 0.40 m), followed by a 90° elbow, 6 feet (2 m) more 16-inch ducting and another 90-degree elbow connected to the Dynactor inlet. For the 1500 cfm (0.71 m^3/s) tests, the first section was about 8 feet (3 m) of 12-inch diameter (0.30 m) ducting. The dust feeder was separated from the sampling probes by about 6 feet (2 m). The Dynactor outlet had a reducer to go from the 16-inch diameter (0.40 m) ducting to 8-inch diameter ducting (0.20 m), and the sampling probes were about 3 feet (1 m) from the reduction.

FLOW PROFILES IN DUCTING

The tube inlets for sampling the dust concentrations upstream and downstream from the Dynactor scrubber were set up to be no less than four diameters downstream from flow disturbances and 1.5 diameters upstream. The flow velocity profiles in the immediate vicinity of the sampling positions were measured to see that they approximated the turbulent flow profiles expected. By the Reynolds analogy, such a matching would be a good indication of fairly homogeneous aerosol mixing. Good mixing is expected because the Reynolds numbers in the ducting are at least 1×10^5 and the sampling points are about 5 diameters or greater downstream from the point of aerosol generation. The traverses were done at the positions labeled "impactor" in Figure 1. Figure 4 shows the velocity profile obtained at the 8-inch (0.20 m) diameter ducting upstream (for somewhat different flow rates).

Preliminary tests at the inlet indicated a typical, nearly flat, turbulent flow profile without the heater blower on, but the flow exhibited swirl once the heater blower was used. Installation of baffling, two 4-inch diameter (0.10 m) ducting pipes about 2 feet long (0.2 m) immediately downstream from the blower, virtually eliminated the swirl effect; Figure 4 was obtained with the blower on. A more detailed pitot traverse was made at the downstream sampling position. The results of eight-point and twelve-point traverses made downstream are given in Figure 5, along with center-line measurements. The flow closely approximates the turbulent flow expected, with no pronounced anomalies. The total volume flow from the equal-area, eight-point traverse was compared with that from the equal-area, twelve-point traverse: for the two such comparisons we made, they agreed within 5 percent and within 2 percent. Figure 6 shows the centerline measurements made simultaneously with the eight-point traverse measurements used to characterize Dynactor air-moving capability; reproducibility was judged adequate for the use of the centerline pitot reading to set the Dynactor flow at the 500, 1000, and 1500 cfm (14, 28, 42 m^3/min) levels when testing the Dynactor fractional collection efficiency.

This completes this section on the equipment used in the Dynactor evaluation and some of the tests performed on this equipment.

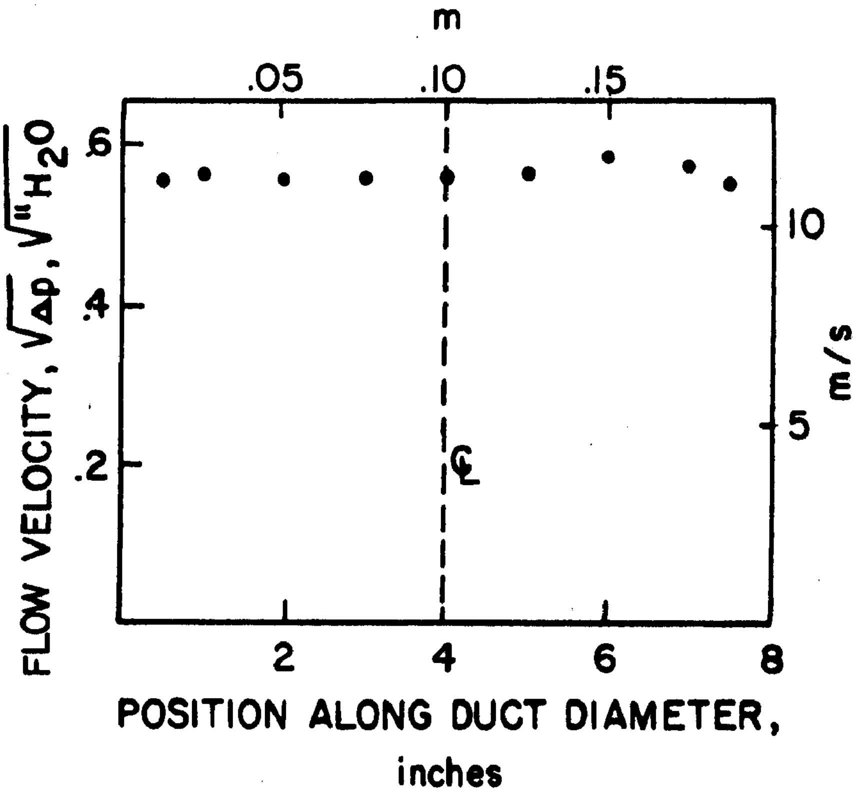
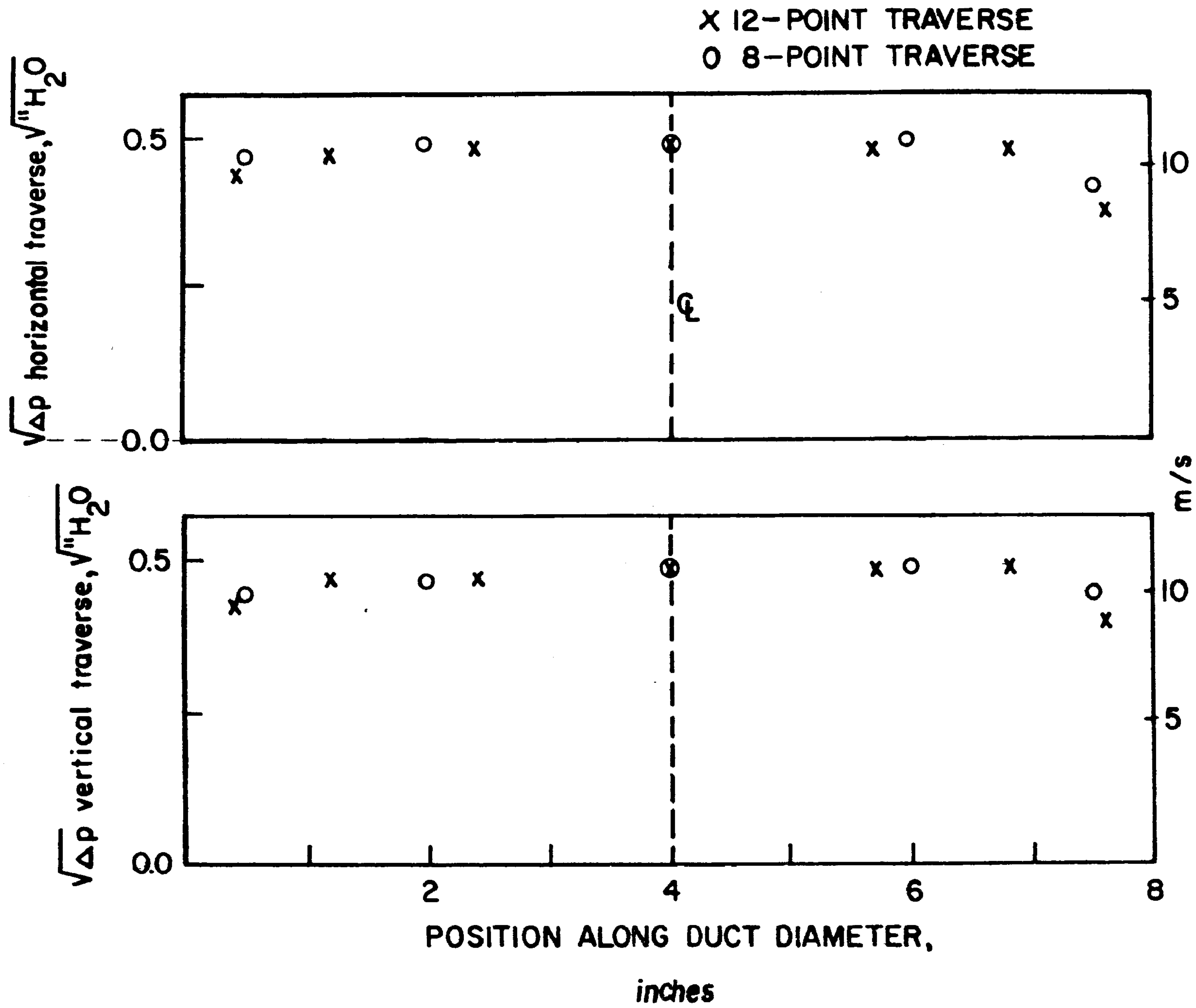


Figure 4. Flow velocity profile in inlet ducting, Dynactor test setup


X 12-POINT TRAVERSE
O 8-POINT TRAVERSE
$\sqrt{\Delta p}$ horizontal traverse, $\sqrt{{}^{\prime\prime}H_2O}$
$\sqrt{\Delta p}$ vertical traverse, $\sqrt{{}^{\prime\prime}H_2O}$
0.5
0.0
10
5
m/s
℄
2
4
6
8
POSITION ALONG DUCT DIAMETER,
inches

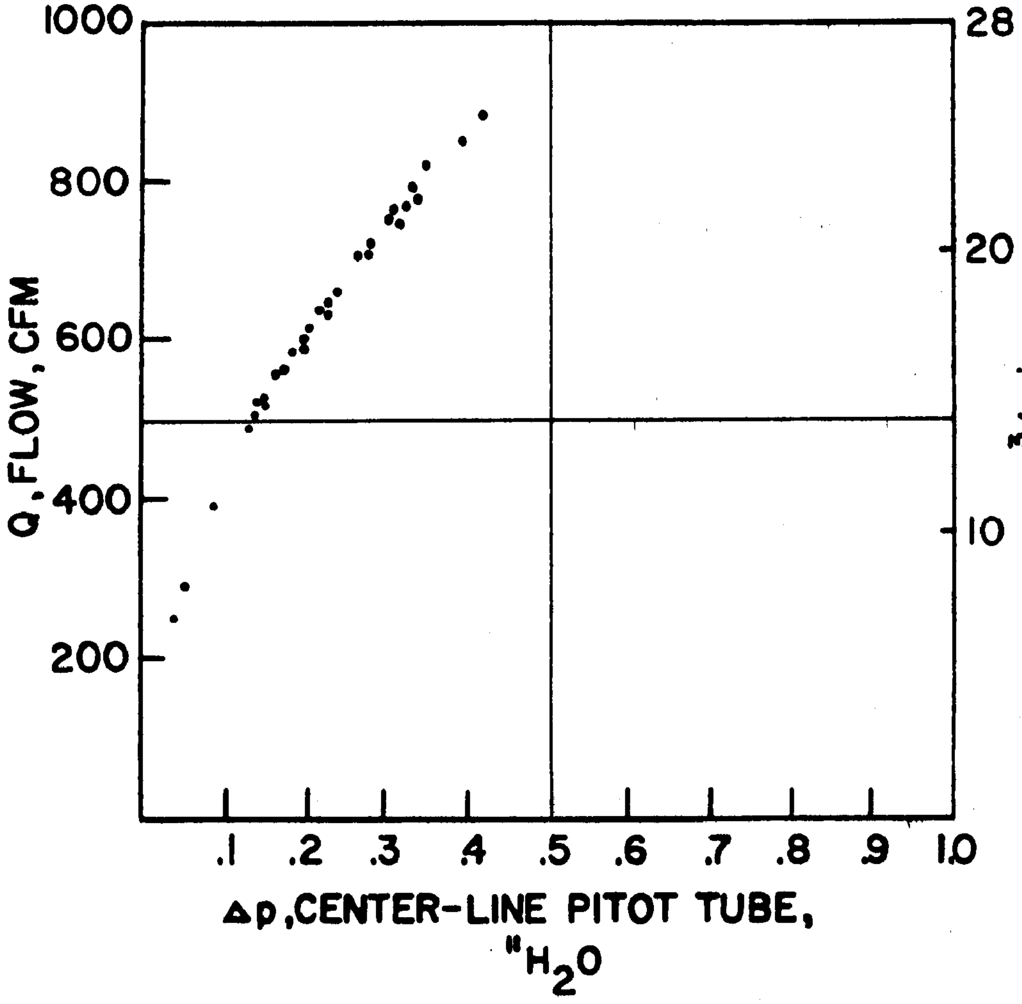


Figure 6. Volume flow rate versus center-line reading with pitot tube, Dynactor test setup

SECTION V

RESULTS

INTRODUCTION

This section contains the results of the work done to characterize the Dynactor's air-moving capabilities, power consumption, and collection efficiency on a mass basis as a function of particle size, determined with cascade impactors. In Section VI these results will be discussed and the Dynactor compared with venturi scrubbers.

AIR MOVING CAPABILITIES

The Dynactor scrubber acts somewhat like a fan, providing a pressure boost rather than a pressure drop to air moving through it, up to some maximum flow which depends upon operating conditions. We tested the pressure gain from Dynactor inlet to Dynactor outlet with a pressure gauge connected to the inlet and outlet ports, as shown by P in Figure 1. The total air flow at 70°F was obtained from eight-point equal-area traverses in the 8-inch diameter duct immediately downstream from the Dynactor. The manufacturer informed us that the inlet of the device should not be at a vacuum in excess of 1/2 inch H_2O (1.2×10^2 N/m^2) below ambient, and we noted that for pressure differences across the device on the order of 1 inch H_2O (2.5×10^2 N/m^2) and greater there was a significant accumulation of water spray in the upper plenum chambers of the device, indicating some disruption of the normal flow patterns, so only a few tests were done under such conditions. The data for flow (at 1 atmosphere pressure and 70°F) versus pressure increase are given in Figure 7 for three different spray nozzle pressures, 100, 150, 200 psig (6.9, 10.4, 13.8 x 10^5 N/m^2). The usual operation of the device, according to the manufacturer, is with pressure differences less than or about 1/2 inch H_2O (1.2 x 10^2 N/m^2). Table 4 has the data for the Dynactor flows with inlet and outlet open to the atmosphere and the pressure increases to be expected (no flow). The flows were somewhat less than expected by the manufacturer; the maximum pressures matched expectations.

POWER CONSUMPTION: PUMPS

The Dynactor scrubber spray nozzles are powered by two high-pressure pumps that run on three-phase 207 volt electrical power. The formula for the power consumption of an electrical device is given by:

$$P = \sqrt{\mu}\ I\ V \cos \Phi$$

in which

μ = number of phases (here, 3)
P = power, watts
I = current magnitude, amps
V = voltage magnitude, volts
Φ = phase angle between voltage and current

The power was determined by measuring the voltage magnitude, the current magnitude and the phase angle at three spray nozzle pressures: 100, 150, and 200 psig (6.9, 10.4, 13.8 x 10^5 N/m^2). The current and voltage measurements were made at a point in the circuit before it branched to feed the two pumps, giving total current in each phase wire and the common voltage. The voltage was 206 to 207 volts regardless of nozzle pressure settings, both nozzles being set to the identical pressures for each measurement. The current readings in each of the phase wires were:

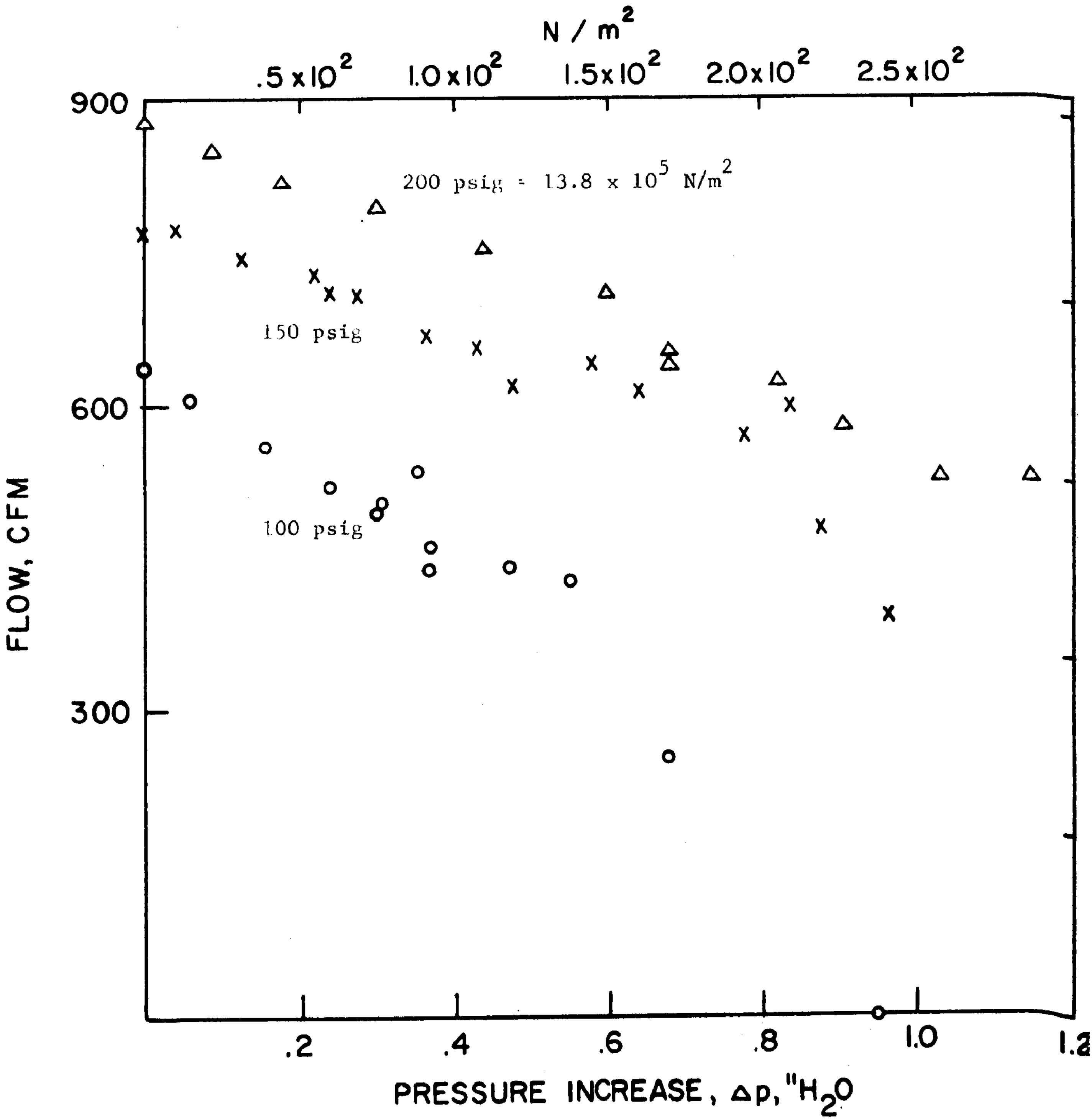


Figure 7. Pressure gain produced by Dynactor versus flow rate through it

Table 4. DYNACTOR AIR-MOVING CAPABILITIES: FLOW WITH INLET AND OUTLET OPEN TO ATMOSPHERE, MAXIMUM PRESSURE GAIN (NO AIR FLOW).

	Spray nozzle pressure		
	100 psig (6.9×10^5 N/m^2)	150 psig (10.4×10^5 N/m^2)	200 psig (13.8×10^5 N/m^2)
Unobstructed flow			
cfm	640	780	880
m^3/min	18.1	22.1	24.9
m^3/s	0.302	0.368	0.415
Maximum pressure gain			
inch H_2O	1.0	1.5	2.0
nt/m^2	2.5×10^2	3.8×10^2	5.0×10^2

Pressure (psig)	Current, I (amps)
100	13.7, 13.5, 14.0 (average: 13.7)
150	13.7, 13.6, 13.9 (average: 13.7)
200	13.5, 13.6, 13.9 (average: 13.7)

Phase angle measurements were performed by connecting vertical oscilloscope trace to measure voltage between phases, and horizontal to measure a small voltage drop between two terminals of the same phase lead in the switch box, the impedence being purely resistive. Phase angles of both pump motors were the same and did not vary with pressure. The resulting Lissajous figure was not a perfect ellipse, indicating some waveform distortion due to the motor characteristics. The measured angles between two adjacent phase lines were:

$\alpha = 49.6^{o}$ and $\beta = 8.2^{o}$ and since

$\alpha = 30^{o} + \Phi$ and $\beta = 30 - \Phi$; $\Phi \cong 20^{o}$,

and thus the total power is

$$P = \sqrt{3} \times 207 \times 13.7 \times \cos 20^{o} = 4616 \text{ watts} \cong 4.6 \text{ kW}$$

POWER CONSUMPTION: DYNACTOR SPRAY NOZZLES

The pumps that drive the Dynactor spray nozzles are both rated at 7 hp (5.2 kW). By measuring the electrical power consumed, we determined that the power consumption was about 6.2 hp (4.6 kW) total with the nozzles at 200 psig (13.8 N/m^2) and with them at half that pressure as well, indicating power consumption was insensitive to nozzle pressures below this value. Because the power used by the system is related to the kind of motor and pump used, the most basic estimate of power consumption is to calculate the power, P, expended by the nozzles, which is the product of the pressure drop across the nozzles, Δp, and the volume rate of flow of water, Q_w. These values are shown in Figure 8, the flow and pressure data were supplied by the manufacturer. (The values are plotted on a log-log plot because the

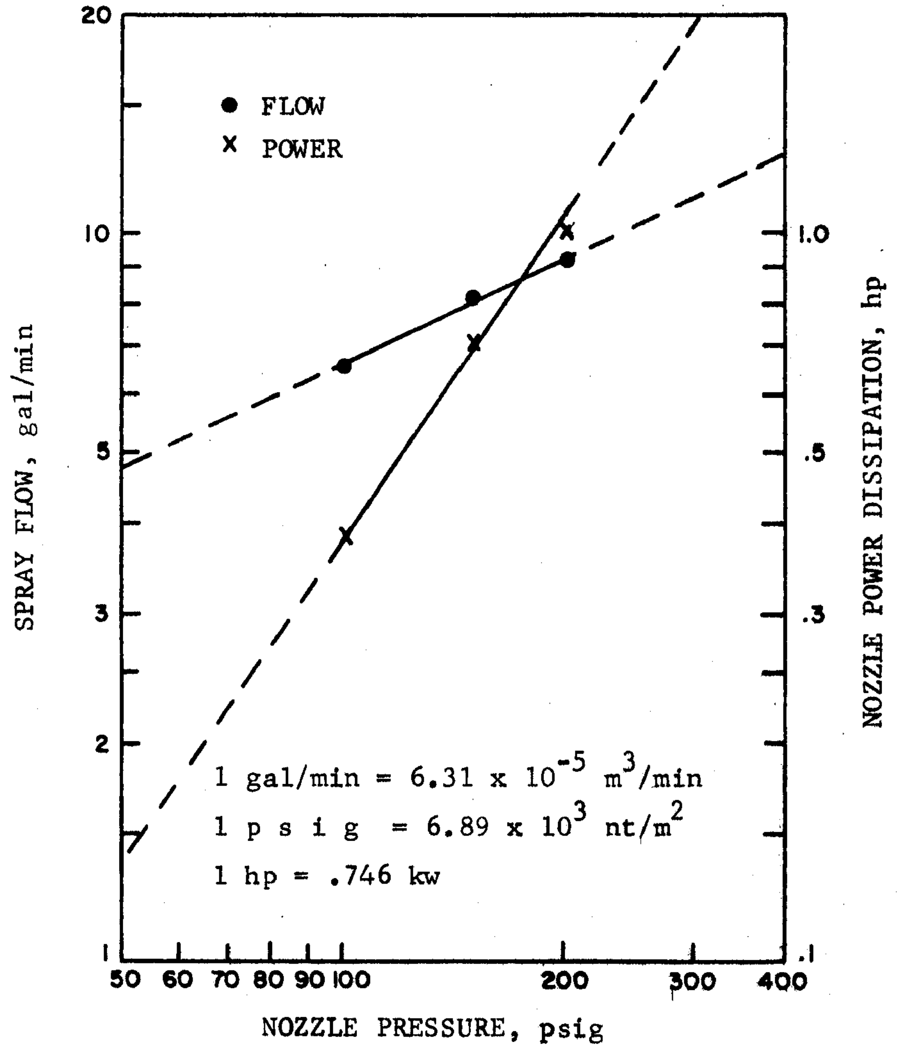


Figure 8. Dynactor spray flow and nozzle power dissipation versus spray pressure

applicable fluid flow theory, potential flow, predicts the spray velocity, thus spray volume flow rate, will be proportional to the square root of the pressure drop across the nozzle; this is supported by the data.)

The nozzle power dissipation is given by

$$P = Q_w \Delta p \qquad (1)$$

The data supplied by the manufacturer were:

Q_w = 6.6 gal/min	at	Δp = 100 psig
(Q_w = 4.2 x $10^{-4} m^3$/sec)		(Δp = 6.89 x 10^5 N/m^2)
Q_w = 8.1 gal/min	at	Δp = 150 psig
(Q_w = 5.1 x $10^{-4} m^3$/sec)		(Δp = 10.4 x 10^5 N/m^2)
Q_w = 9.2 gal/min	at	Δp = 200 psig
(Q_w = 5.8 x $10^{-4} m^3$/sec)		(Δp = 12.8 x 10^5 N/m^2)

The power dissipation calculated for these three nozzle pressures is then: 0.38 hp (0.29 kW), 0.70 hp (0.52 kW), 1.00 hp (0.74 kW). These values for power are also shown in Figure 8, and are consistent with the expected $(\Delta p)^{3/2}$ dependence of power on nozzle pressure.

The efficiency of the small pumps used in this model Dynactor was only 35%, but larger pumps on larger models would be expected to yield 60-70% efficiency.

WATER CONSUMPTION

The maximum amount of water used by the Dynactor would be the volume flow rate through the spray nozzles. At 1000 cfm (28.3 m^3/min) this would be 2 x 9.2 gal/min = 18.4 gal/min (0.070 m^3/min) or 18.4 gallons of water per 1000 ft^3 air treated (2.47 x $10^{-3} m^3$ water per m^3 air treated), at standard conditions. If this could be recycled, as it was in our tests, actual consumption would be decreased.

TEMPERATURE LIMITATION

In preliminary testing, the Dynactor spray was started and the heater used to raise the temperature of the inlet gas to 300°F (200°C ± 5°C) while generating and sampling an iron oxide aerosol at 1 gr/ft^3. Although we had hoped to be able to make tests at this temperature, the obvious damage done to certain plastic materials in the Dynactor made the device inoperable. It was agreed by all parties that future tests at elevated temperatures should be done at 200°F. We were told that other models of the device do not use these plastic parts and can operate at higher temperatures.

MASS COLLECTION EFFICIENCY VERSUS PARTICLE SIZE

The remainder of the section on results will contain material from tests done to determine collection efficiency, by mass, as a function of particle size, or more precisely as a function of particle aerodynamic diameter. The data from these tests are presented in Appendix B. Sizing was done by using Andersen Model III In-Stack Impactors at 14 ℓpm flow rate (0.5 cfm), and the material on a given stage of the impactor was classified as being of an aerodynamic diameter greater than or equal to the aerodynamic cutoff diameter for that impaction stage and less than the aerodynamic cutoff diameter of the impaction stage immediately upstream. The cutoff diameter is the diameter for which the collection efficiency of the given impaction stage would be 0.50. The cutoff diameters were taken from information supplied by the impactor manufacturer. Figure 9 shows four measurements of the inlet cumulative particle size distribution by mass of the iron oxide pigment (Mapico Black) as generated with the Acrison dust feeder. Figure 10 gives the same information for the fly ash aerosol. The cutoff diameters for the impactors were: 13.7, 8.6, 5.6, 4.0, 2.5, 1.3, 0.80, and 0.54 μm. Conditions such as humidity and feed rate would be expected to alter the size distributions somewhat for different tests. The efficiency tests measured the outlet concentration in a certain size interval versus the inlet concentration in that size

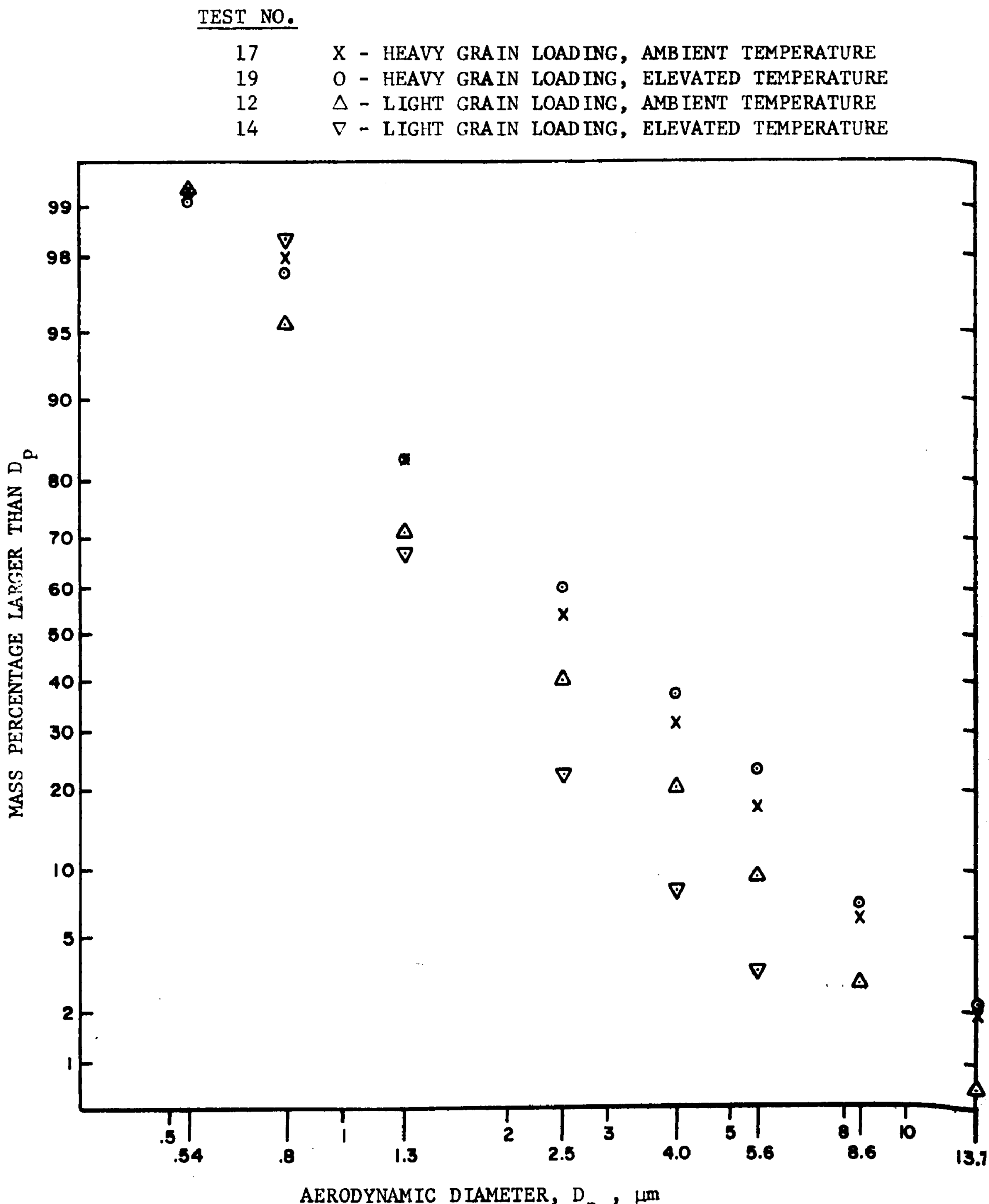


Figure 9. Inlet size distribution, iron oxide at 1000 cfm (28 m^3/min)

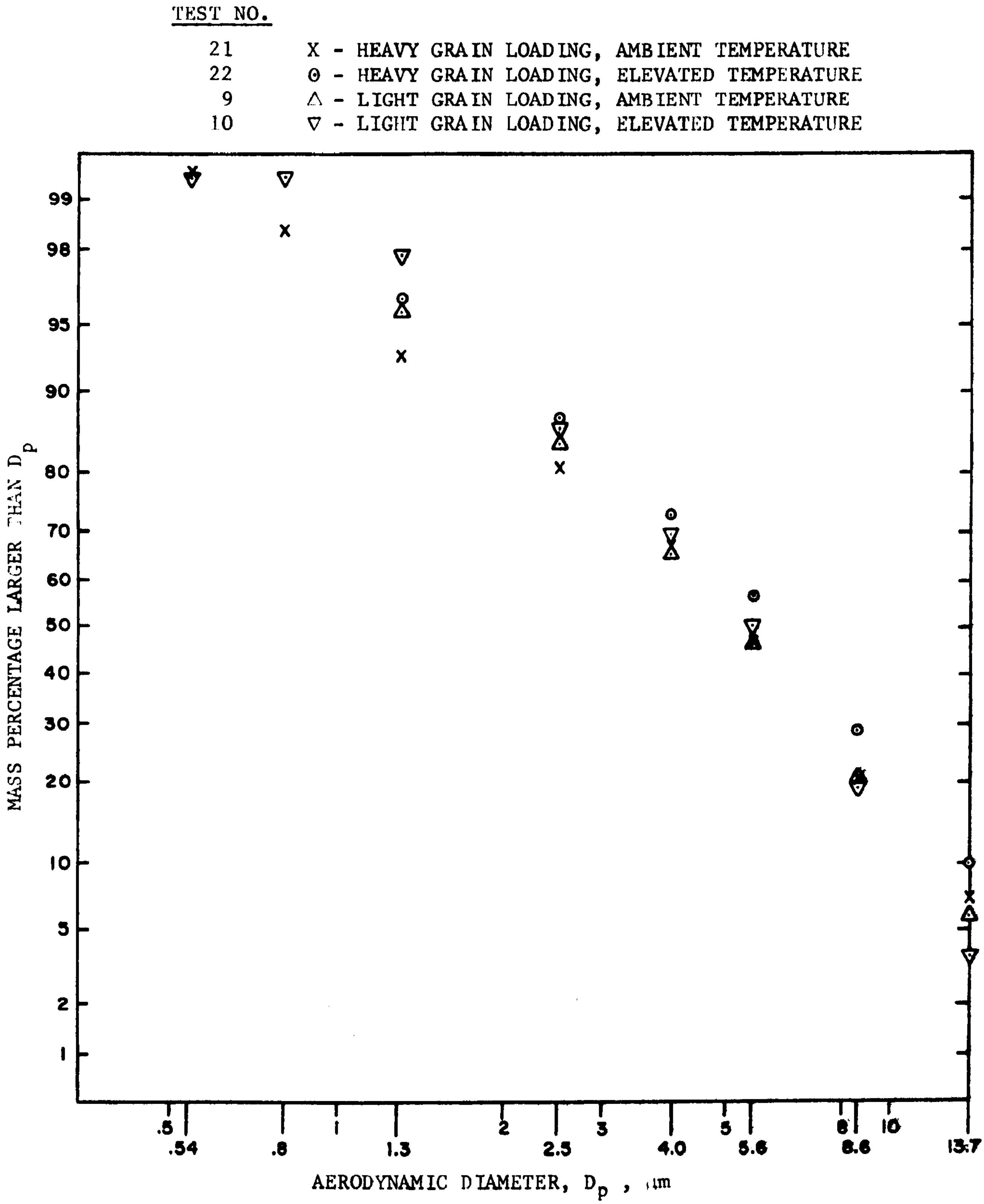


Figure 10. Inlet size distribution, fly ash at 1000 cfm (28 m^3/min)

interval, thus eliminating most of the effect of variations in inlet size distribution on collection efficiency.

Fractional Efficiency of Collection: Factorial Tests

A factorial test design was used to determine the Dynactor efficiency and the effects, if any, of flow rate, dust concentration, temperature, and dust type. Two levels of each of these parameters were used, which meant $2^4 = 16$ tests. Tables 5a and 5b give the levels of the parameters for both dusts and the number designating the test at each particular set of parameters. The data from these tests are in Appendix B. In Tables 5a and 5b the balanced factorial design test matrix is enclosed in a heavier line box. The design allowed testing whether or not each of the parameters was significant and whether or not interactions of two parameters were significant, using standard analysis of variance, and allowed estimates of the experimental error of measurement. The other tests done with iron oxide were made to investigate the efficiency of a single stage, the effect of a lower spray nozzle pressure, the effect of the addition at the inlet of water vapor, and the effect of addition of surfactant to the spray. Three measurements were made at one set of conditions to provide a second estimate of experimental variation. In all, 25 tests have been reported and the results of another seven not reported because of various failures during the experiments, primarily among the first experiments done.

Statistical Analysis of Data

The data analysis was designed through a cooperative effort with GCA, University of Dayton Research Institute, and the Control Systems group at EPA. The computer program used to analyze the data was the BMDO2V program from the Biomedical series, 1966 revision (Dixon, 1973).

Table 5a. TEST MATRIX, FLY ASH AEROSOL

	500 cfm (14 m^3/min)		1000 cfm (28 m^3/min)	
	~ 1 gr/ft^3 (~ 1 g/m^3)	~ 0.1 gr/ft^3 (~ 0.1 g/m^3)	~ 1 gr/ft^3 (~ 1 g/m^3)	~ 0.1 gr/ft^3 (~ 0.1 g/m^3)
Heated[a]	#7	#27	#22	#10
Ambient[b]	#8	#26	#21	#9

[a]Inlet air T = 95°C = 200°F

[b]Inlet air T = 21°C = 70°F

Table 5b. TEST MATRIX, IRON OXIDE AEROSOL

	500 cfm ($14\ m^3/min$)		1000 cfm ($28\ m^3/min$)		1500 cfm ($42\ m^3/min$)
	$\sim 1\ gr/ft^3$ ($\sim 1\ g/m^3$)	$\sim 0.1\ gr/ft^3$ ($\sim 0.1\ g/m^3$)	$\sim 1\ gr/ft^3$ ($\sim 1\ g/m^3$)	$\sim 0.1\ gr/ft^3$ ($\sim 0.1\ g/m^3$)	$\sim 1\ gr/ft^3$ ($\sim 1\ g/m^3$)
Heated[a]	#5	#24	#19	#14	#30
Ambient[b]	#4	#23	#16,17,18	#12	#29
First stage[b]				#32	
Steam added	#28, 31				
Surfactant[b]			#25		
Low spray pressure[b]				#13	

[a]Inlet air T = $95^\circ C = 200^\circ F$

[b]Inlet air T = $21^\circ C = 70^\circ F$

The following were treated as independent variables for this analysis: total concentration (total filter), total impactor sample, impactor samples on each of stages 4, 5, 6, 7, 8, and impactor final filter. The efficiencies of each of these eight aerosol size fractions were put through an analysis of variance, using the standard F-test.

The computer program calculated the following for each of the size fractions used:

- "grand mean" of all 16 tests
- "marginal means" of sets of eight tests having one or the other of the treatment parameters: dust types, flow rates, inlet concentrations, temperatures
- "sum of squares" due to each of the four treatment parameters as well as those due to two-factor and three-factor interactions between the parameters.

A decision had to be made whether to test for the four three-factor interactions and have only one estimate of the experimental error (the residual sum of squares) or to limit the tests to one- and two-factor analysis and have five estimates of the experimental error (the residual sum of squares and the four three-factor sums of squares). The latter choice was made, increasing the sensitivity of the tests for the one- and two-factor contributions. This meant that the appropriate F-test to use was a comparison with confidence estimate tables for an F-test distribution having one degree of freedom in the numerator and five in the denominator, $F(1,5)$.

The results of the factorial test are summarized in Table 6. The mean efficiencies for the tests and the corresponding uncertainties are listed with the aerosol fraction to which they correspond. The aerosol fraction is either the size interval between impactor cutoffs or the total filter or the sum of the material collected on the impactor, the latter having somewhat smaller mean sizes than the total filter due to losses of the very largest particles in the drying sections. The efficiencies for the two different dusts for the total filter and the total impactor have been presented separately because these would be expected

Table 6. SUMMARY OF RESULTS OF 16 COLLECTION EFFICIENCY TESTS FOR DYNACTOR (FACTORIAL TEST DESIGN).

Aerosol fraction	Mean efficiency	Number of tests, n	Estimated uncertainty[a] ($\pm \sigma_e/\sqrt{n}$)
Total filter	96.04 %	16	± 0.32 %
Iron oxide	93.11	8	0.46
Flyash	98.97	8	0.46
Total impactor	93.71	16	0.32
Iron oxide	89.81	8	0.45
Flyash	97.60	8	0.45
4.0 - 5.6 μm	99.02	16	0.17
2.5 - 4.0 μm	98.37	16	0.12
1.3 - 2.5 μm	93.00	16	0.21
0.8 - 1.3 μm	75.4	16	2.1
0.54 - 0.8 μm	27.4	16	6.6
≤ 0.54 μm	47.4	16	3.7

[a]From analysis of variance. See Table 10.

to have very different median aerodynamic diameters, as seen from the size distributions shown in Figures 9 and 10. The uncertainty figures are derived from the uncertainty estimates for a single test, which will be explained below.

Tables 7a through 7h present a much more detailed picture of the results of the efficiency tests. Here are listed:

- The aerosol fraction
- The mean of all the efficiency tests in the factorial design
- The means of the eight tests each at two different levels of flow, temperature, and concentration, and two different dusts
- The results of the standard F-test analysis of variance, for an F ratio having a numerator of 1 degrees of freedom and a denominator of 5 degree of freedom
- The mean square error associated with one measurement at this size fraction.

The analysis of variance allows one to determine what likelihood there is that the differences noted between measurements come from differences in the parameters under study rather than from extraneous variations. The "significance level" is the probability that one would be correct in ascribing a difference in the results to a difference in the level of the parameter under test, here flow, dust, temperature, concentration, making the usual statistical assumptions about normal populations. Table 8 lists the significance levels for the effects of these parameters on efficiencies of collection for the various aerosol fractions.

The information in the Tables 7a through 7h, Table 8, and in Figures 11 and 12 allow us to draw the following conclusions:

1. The lower flow rate yielded higher efficiencies for all size fractions and the differences were usually statistically significant.
2. Fly ash was collected with greater efficiency than iron oxide for all size fractions, and these differences were usually statistically significant.

Table 7a. RESULTS OF STATISTICAL ANALYSIS ON EFFICIENCY

PARTICLE SIZE FRACTION: Total Filter

GRAND MEAN OF EFFICIENCY TESTS: 96.04

MARGINAL MEANS PARAMETER	LEVEL	MEAN
FLOW	14.2 m^3/min (500 cfm) 28.3 m^3/min (1000 cfm)	96.69 95.40
DUST	IRON OXIDE FLY ASH	93.11 98.97
TEMPERATURE	~ 20°C (~ 70°F) ~ 95°C (~ 200°F)	96.50 95.59
CONCENTRATION	~ 0.2 g/m^3 (0.1 gr/ft^3) ~ 2.0 g/m^3 (1.0 gr/ft^3)	94.87 97.21

RESULTS OF F-TEST ANALYSIS OF VARIANCE

EFFECT	F (1,5)	SIGNIFICANCE LEVEL (IF $\geq$ 0.90)
(1) Flow	3.95	-
(2) Dust	81.99	> .99
(3) Temperature	1.99	-
(4) Concentration	13.04	> .95
(2)(4)	11.93	> .95
(1)(4)	1.98	-

MEAN SQUARE ERROR: 1.677

Table 7b. RESULTS OF STATISTICAL ANALYSIS ON EFFICIENCY

PARTICLE SIZE FRACTION: Total Impactor

GRAND MEAN OF EFFICIENCY TESTS: 93.71

MARGINAL MEANS PARAMETER	LEVEL	MEAN
FLOW	14.2 m^3/min (500 cfm) 28.3 m^3/min (1000 cfm)	94.05 93.36
DUST	IRON OXIDE FLY ASH	89.81 97.60
TEMPERATURE	~ 20°C (~ 70°F) ~ 95°C (~ 200°F)	94.40 93.01
CONCENTRATION	~ 0.2 g/m^3 (0.1 gr/ft^3) ~ 2.0 g/m^3 (1.0 gr/ft^3)	91.62 95.79

RESULTS OF F-TEST ANALYSIS OF VARIANCE

EFFECT	F (1,5)	SIGNIFICANCE LEVEL (IF ≥ 0.90)
(1) Flow	1.19	-
(2) Dust	152.6	> .99
(3) Temperature	4.83	> .90
(4) Concentration	43.50	> .99
(2)(4)	24.33	> .99
(1)(3)	6.33	> .90

MEAN SQUARE ERROR: 1.593

Table 7c. RESULTS OF STATISTICAL ANALYSIS ON EFFICIENCY

PARTICLE SIZE FRACTION: Impactor stage #4 , 4.0 - 5.6 μm

GRAND MEAN OF EFFICIENCY TESTS: 99.02

MARGINAL MEANS PARAMETER	LEVEL	MEAN
FLOW	14.2 m^3/min (500 cfm) 28.3 m^3/min (1000 cfm)	99.21 98.82
DUST	IRON OXIDE FLY ASH	98.35 99.69
TEMPERATURE	~ 20°C (~ 70°F) ~ 95°C (~ 200°F)	99.29 98.75
CONCENTRATION	~ 0.2 g/m^3 (0.1 gr/ft^3) ~ 2.0 g/m^3 (1.0 gr/ft^3)	98.60 99.43

RESULTS OF F-TEST ANALYSIS OF VARIANCE		
EFFECT	F (1,5)	SIGNIFICANCE LEVEL (IF ≥ 0.90)
(1) Flow	1.31	-
(2) Dust	15.67	> .95
(3) Temperature	2.54	-
(4) Concentration	6.14	> .90
(2)(4)	4.44	> .90
(3)(4)	2.30	-
MEAN SQUARE ERROR: .457		

Table 7d. RESULTS OF STATISTICAL ANALYSIS ON EFFICIENCY

PARTICLE SIZE FRACTION: Impactor Stage #5 , 2.5 - 4.0 μm

GRAND MEAN OF EFFICIENCY TESTS: 98.37

MARGINAL MEANS PARAMETER	LEVEL	MEAN
FLOW	14.2 m^3/min (500 cfm) 28.3 m^3/min (1000 cfm)	98.75 97.99
DUST	IRON OXIDE FLY ASH	97.47 99.26
TEMPERATURE	~ 20°C (~ 70°F) ~ 95°C (~ 200°F)	98.57 98.16
CONCENTRATION	~ 0.2 g/m^3 (0.1 gr/ft^3) ~ 2.0 g/m^3 (1.0 gr/ft^3)	98.00 98.74

RESULTS OF F-TEST ANALYSIS OF VARIANCE

EFFECT	F (1,5)	SIGNIFICANCE LEVEL (IF ≥ 0.90)
(1) Flow	10.50	> .95
(2) Dust	57.83	> .99
(3) Temperature	3.08	-
(4) Concentration	9.86	> .95
(2)(4)	20.45	> .99
(3)(4)	3.43	-
(2)(3)	2.71	-

MEAN SQUARE ERROR: 0.221

Table 7e. RESULTS OF STATISTICAL ANALYSIS ON EFFICIENCY

PARTICLE SIZE FRACTION: Impactor stage #6, 1.3 - 2.5 μm

GRAND MEAN OF EFFICIENCY TESTS: 93.00

MARGINAL MEANS PARAMETER	LEVEL	MEAN
FLOW	14.2 m^3/min (500 cfm) 28.3 m^3/min (1000 cfm)	94.82 91.17
DUST	IRON OXIDE FLY ASH	92.37 93.62
TEMPERATURE	~ 20°C (~ 70°F) ~ 95°C (~ 200°F)	93.54 92.46
CONCENTRATION	~ 0.2 g/m^3 (0.1 gr/ft^3) ~ 2.0 g/m^3 (1.0 gr/ft^3)	92.59 93.41

RESULTS OF F-TEST ANALYSIS OF VARIANCE

EFFECT	F (1,5)	SIGNIFICANCE LEVEL (IF ≥ 0.90)
(1) Flow	75.80	> .99
(2) Dust	8.89	> .95
(3) Temperature	6.57	> .95
(4) Concentration	3.86	-
(2)(4)	40.71	> .99
(1)(4)	25.69	> .99
(1)(3)	11.55	> .95
(1)(2)	8.19	> .95

MEAN SQUARE ERROR: 0.703

Table 7f. RESULTS OF STATISTICAL ANALYSIS ON EFFICIENCY

PARTICLE SIZE FRACTION: Impactor stage #7, 0.8 - 1.3 μm

GRAND MEAN OF EFFICIENCY TESTS: 75.44

MARGINAL MEANS PARAMETER	LEVEL	MEAN
FLOW	14.2 m^3/min (500 cfm) 28.3 m^3/min (1000 cfm)	83.45 67.44
DUST	IRON OXIDE FLY ASH	81.87 69.01
TEMPERATURE	~ 20°C (~ 70°F) ~ 95°C (~ 200°F)	78.95 71.94
CONCENTRATION	~ 0.2 g/m^3 (0.1 gr/ft^3) ~ 2.0 g/m^3 (1.0 gr/ft^3)	72.79 78.10

RESULTS OF F-TEST ANALYSIS OF VARIANCE		
EFFECT	F (1,5)	SIGNIFICANCE LEVEL (IF ≥ 0.90)
(1) Flow	3.79	-
(2) Dust	2.45	-
(3) Temperature	0.73	-
(4) Concentration	0.42	-
(1)(2)	2.45	-
(1)(3)	1.63	-
MEAN SQUARE ERROR: 270.6		

Table 7g. RESULTS OF STATISTICAL ANALYSIS ON EFFICIENCY

PARTICLE SIZE FRACTION: Impactor stage #8 , 0.54 - 0.8 μm

GRAND MEAN OF EFFICIENCY TESTS: 27.39

MARGINAL MEANS PARAMETER	LEVEL	MEAN
FLOW	14.2 m^3/min (500 cfm) 28.3 m^3/min (1000 cfm)	26.66 28.12
DUST	IRON OXIDE FLY ASH	16.92 37.86
TEMPERATURE	~ 20°C (~ 70°F) ~ 95°C (~ 200°F)	25.04 29.75
CONCENTRATION	~ 0.2 mg/m^3 (0.1 gr/ft^3) ~ 2.0 mg/m^3 (1.0 gr/ft^3)	26.51 28.27

RESULTS OF F-TEST ANALYSIS OF VARIANCE

EFFECT	F (1,5)	SIGNIFICANCE LEVEL (IF ≥ 0.90)
(1) Flow	0.01	-
(2) Dust	2.50	-
(3) Temperature	.13	-
(4) Concentration	.02	-
(1)(3)	2.22	-

MEAN SQUARE ERROR: 700.9

Table 7h. RESULTS OF STATISTICAL ANALYSIS ON EFFICIENCY

PARTICLE SIZE FRACTION: Final filter after impactor, ≤ 0.54 μm

GRAND MEAN OF EFFICIENCY TESTS: 47.38

MARGINAL MEANS PARAMETER	LEVEL	MEAN
FLOW	14.2 m^3/min (500 cfm) 28.3 m^3/min (1000 cfm)	49.26 45.50
DUST	IRON OXIDE FLY ASH	39.94 54.82
TEMPERATURE	~ 20°C (~ 70°F) ~ 95°C (~ 200°F)	51.36 43.40
CONCENTRATION	~ 0.2 g/m^3 (0.1 gr/ft^3) ~ 2.0 g/m^3 (1.0 gr/ft^3)	23.51 71.25

RESULTS OF F-TEST ANALYSIS OF VARIANCE

EFFECT	F (1,5)	SIGNIFICANCE LEVEL (IF ≥ 0.90)
(1) Flow	0.26	-
(2) Dust	4.05	.90
(3) Temperature	1.16	-
(4) Concentration	41.62	> .99
(2)(4)	7.04	> .95
(1)(4)	4.60	> .90
(1)(3)	1.83	-

MEAN SQUARE ERROR: 219.0

Table 8 . SIGNIFICANCE OF EFFECTS OF FLOW, DUST, TEMPERATURE, AND CONCENTRATION ON SCRUBBER COLLECTION EFFICIENCY

Aerosol fraction	Significance level			
	Flow	Dust	Temp.	Conc.
Total filter	~ 0.90	> 0.99	--	> 0.95
Total impactor	--	> 0.99	> 0.99	> 0.99
4.0-5.6 μm	--	> 0.95	--	> 0.90
2.5-4.0 μm	> 0.95	> 0.99	--	> 0.95
1.3-2.5 μm	> 0.99	> 0.95	> 0.95	~ 0.90
0.8-1.3 μm	~ 0.90	--	--	--
0.54-0.8 μm	--	--	--	--
≤ 0.54 μm	--	~ 0.90	--	> 0.99

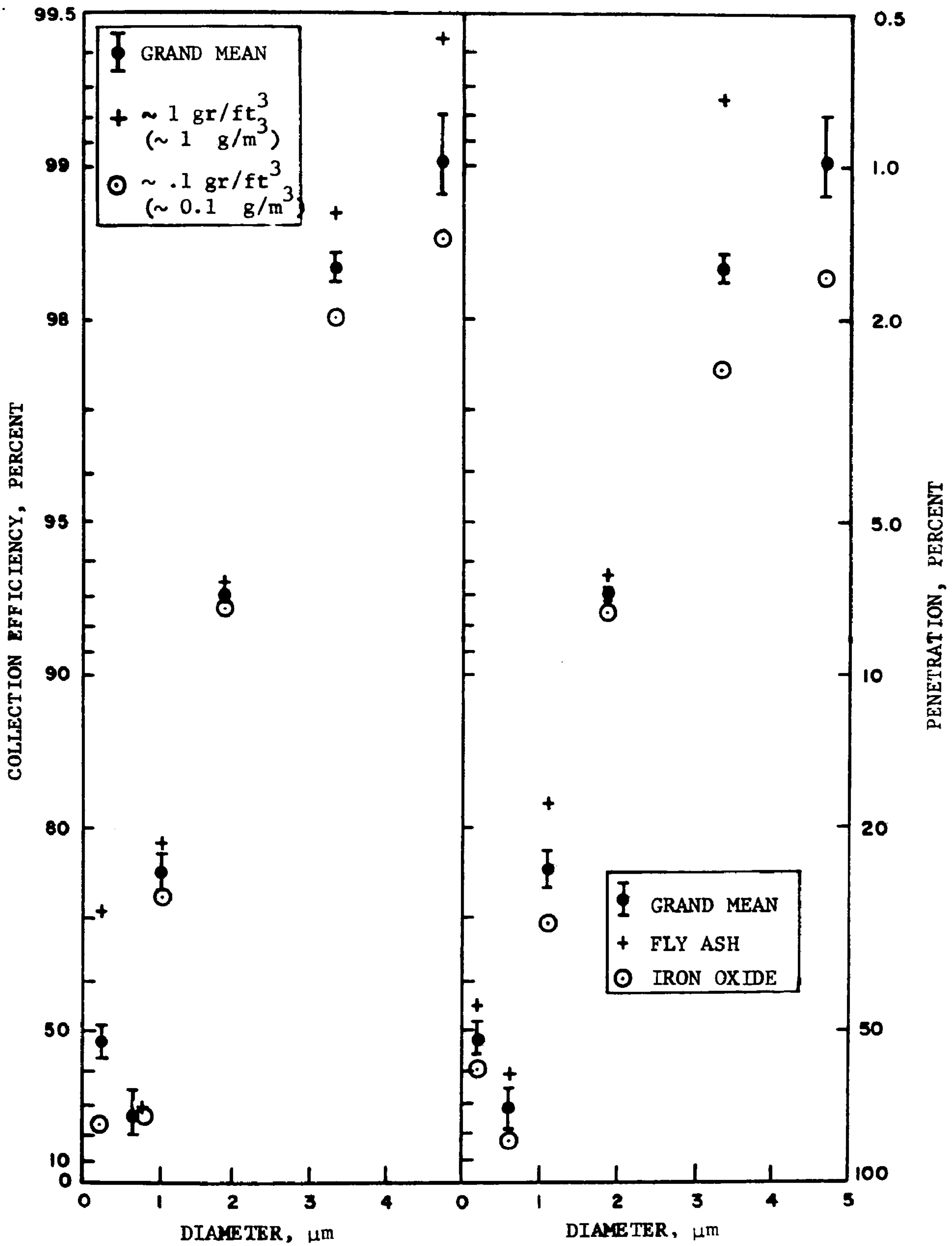


Figure 11. Dynactor scrubber collection efficiency versus particle aerodynamic diameter, effects of loading and dust type

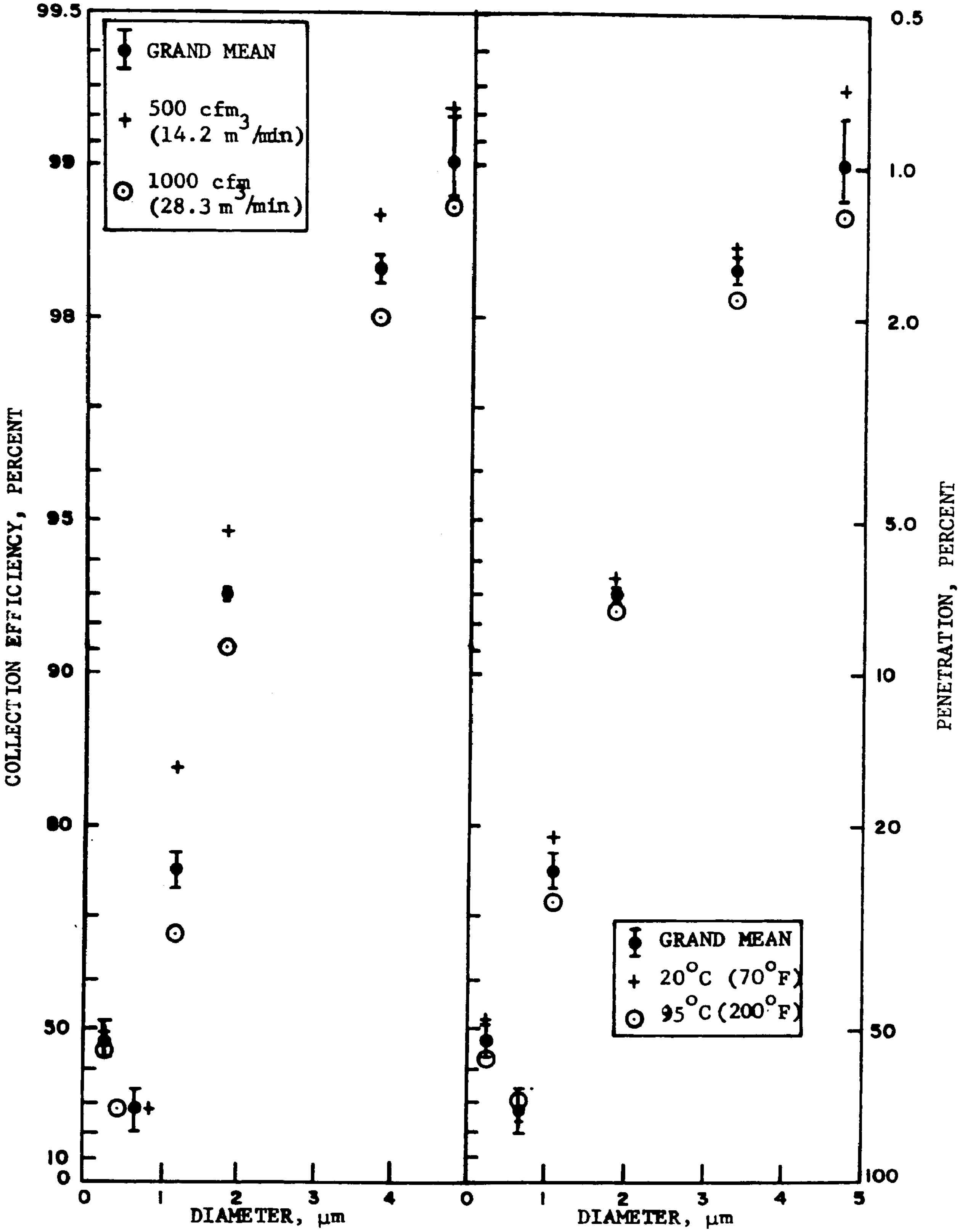


Figure 12. Dynactor scrubber collection efficiency versus particle aerodynamic diameter, effects of flow rate and inlet temperature

3. The lower temperature produced greater efficiencies than did the higher temperature, in seven of eight aerosol fractions, but this was statistically significant in only two fractions.
4. Higher concentrations were collected with greater efficiency than lower concentrations and this was statistically significant in most fractions.

The F-test analysis of variance also gave information on the significance of interactions between the variables flow (1), dust (2), temperature (3) and concentration (4). Thus the interaction labeled (2) (4) in the Tables 7a, b, c, d, e, h is the interaction of dust and concentration, which can be interpreted in either of two ways: the degree to which different dusts gave a different dependence of efficiency upon concentration <u>or</u> the degree to which different concentrations gave a different dependence of efficiency upon dust type. In Table 9 are arrayed the averages of four tests each at the particular combinations of parameters whose interaction was found to be significant for the 1.3 to 2.5 μm aerosol fraction, Table 7e. Thus, the first group contains two levels of concentration and two types of dust, from which we see that the difference in efficiency between high and low concentrations was more pronounced for iron oxide than it was for flyash. The next set in Table 9 shows that the difference in efficiency between the two types of dust was greater at the lower flow rate than at the higher. Similar interpretations would be appropriate for the other two sets of data in Table 9: the effect of temperature was greater at the higher flow rate and the effect of concentration was greater at the lower flow rate. The F-test values in Table 7e indicate all these statements are statistically significant. The flow interactions are displayed in Figure 13. The explanations of all these interactions for all the stages would be difficult to make, but an example of one such explanation would be that the difference in efficiency for the two dusts is caused by collection mechanisms that increase with increased residence time, thus being more significant at the lower flow rate than at the higher.

Table 9. DETAILED ANALYSIS OF INTERACTIONS FOR DYNACTOR EFFICIENCY ON 1.3 - 2.5 μm AEROSOL FRACTION (STAGE #6)

Efficiencies (N=4)	Parameter: Dust (2)	
	Iron oxide	Fly ash
Concentration (4)		
~ 0.1 g/m^3	90.6	94.6
~ 1.0 g/m^3	94.2	92.7
	Parameter: Flow (1)	
	500 cfm	1000 cfm
Dust (2)		
Iron oxide	93.6	91.2
Fly ash	96.0	91.2
Temperature (3)		
20°C	94.6	92.4
95°C	95.0	89.9
Concentration (4)		
~ 0.1 g/m^3	93.4	91.8
~ 1.0 g/m^3	96.3	90.6

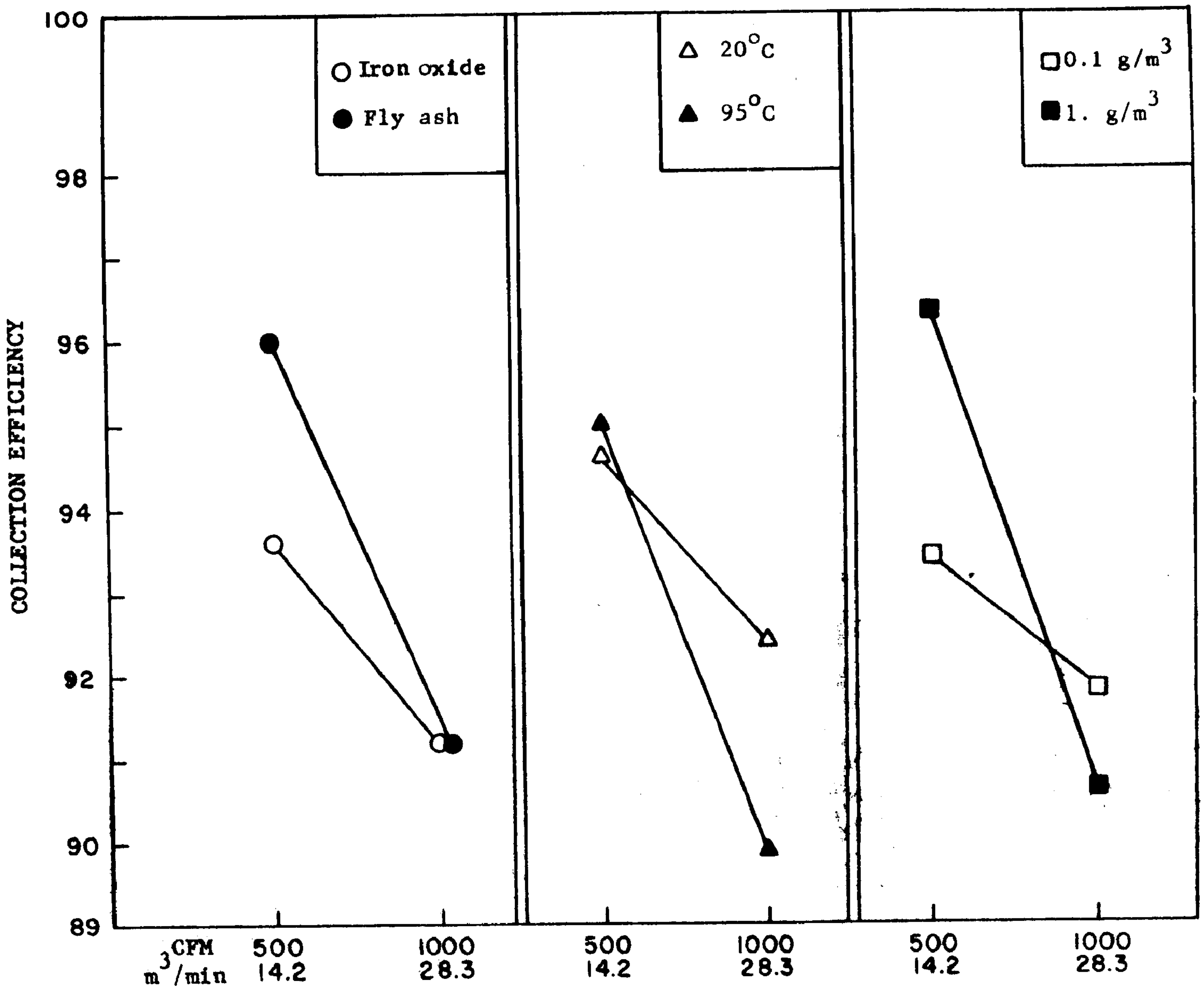


Figure 13. Collection efficiency, 1.3-2.5 μm, versus flow for different dusts, temperatures, and concentrations

Estimates of Experimental Error

Two methods were used to get estimates of the experimental error. The first involved dividing the residual sum of squares by the number of degrees of freedom (5) and taking the square root, for the data in the balanced 2^4 test matrix used in the analysis of variance. This is a standard method. The residuals were those from the analysis of the individual factors (flow, dust, temperature, and concentration) and two-factor interactions. Such residuals would include three-factor interactions, if any, and mistakenly treat them as experimental error. (Nearly always, these three-factor contributions to the sum of squares were of the same magnitude as the residuals left even after the three-factor interactions were taken into account.) The second estimate of the experimental error came from the three replications for iron oxide at 1000 cfm (28 m^3/min), ~ 1 gr/ft^3 (~ 1 g/m^3), at ambient temperature. Both are given in Table 10. In six of eight cases, the estimates from the replication tests were lower. The standard deviation of an average of N such tests would be the standard deviation for one test divided by $N^{1/2}$. For any one of the measurements to be significantly different from a given value, it should be at least two standard deviations different from that value, which gives a guideline for comparing the results of the tests done outside the factorial design test matrix.

Collection Efficiency Tests at 1500 cfm (42 m^3/min)

An 8-point pitot tube traverse was used downstream in 8 inch (0.20 m) diameter duct and yielded an outlet flow of 1510 cfm (43 m^3/min). Twenty point pitot tube traverse used upstream in 12 inch (0.30 m) diameter duct yielded an inlet flow of 1250 cfm (35 m^3/min). Magnehelic gauges used for the above traverses were checked with an upright manometer. They were in good agreement which determined that the gauges were not the cause of the above flow discrepancy.

Table 10. ESTIMATES OF EXPERIMENTAL ERROR FOR SINGLE TEST FROM THE RESIDUALS OF THE SUM OF SQUARES AND FROM THE REPLICATION TESTS, Nos. 16, 17, 18

	Standard deviation estimates	
Aerosol fraction	$(M.S.E)^{1/2}$ [a] (%)	0.59 x range[b] (%)
Total filter	1.29	0.41
Total impactor	1.26	1.00
4.0-5.6 μm	0.68	0.18
2.5-4.0 μm	0.47	0.59
1.3-2.5 μm	0.84	0.12
0.8-1.3 μm	8.4 (17.7)[c]	3.7
0.54-0.8 μm	26.5	34.0
$\leq$ 0.54 μm	14.8	11.2

[a]Root mean square of residual sum of squares after two-factor analysis of factorial design tests.

[b]Best estimate of standard deviation from range of three measurements (Wilson, 1952).

[c]Value including a discarded datum, test No. 10 (12.5)

An attempt was made to seal leaks in the Dynactor and peripheral ducting, but it must be assumed that with a static pressure loss greater than 2 inch H_2O (5×10^2 nt/m^2) at the outlet some leakage occured. Flow through the Dynactor was calculated as the average between inlet and outlet volumes, but grain loading was calculated on the basis of the flows measured upstream and downstream. Efficiency was determined by the ratio of the rate of particulate mass flow out of the Dynactor to the rate of particulate mass flow into the Dynactor.

The results for the tests at 1500 cfm (42 m^3/min) and at 1000 cfm (28 m^3/min) for iron oxide at 1 mg/m^3 are given in Table 11 to facilitate comparison. At ambient temperature, the lower flow rate produced a higher efficiency in six of the eight aerosol fractions measured and indistinguishable efficiencies in two (4.0 - 5.6 μm, 0.54 μm). In three cases (total impactor, 2.5 to 4.0 μm, 1.3 to 2.5 μm) the higher flow rate value was more than two of its estimated standard deviations away from the low flow rate mean, which would support the conclusion that at ambient temperature the effect of increasing the flow lowered the efficiency. At the elevated temperature, 95°C (200°F), raising the flow seems not to have decreased the efficiency. Three efficiencies were lower and three were higher. The data from the tests at 1000 cfm (28 m^3/min) and 1500 cfm (42 m/min) displayed lower efficiencies for increased flow at 20°C but not at 95°C; at 1000 cfm (28 m^3/min), six of six fractions showed higher efficiencies at 21°C than at 95°C, but at 1500 cfm (42 m^3/min) six of seven fractions showed higher efficiencies at 95°C than at 21°C, suggesting an interaction between the two variables.

Collection Efficiency Tests With Inlet Air Humidified

Efficiency tests were performed using heated air to evaporate a fine water spray upstream from the Dynactor inlet to use the subsequent condensation of water vapor to enhance particle collection (diffusiophoresis

Table 11. RESULTS OF DYNACTOR COLLECTION EFFICIENCY TESTS UNDER SIMILAR CONDITIONS EXCEPT FOR FLOW RATE (IRON OXIDE, ~ 1 g/m^3)

Aerosol fraction	21°C (70°F) 1500 cfm ($42\ m^3/min$)	21°C (70°F) 1000 cfm ($28\ m^3/min$)	95°C (200°F) 1500 cfm ($42\ m^3/min$)	95°C (200°F) 1000 cfm ($28\ m^3/min$)
Total filter	94.8	95.4	94.7	94.9
Total Impactor	88.9	93.9	93.8	91.7
4.0-5.6 μm	≥ 97.5	≥ 99.2	≥ 98.4	99.1
2.5-4.0 μm	97.0	98.5	98.6	97.6
1.3-2.5 μm	87.1	93.1	89.4	89.9
0.8-1.3 μm	75.0	83.7	83.1	75.9
0.54-0.8 μm	≤ 19.4	46.4	75.8	--
≤ 0.54 μm	--	≤ 82.5	--	66.1
Test number	29	16,17,18 avg.	30	19

The spray was introduced downstream from the inlet sampling probes. Two # 1511 Sprayco pinjet nozzles operated at 80 psi (5.5×10^5 N/m^2) were used, spraying 0.56 gal/min (3.5×10^{-5} m^3/s) into air at 350°F (177°C). The humidity ratio was determined two ways: by weight change of dessicant material after the gas passed through a cyclone (10 mm) and by wet bulb/dry bulb thermometer measurements (and comparison with a psychometric chart). During test #28, the wet and dry bulb thermometers were inserted into the duct immediately upstream from the Dynactor inlet. During test #31 the gas sample was made to pass not only through a cyclone but also through a heating section into which the wet bulb and dry bulb thermometers were placed, and from which it passed into the dessicant. The ratio, by weight, of water vapor to dry air for test #28 was 0.032 as determined by dessicant weight gain and 0.057 as determined by the thermometric measurements. Some of this discrepancy was thought to be due to condensation in the sampling line to the dessicant, one of the reasons the heated section was introduced for test #31. For test #31, the humidity ratio was 0.070 as determined by the dessicant and 0.071 and 0.086 as determined by thermometric measurements near the beginning and end of the test. No intentional changes were made in the system in producing the higher humidity ratio the second time, so although we have reported the tests as having two different average humidity ratios (0.044, 0.076), they may have had nearly the same.

The data from these two tests are given in Table 12, along with data from two tests most nearly matching the conditions of the steam addition tests. In each aerosol size fraction the ranges of the steam added tests and the tests without added steam overlap, with the exception of the interval 1.3 to 2.5 μm, for which the efficiencies without steam addition are higher than those with added steam. The addition of water vapor to achieve an inlet humidity ratio of about 0.05 g water per g dry air did not appreciably enhance collection efficiency, an unexpected result.

Table 12. RESULTS OF DYNACTOR COLLECTION EFFICIENCY TESTS UNDER SIMILAR CONDITIONS BUT WITH AND WITHOUT STEAM ADDITION (IRON OXIDE, 500 cfm = 0.24 m^3/sec, ~ 1 g/m^3)

	Tests					
	No steam			Steam added		
Aerosol fraction	#4	#5[a]	Avg.	#28	#31	Avg.
Total filter	96.4	91.1	93.8	--	96.2	96.2
Total impactor	93.9	94.3	94.1	95.4	93.0	94.2
4.0-5.6 μm	99.1	≥ 99.2	≥ 99.1	≥ 99.3	≥ 98.9	≥ 99.1
2.5-4.0 μm	98.3	99.1	98.7	99.3	98.9	99.1
1.3-2.5 μm	96.0	97.5	96.8	95.0	94.0	94.5
0.8-1.3 μm	85.2	89.3	87.2	85.7	80.3	83.0
0.54-0.8 μm	--	--	--	48.4	70.0	59.2
≤ 0.54 μm	73.3	72.0	72.6	≤ 64.4	≤ 80.0	≤ 72.2

[a]This test done at 95°C (= 200°F)

Collection Efficiency Test With Surfactant Added to the Spray

The addition of a surfactant chemical to the spray used in the Dynactor might be expected to affect efficiency by changing the droplet size distribution in the spray somewhat and changing the wetting efficacy of the droplets, both changes due to the lowering of the surface tension of the water in the spray. A surfactant was added to the water reservoir in the Dynactor's stages to form a 10 parts per million solution. An efficiency test (test #15) was run using this solution, but otherwise at the conditions at which the replicative tests (#17, 18, 16) were run; that is, 1000 cfm (28 m^3/min), ~ 1 gr/ft^3 (~ 1 g/m^3), iron oxide aerosol, ambient temperature. Table 13 contains the efficiencies from the two types of test. In six of six aerosol fractions, the surfactant additive gave a higher efficiency than had been obtained without it, and in the other two fractions there were no distinguishable differences. In the range 1.3 to 4.0 μm, the efficiencies were more than one standard deviation apart but less than two. For most applications, the differences would not be substantial.

Collection Efficiency Tests At Reduced Nozzle Pressure

One efficiency test was made using the Dynactor spray nozzles at 100 psig (6.9×10^5 N/m^3), half their normal pressure. This test, #13 listed in Appendix B, is directly comparable with test #12, also listed in Appendix B, and in every size fraction it gave a lower efficiency. The total efficiency on iron oxide at 1000 cfm (28 m^3/min) at ~ 0.1 g/m^3 (~ 0.1 gr/ft^3) at ambient temperature was 81.8 percent for this reduced pressure, compared with 90.0 percent at the usual nozzle pressure for these same conditions.

Some of these results are discussed more fully in the next section, which also contains a comparison between the Dynactor scrubber and conventional venturi scrubber technology.

Table 13. RESULTS OF DYNACTOR COLLECTION EFFICIENCY TESTS UNDER SIMILAR CONDITIONS EXCEPT FOR THE ADDITION OF 10 ppm SURFACTANT TO THE SPRAY WATER

	Collection efficiencies	
Aerosol fraction	Surfactant added	No surfactant
Total filter	95.5	95.4
Total impactor	94.4	93.9
4.0-5.6 μm	≥ 99.2	≥ 99.2
2.5-4.0 μm	99.2	98.5
1.3-2.5 μm	94.2	93.1
0.8-1.3 μm	84.9	83.7
0.54-0.8 μm	62.2	46.4
≤ 0.54 μm	≤ 82.2	≤ 82.2
Test number	25	16,17,18 avg.

SECTION VI

DISCUSSION

In this section, we compare the Dynactor Scrubber with a widely-used control device which also uses the collection of particles by spray droplets, the venturi scrubber. Costs are compared for the two different scrubbers when used so as to obtain very similar efficiencies. The effects of the factors studied with the factorial design tests is discussed as well.

DYNACTOR SCRUBBER VERSUS VENTURI SCRUBBER

Both the typical venturi scrubber and the "ejector venturi" (Harris, 1964) use a fine water spray to clean a gas stream. The latter uses this spray to supply some of the motive power to the air stream. Fairly similar flow versus pressure gain curves are obtained with the Dynactor scrubber operating at 200 psig and 18.4 gpm water spray (13.8×10^5 N/m^2 and $1.17 \times 10^{-3} m^3/s$) and with the ejector venturi operating at 40 psig and 24 gpm (2.8×10^5 N/m^2 and $1.53 \times 10^{-3} m^3/s$), according to the published data (Harris, 1964), which would mean that the latter acts as a fan about 4 times more efficiently than does the Dynactor. The collection efficiency information on the ejector venturi is sketchy, but at a comparable power consumption by the nozzles in the two systems (2 hp/1000 cfm, 3.2 $kw/m^3/s$) the observed mass efficiency for the ejector venturi (Takishima et al., 1961) was 97.8 percent and for the Dynactor scrubber 99.0 percent, for fly ash aerosols having mass median diameters near 6 μm. Thus the two-stage Dynactor yielded half the penetration compared to an ejector venturi operating at the same spray input power per volume flow of air. Much more experience has been gained with the usual venturi scrubber, so that the remainder of this comparison segment will concern the Dynactor and the conventional venturi scrubber. The prime function of the Dynactor scrubber is to remove particulate material rather than to aid flow, so the comparison should be made with venturi scrubbers having the same collection efficiency. Figure 14 is derived from the Scrubber Handbook (Calvert et al., 1972). It gives the theoretical collection efficiency of venturi scrubbers as a function of the air flow pressure drop produced by the venturi; these curves match experimental results obtained with venturis rather well. From the grand mean mass collection efficiencies measured for the Dynactor we have plotted the interpolated collection efficiency at 1, 2, and 4 μm aerodynamic diameter to obtain the pressure drop associated with a venturi scrubber having the same collection efficiency. The data indicate that the corresponding venturi scrubber pressure drop would be about 40-inch H_2O or 10×10^3 N/m^2. Using a 40-inch H_2O venturi as an equivalent for comparison, we investigated the question of relative costs. Both devices use water sprays and thus must consume clean water, dispose of contaminated water. Both would be expected to have similar maintenance problems.

Power Consumption

The Dynactor power consumption is the power used by the nozzles divided by the efficiency of the pumps and associated plumbing. The Dynactor nozzles use a total theoretical power (flow times pressure drop) of 1.6 kw for the 1000 cfm treated by the DY-12-F2. (The slight air flow pressure drop is negligible.) The venturi scrubber power consumption is the product of the air flow times the pressure drop, which would be 4.7 kw for 40-inch H_2O and 1000 cfm, plus any power other than the air flow pressure drop used in supplying the water spray. Thus, comparable Dynactor scrubbers and venturi scrubbers have intrinsic power requirements which are nearly three times lower for the Dynactor.

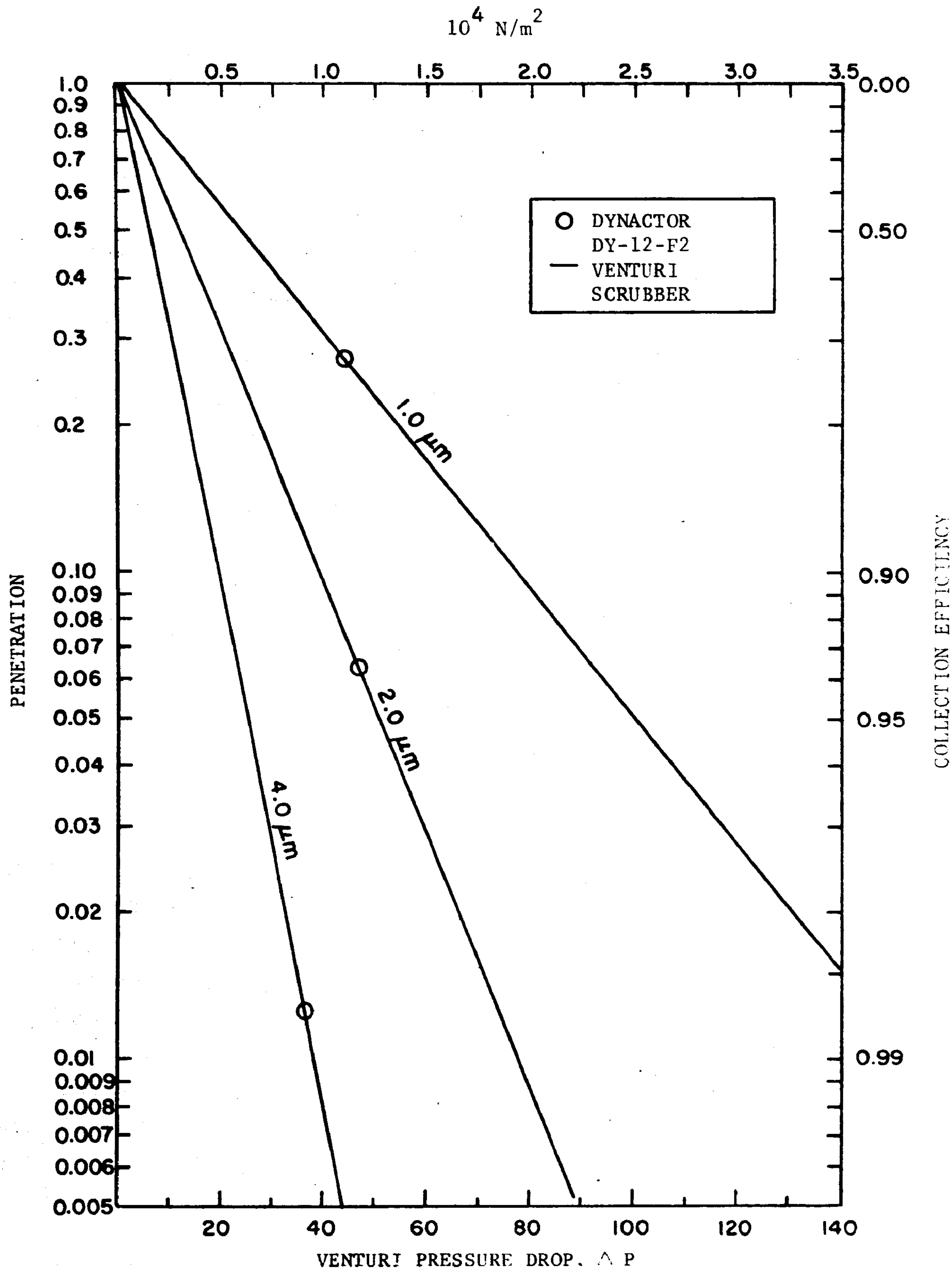


Figure 14. Collection efficiency curves for venturi scrubbers and Dynactor efficiency data

Water Consumption

The two-stage Dynactor scrubber we tested worked with nozzles having a flow of 18.4 gal/min for 1000 cfm or 2.5×10^{-3} m^3/s water per 1 m^3/s of air.

Cost estimates in the Scrubber Handbook (Calvert et al., 1972) used 8.4 gal/1000 ft^3 or 1.1×10^{-3} m^3 water per m^3 air as typical for venturi scrubbers, which is somewhat less than half that used by the Dynactor.

The amount of water actually consumed by both systems would depend on the dust loadings and on their relative abilities to recirculate the contaminated water.

Costs

Scrubber applications vary, as do the trade-offs made by scrubber manufacturers in meeting their user's requirements. Any cost comparison has to be used with an awareness of the uncertainties in such projections, and this one is no exception. The one which follows has an added difficulty: it is based on two different sources of data, the open literature on venturi scrubbers and the data supplied by RP Industries, manufacturers of the Dynactor scrubber.

We chose to compare the two types of scrubber at 40,000 cfm (19 m^3/s), which is more nearly typical of industrial applications than the 1000 cfm at which the Dynactor DY-12-F2 was tested. The systems were assumed to be operated 8,000 hours a year, nearly full-time.

Following is an explanation of the information contained in the tables.

Estimated Capital Investment - Capital investment is the sum of purchased equipment cost and installation. Venturi installation was assumed to be 200 percent of the purchased cost, from material in the Scrubber Handbook (Calvert et al., 1972).

Annual Operating Costs - The annual operating cost includes the following fixed, variable, and semi-variable costs.

Fixed costs -

1. Amortization of capital investment - The capital investments have been amortized over a period of 20 years. This reflects the expected lifetime of the equipment based upon literature review. (Blecker and Nichols, 1973)

2. Interest on loan - An interest rate of 8 percent of the total capital investment was used. It was further assumed that the interest is to be paid after one year, but is capitalized uniformly over the estimated 20-year lifetime of the equipment. This method is used in similar engineering estimates. (NAPCA, 1969)

3. Insurance - The cost of insurance was estimated to be 1.0 percent of total capital investment. This figure is suggested by Peters and Timmerhaus (1968) as a reasonable estimate.

Variable and semi-variable costs -

1. Labor and maintenance - Annual labor and maintenance was estimated to be 1.4 percent of the installed equipment cost. This represents the lower end of the range for this type of equipment. (Blecker and Nichols, 1973; Calvert, Goldschmidt, Leith, Mehta, 1972)

2. Electric power - Electric power requirements for the high energy venturi scrubber were obtained from the Scrubber Handbook. (Calvert et al., 1972) Power needed for the Dynactor System was obtained from manufacturers literature. Power costs were assumed to be be $0.025 per kilowatt-hour. (Boston Edison rate schedule, 1974)

3. Water - Water requirements for the Dynactor system were obtained from manufacturer's literature. Water needs for the venturi scrubber were obtained from the Scrubber Handbook. Water costs were assumed to be $0.50 per 100 cubic feet. (Boston Public Works Dept., July 1974)

Table 14a. Estimated capital cost of Dynactor system, based on manufacturer's data (1973 dollars)

FLOW CAPACITY:		
40,000 cfm = 1.13×10^3 m^3/min = 18.9 m^3/s		
TOTAL CAPITAL INVESTMENT		$120,000
Purchased Equipment	$60,000	
Installation	$60,000	
Estimated Operating Cost of Dynactor System		
TOTAL CAPITAL INVESTMENT (C.I.)		$120,000
FIXED COST (ANNUAL)		
Amortization at 5% C.I.		$ 6,000
Interest on Loan (8% of C.I.)[a]		$ 480
Insurance (1.0% of C.I.)		$ 1,200
VARIABLE AND SEMI-VARIABLE COST (ANNUAL)		
Labor and Maintenance (1.0% of C.I.)		$ 1,200
Electric Power ($0.025/kw.-hr.)		$ 11,936
Water ($0.50/100 cubic feet)		$ 4,825

[a] Paid in one year; amortized over 20 years.

Table 14b. Estimated capital cost of high energy Venturi scrubbers, yielding similar collection efficiency to Dynactor (1973 dollars)

FLOW CAPACITY		
40,000 cfm = 1.13 x 10^3 m^3/min = 1.89 m^3/s		
TOTAL CAPITAL INVESTMENT		$147,000
Purchased Equipment	$49,000	
Installation	$ 98,000	

<u>Estimated Operating Cost of High Energy Venturi Scrubber</u>

TOTAL CAPITAL INVESTMENT (C.I.)	$147,000
FIXED COST (ANNUAL)	
Amortization at 5% C.I.	$ 7,350
Interest on Loan (8% of C.I.)[a]	$ 588
Insurance (1.0% of C.I.)	$ 1,470
VARIABLE AND SEMI-VARIABLE COST (ANNUAL)	
Labor and Maintenance (1.0% of C.I.)	$ 1,470
Electric Power ($0.025/kw.-hr.)	$63,300
Water ($0.50/100 cubic feet)	$ 6,420

[a] Paid in one year; amortized over a 20-year period.

From the material on costs in the foregoing two tables, we conclude that the primary difference in costs between the Dynactor system and an equivalent venturi scrubber is the difference in electrical power costs, estimated here to be a difference on the order of $50,000/yr for treating 40,000 cfm (19 m^3/s) in favor of the Dynactor, based on $0.025/kw.-hr. For the 1000 cfm model we tested, the difference in intrinsic power requirements was a factor of three to one in favor of the Dynactor in comparison with an equivalent venturi. Using this ratio, the difference between Dynactor power cost per year and the power cost per year of an equivalent venturi would be expected to be $42,000 for treating 40,000 cfm. These yearly savings would be about 40% of the capital investment.

EFFECTS OF FLOW, DUST, TEMPERATURE, CONCENTRATION, ETC.

As noted in the results, there were statistically significant effects on collection efficiency due to flow, dust, temperature, and concentration of particulates. Here we will discuss these effects and link these results with those of others.

Flow

Increasing the flow rate will increase the velocity gradients, which would be expected to increase deposition due to impaction and interception and to increase the turbulent eddy diffusivity, which is a linear function of the Reynolds number (Calvert et al., 1972), and thus increase the rate of mass transfer to the droplets. Increasing the flow rate will also decrease the residence time, which would give less time for the collection mechanisms to act, significant for the smallest particles, where diffusion would predominate the collection mechanisms, and for the largest particles, for which settling would become important. We found somewhat higher collection efficiencies at the lower flow rate, as did Lancaster and Strauss (1971) in their experiments with spray scrubbers, using ZnO particles with a number median diameter of 1.0 μm.

Dust

Particles of fly ash were consistently collected with greater efficiency than particles of iron oxide having the same aerodynamic diameter in our tests. Different aerodynamic behavior by particles having the same aerodynamic diameter is unexpected, but perhaps the particles differed in the likelihood with which a particle/droplet collision produced capture or in the degree to which they served as nuclei during condensation or the degree to which high humidities facilitated their agglomeration. The iron oxide powder seemed less hydrophilic than did the fly ash, thus the iron oxide would have been less wettable and more difficult for the water droplets to entrap. Lohs (1969) found that making hydrophobic polystyrene particles into hydrophilic ones, by coating their surfaces with a wetting agent, increased the capture of these particles by a spray scrubber. From their experiments with venturi scrubbers, Calvert, Lundgren, and Mehta (1972) concluded that particle wettability enhanced collection efficiency.

Temperature

Temperature can influence collection efficiency in a variety of ways. Higher temperatures means higher viscosity for gases; for example, as air goes from $20^{o}C$ to $100^{o}C$, its viscosity increases a factor of 1.20 (Bird et al., 1960), which increases its resistance to particle motion, hindering the various collection mechanisms. For the submicron particles, this can be offset by the increase in the Cunningham slip correction factor as temperature increases and by the increase in the particle diffusivity due to Brownian motion. Our experiments showed a statistically significant decrease in collection efficiency for 1.3-2.5 μm aerodynamic diameter particles as temperature increased from $20^{o}C$ to $95^{o}C$, as well as a general trend toward decreased efficiencies for all the aerosol size fractions. Lancaster and Strauss (1971) measured a decrease in efficiency in going from $20^{o}C$ to $30^{o}C$ with a spray scrubber operating on water-saturated air containing particulate material.

Concentration

As particle concentration increases, particle agglomeration increases due to coagulation. Increased agglomeration means an aerosol having larger mean size, which generally enhances collection efficiency in spray scrubbers. Increased concentrations yielded higher collection efficiencies in all the aerosol size fractions in our tests. Lancaster and Strauss (1971), among others, reported increased efficiency with increased mass loading. In our tests with the Dynactor, the improvement in collection was most dramatic for the smallest particles, indicative of coagulation.

Surfactant Addition

The addition of wetting agent, surfactant, to the spray water lowers the surface tension of the water, which would mean it improves the ability of the droplets to wet and engulf particles and it tends to decrease the droplet size of the spray, the latter being determined by the equilibrium between the force of surface tension and the forces tending to break up the droplets. Improved wetting should improve collection efficiency in situations where poor wetting is an inhibitor, which we believe was the situation with iron oxide. Smaller droplet sizes generally improve collection efficiency as well, for a given droplet mass concentration. Our results showed a trend toward a slight improvement in efficiencies using a surfactant additive.

Water Vapor Addition, Diffusiophoresis, Thermophoresis

Lapple and Kamack (1955) were among the first of many to note that the addition of steam upstream from a scrubber could produce substantial improvements in collection efficiencies. Lohs (1969) attributed the enhancement of efficiency, which he too measured, to the following causes: condensation on the particles which made them into relatively massive droplets, improved adhesion between particles and particles and between particles and spray droplets, diffusiophoresis. Sparks and Pilat (1970) calculated the contribution of diffusiophoresis to collection by spray droplets and concluded the effect could be dramatic, increasing for smaller particles and lower gas/droplet relative velocities. On the other hand, Slinn and Hales (1971) analyzed the roles played by thermophoresis and diffusiophoresis in the scavenging of atmospheric aerosols by cloud droplets and concluded that thermophoresis generally predominates.

If the condensation process begins with a drop which is at the ambient temperature, then the condensation heats the drop and this heating produces an opposing thermophoresis; if evaporation begins with the drop at ambient temperature, these two mechanisms are reversed and still oppose each other. Relatively hot droplets which evaporate will repel particles due to both diffusiophoresis and thermophoresis until they cool to below ambient temperatures; relatively cool droplets which condense moisture will attract particles by both mechanisms until they heat to above ambient temperatures. For droplets starting at the ambient temperature (T_∞), condensation causes the droplet to heat up due to the latent heat of condensation, λ, and thermal forces inhibit collection. An approximate ratio of the two flux forces was given by Slinn and Hales as

$$\frac{\text{thermophoresis}}{\text{diffusiophoresis}} = - \frac{M_a \lambda}{5 R T_\infty}$$

where

M_a = "molecular weight" of air,

λ = latent heat of evaporation/condensation

R = gas constant

T_∞ = temperature of the fluid medium

from which they computed that thermophoretic transport will exceed diffusiophoretic transport by a factor of about 6 and oppose it. Lancaster and Strauss (1971) tried to separate the effects of these flux force mechanisms from the effects of particle size increase and adhesion improvement due to water vapor. They used cold and hot sprays to scrub water-saturated air and found no improvement with the cold spray, which would have produced greater condensation upon the spray droplets and would have produced an enhancing thermophoresis. Lancaster and Strauss did find that steam addition helped increase collection efficiency, decreasing the particle penetration by a factor of (1- 5Q), Q being the mass ratio of steam to air; this increase they attributed to particle build-up due to condensation. A recent survey of "flux force/condensation scrubbing," the use of steam with spray scrubbers, concluded that particle growth probably predominates over diffusiophoresis as the enhancement mechanism (Calvert et al., 1973). The relative roles of these mechanisms seem as yet in question, but they are important considerations in the design of scrubbers: if the improvement in collection efficiency is due to particle build-up, then steam should be added as early in the flow as practicable; if diffusio-phoresis is enhancing collection and doing so more vigorously than particle build-up, then the steam should be added just shortly before the scrubbing takes place.

Although we did not find a major improvement in efficiency when we used ~ 0.05 water vapor to air ratio, this ratio was about one-third that ratio recommended in the study of "flux force scrubbing" by Calvert et al., (1973).

SECTION VIII

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APPENDIX A

MANUFACTURER'S DESCRIPTION OF DYNACTOR

The continuous gas/liquid contactor, the Dynactor, is a proprietary development of R P Industries, Inc. Figure A-1 is a cross section of a single stage Dynactor diffusion contactor. Liquid entering the system under a pressure to 140 to 200 pounds per square inch (typical) is atomized into thin films and droplets of average thickness or diameter less than 1/64 inch. This liquid discharge diffuses or expands into the reaction chamber causing air or gas to be aspirated by being trapped within the moving shower of films and particles. The resulting mixed fluid then continues to travel down the reaction column with intimate contact maintained between gas and liquid. This causes physical and chemical equilibria to occur by the time the mixed fluid exits from the reaction column into the separation reservoir. The Dynactor can be viewed as a macroscopic diffusion pump which makes use of diffusion principles in order to aspirate large volumes of air per volume of motive liquid. By utilizing diffusion rather than Bernoulli principles, the Dynactor aspirates up to 4,800 standard volumes of gas per volume of motive liquid. In comparison, venturi eductors will aspirate not more than 100 volumes of gas per volume of motive liquid.

Because there are no venturi or other constrictions in the Dynactor, energy requirements are considerably lower than for conventional jet or venturi eductor systems. If gas carries small solid particles along with it, such as activated carbon or powdered neutralizing and precipitating agents, such particles are wetted and captured by the

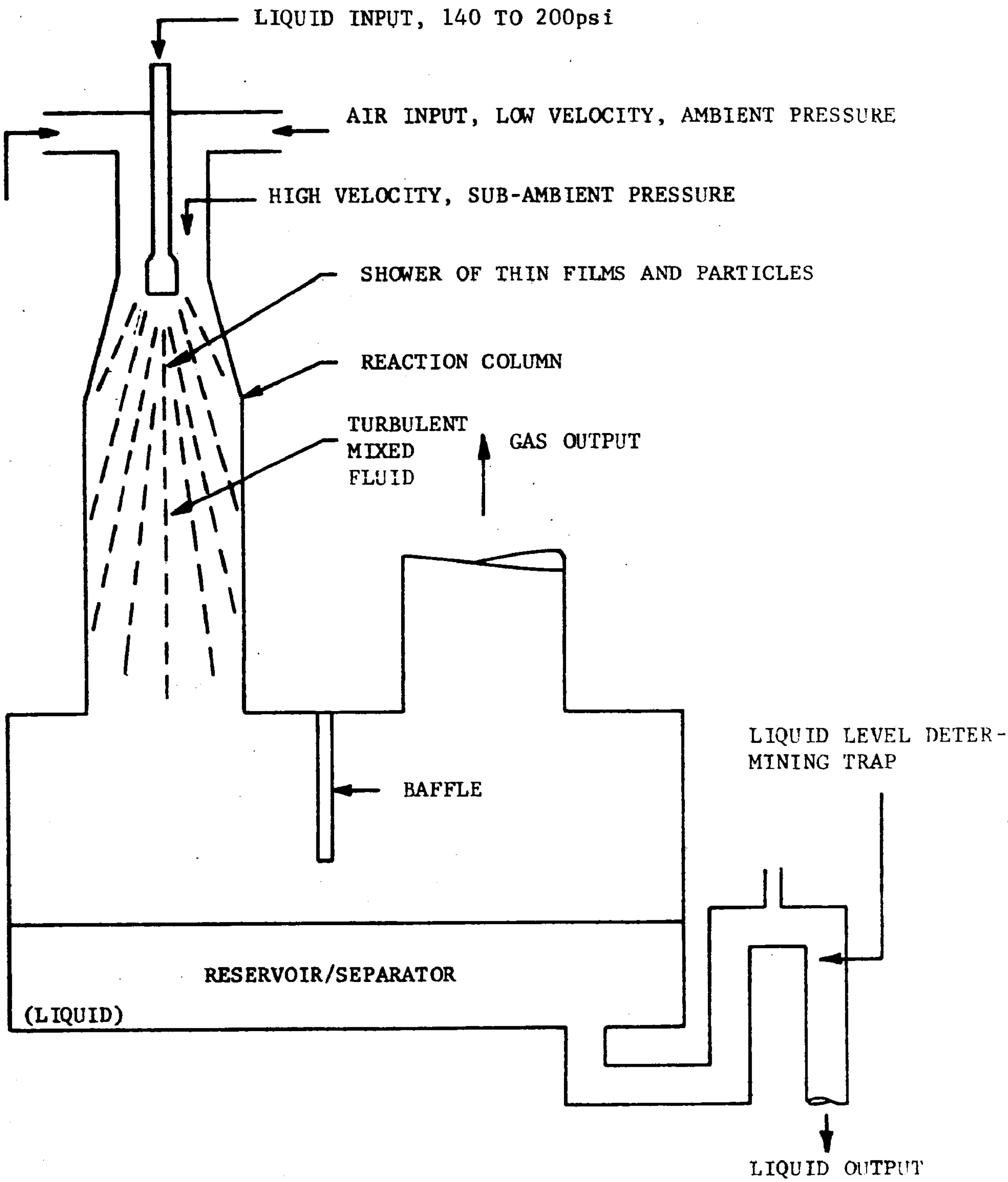

Figure A-1. Single-stage Dynactor diffusion system cross sectional view liquid throughout the entire length of the reaction chamber. By contrast, venturi wet scrubbers make effective contact between gas and liquid only in the constricted throat region. Contact time, therefore, in the Dynactor is about 20 times longer than in venturi devices.

Just as in oil and mercury diffusion vacuum pumps, it is also possible to construct Dynactors having multistage gas inputs. Figure A-2 is a drawing of the two-stage Dynactor diffuser system employed in these studies. The internal configuration was constructed to maximize gas/liquid turbulence and contact throughout the length of the six-foot long, 12-inch diameter reaction column.

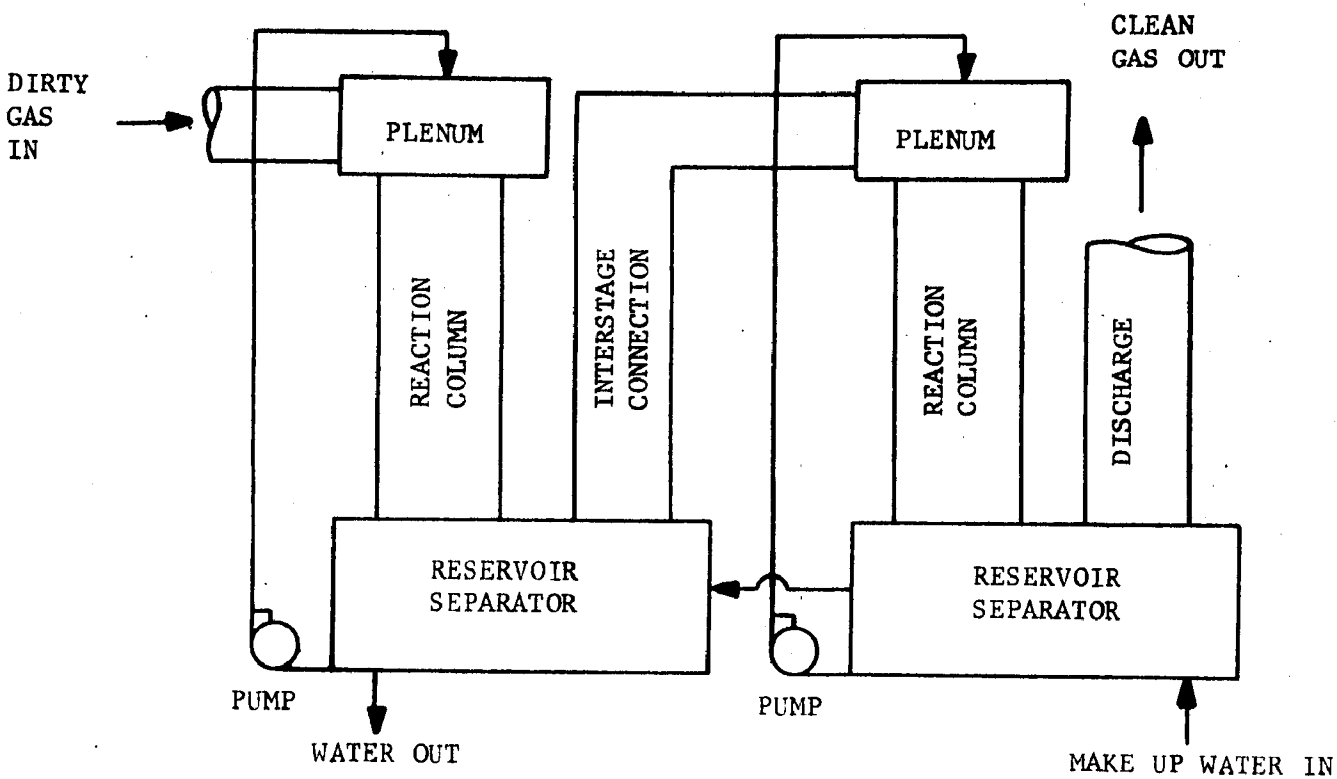

Figure A-2. Two-stage Dynactor

APPENDIX B

DYNACTOR EFFICIENCY DATA

This appendix presents all the data on the Dynactor efficiency tests used as a basis for the Dynactor evaluation. It includes the tests for the balanced 2^4 factorial design study, as well as tests involving flow at 1500 cfm (42.5 m^3/min), moisture addition with a spray nozzle upstream from the Dynactor, use of surfactant in the Dynactor spray, and testing of a single stage of the two-stage device.

The efficiency data sheets, one for each individual set of test conditions, contain the following information:

- Test identification number
- Concentration at Dynactor inlet
- Concentration at Dynactor outlet
- Total mass efficiency, based on the preceding two numbers
- Aerosol material used in test
- Air flow through Dynactor
- Volume rate of flow of Dynactor spray
- Temperature at Dynactor inlet
- Remarks, where appropriate
- Flow rate and sample duration for the various sampling devices
- Fractional efficiency data, including:
    - Limits, aerodynamic diameter, of size interval
    - Concentration of aerosol in that size interval at Dynactor inlet
    - Concentration of aerosol in that size interval at Dynactor outlet

- Mass efficiency on particles of sizes in that size interval, based on the preceding two numbers
- Total concentrations measured by the Andersen impactors at inlet and outlet and mass efficiency based on them

As discussed in the report, the substrate material onto which impaction occurred sometimes showed a weight loss or a weight gain that was less than 0.3 mg. These small or negative weight changes were given the same value, $\leq$0.3 mg, which was used to derive those efficiencies given as inequalities. For the large end of the particle size spectrum, 4 μm and above, the inequalities were calculated with the assumption that collection efficiency did not decrease as particle size increased.

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 4 — INLET CONCENTRATION .86 gr/ft^3 =1979 mg/m^3

AEROSOL Iron oxide — OUTLET CONCENTRATION .031 gr/ft^3 =71.4 mg/m^3

TOTAL MASS EFFICIENCY .964

FLOW: 500 ft^3/min = 14.2 m^3/min — Total Spray: 18.4 gal/min = 1.16 x 10^{-3} m^3/sec

TEMPERATURE: 70 °F = 21 °C

REMARKS: Size distribution obtained from impactors at 1.0 cfm flow was interpolated to match sizing intervals for impactors at 0.5 cfm flow.

SAMPLING DEVICE	FLOW RATE (ft^3/min)		(m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		(m^3)
INLET TOTAL FILTER	1.0	=	.028	1.	1.0	=	.028
INLET IMPACTOR	1.0	=	.028	1.	1.0	=	.028
OUTLET TOTAL FILTER	1.0	=	.028	15.	15.0	=	.43
OUTLET IMPACTOR	1.0	=	.028	15.	15.0	=	.43

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	≤ 10.6	≤ .7	≥ 99.1
2	8.6 - 13.6	≤ 10.6	~ .7	≳ 99.1
3	5.6 - 8.6	41.0	.85	≥ 99.1
4	4.0 - 5.6	96.8	.85	99.1
5	2.5 - 4.0	247.	4.1	98.3
6	1.3 - 2.5	495.	19.8	96.0
7	0.80 - 1.3	155.	23.1	85.2
8	0.54 - 0.80	≤ 10.6	11.8	≲ 0
Final filter ≤ 0.54		17.7	4.7	73.3
TOTAL, Andersen Impactor		1074.	66.0	93.9

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 5 INLET CONCENTRATION ~ .8 gr/ft^3 =~2000 mg/m^3

AEROSOL Iron oxide OUTLET CONCENTRATION .040 gr/ft^3 = 91.4 mg/m^3

TOTAL MASS EFFICIENCY ~ .95

FLOW: 500 ft^3/min = 14.2 m^3/min Total Spray: 18.4 gal/min = 1.16×10^{-3} m^3/sec

TEMPERATURE: 205 °F = 97 °C

REMARKS: Size distribution obtained by impactors at 1.0 cfm flow was interpolated to match sizing intervals for impactors at 0.5 cfm flow.

SAMPLING DEVICE	FLOW RATE (ft^3/min)		FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		TOTAL VOLUME (m^3)
INLET TOTAL FILTER	1.0	=	.028	1.	1.0	=	.028
INLET IMPACTOR	1.0	=	.028	1.	1.0	=	.028
OUTLET TOTAL FILTER	1.0	=	.028	15.	15.	=	.43
OUTLET IMPACTOR	1.0	=	.028	15.	15.	=	.43

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	≤ 3.5	≤ .7	≥ 99.1
2	8.6 - 13.6	≤ 3.5	≤ .7	≥ 99.1
3	5.6 - 8.6	26.9	≤ .7	≥ 99.1
4	4.0 - 5.6	84.8	≤ .7	≥ 99.1
5	2.5 - 4.0	205.	1.9	99.1
6	1.3 - 2.5	417.	10.4	97.5
7	0.80 - 1.3	134.	14.4	89.3
8	0.54 - 0.80	10.6	17.9	≤ 0.0
Final filter ≤0.54		17.7	4.9	72.0
TOTAL, Andersen Impactor		898.	49.7	94.3

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 7

AEROSOL Fly ash

INLET CONCENTRATION ~ 0.7 gr/ft^3 ≈1600 mg/m^3

OUTLET CONCENTRATION .0059 gr/ft^3 = 13.6 mg/m^3

TOTAL MASS EFFICIENCY ~ .99

FLOW: 500 ft^3/min = 14.2 m^3/min Total Spray: 18.4 gal/min = 1.16×10^{-3} m^3/sec

TEMPERATURE: 200 °F = 95 °C

REMARKS: Inlet concentration sampler malfunctioned, so inlet concentration (0.7 gr/ft^3) estimated from other tests.

SAMPLING DEVICE	FLOW RATE (ft^3/min)		(m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		(m^3)
INLET TOTAL FILTER	1.0	=	.028	3.	3.0	=	.085
INLET IMPACTOR	.5	=	.014	3.	1.5	=	.043
OUTLET TOTAL FILTER	1.0	=	.028	69.	69.	=	1.95
OUTLET IMPACTOR	.5	=	.014	90.	45.	=	1.27

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	37.7	≤ .24	≥ 99.9
2	8.6 - 13.6	118.	≤ .24	≥ 99.9
3	5.6 - 8.6	186.	≤ .24	≥ 99.9
4	4.0 - 5.6	141.	≤ .24	≥ 99.8
5	2.5 - 4.0	113.	.5	99.5
6	1.3 - 2.5	82.	3.2	96.1
7	0.80 - 1.3	21.2	4.0	81.1
8	0.54 - 0.80	≤ 7.1	2.9	≤ 58.9
Final filter ≤ 0.54		≤ 7.1	4.0	≤ 43.3
TOTAL, Andersen Impactor		704.	14.9	97.9

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 8

AEROSOL Fly ash

INLET CONCENTRATION .90 gr/ft^3 = 2076 mg/m^3

OUTLET CONCENTRATION .0067 gr/ft^3 = 15.4 mg/m^3

TOTAL MASS EFFICIENCY .993

FLOW: 500 ft^3/min = 14.2 m^3/min Total Spray: 18.4 gal/min = 1.16×10^{-3} m^3/sec

TEMPERATURE: 70 °F = 21 °C

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)	FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)	TOTAL VOLUME (m^3)
INLET TOTAL FILTER	1.0	= .028	2.	2.0	= .057
INLET IMPACTOR	.5	= .014	3.	1.5	= .043
OUTLET TOTAL FILTER	1.0	= .028	88.	88.	= 2.49
OUTLET IMPACTOR	.5	= .014	90.	45.	= 1.37

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	61.2	≤ .2	≥ 99.9
2	8.6 - 13.6	160.	≤ .2	≥ 99.9
3	5.6 - 8.6	278.	≤ .2	≥ 99.9
4	4.0 - 5.6	151.	≤ .2	≥ 99.8
5	2.5 - 4.0	132.	.5	99.6
6	1.3 - 2.5	80.	3.5	95.6
7	0.80 - 1.3	19.	4.1	78.3
8	0.54 - 0.80	≤ 7.0	3.0	≤ 57.8
Final filter	≤0.54	≤ 7.0	2.0	≤ 72.2
TOTAL, Andersen Impactor		881.	13.4	98.5

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 9

AEROSOL Fly Ash

INLET CONCENTRATION .25 gr/ft^3 = 568 mg/m^3

OUTLET CONCENTRATION .0015gr/ft^3 = 3.3 mg/m^3

TOTAL MASS EFFICIENCY .994

FLOW: 1000 ft^3/min = 28.3 m^3/min Total Spray: 18.4 gal/min = 1.16 x 10^{-3} m^3/sec

TEMPERATURE: 68 ^oF = 20 ^oC

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)		(m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		(m^3)
INLET TOTAL FILTER	2.0	=	.057	10.	20.	=	.57
INLET IMPACTOR	0.5	=	.014	26.	13.	=	.37
OUTLET TOTAL FILTER	2.0	=	.057	296.	592.	=	16.8
OUTLET IMPACTOR	0.5	=	.014	300.	150.	=	4.3

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	7.3	≤.07	≥ 99.8
2	8.6 - 13.6	16.3	≤.07	≥ 99.8
3	5.6 - 8.6	29.6	≤.07	≥ 99.8
4	4.0 - 5.6	22.3	≤.07	≥ 99.7
5	2.5 - 4.0	20.9	.14	99.3
6	1.3 - 2.5	13.0	.82	93.7
7	0.80 - 1.3	4.9	1.2	74.5
8	0.54 - 0.80	≤ .8	.72	≤ 50.9
Final filter	≤ 0.54	≤ .8	.40	≤ 10.4
TOTAL, Andersen Impactor		114.	3.3	97.0

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 10 — INLET CONCENTRATION 0.17 gr/ft^3 = 396 mg/m^3

AEROSOL Fly ash — OUTLET CONCENTRATION .0015gr/ft^3 = 3.5 mg/m^3

TOTAL MASS EFFICIENCY .991

FLOW: 1000 ft^3/min = 28.3 m^3/min — Total Spray: 18.4 gal/min = 1.16 x 10^{-3} m^3/sec

TEMPERATURE: 200 °F = 95 °C

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)	(m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)	(m^3)
INLET TOTAL FILTER	2.0 =	.057	10	20 =	.57
INLET IMPACTOR	0.5 =	.014	20	10 =	.28
OUTLET TOTAL FILTER	2.0 =	.057	240	480 =	13.6
OUTLET IMPACTOR	0.5 =	.014	240	120 =	3.4

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	3.2	≤ .09	≥ 99.6
2	8.6 - 13.6	12.7	≤ .09	≥ 99.6
3	5.6 - 8.6	25.1	≤ .09	≥ 99.6
4	4.0 - 5.6	15.5	≤ .09	≥ 99.4
5	2.5 - 4.0	14.1	.15	99.0
6	1.3 - 2.5	9.9	.8	92.0
7	0.80 - 1.3	1.4	1.2	12.5
8	0.54 - 0.80	≤ 1.1	.7	≤ 36.1
Final filter	≤ 0.54	≤ 1.1	.6	≤ 44.4
TOTAL, Andersen Impactor		82.3	3.45	95.8

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 12 | INLET CONCENTRATION .244 gr/ft^3 = 560 mg/m^3

AEROSOL Iron oxide | OUTLET CONCENTRATION .0244 gr/ft^3 = 56 mg/m^3

TOTAL MASS EFFICIENCY .900

FLOW: 1000 ft^3/min = 28.3 m^3/min Total Spray: 18.4 gal/min = 1.16×10^{-3} m^3/sec

TEMPERATURE: 70 °F = 21 °C

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)		FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		TOTAL VOLUME (m^3)
INLET TOTAL FILTER	2.0	=	.057	5	10	=	.28
INLET IMPACTOR	0.5	=	.014	10	5	=	.14
OUTLET TOTAL FILTER	2.0	=	.057	50	100	=	2.8
OUTLET IMPACTOR	0.5	=	.014	120	60	=	1.7

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	≤ 2.1	≤ .2	≥ 99.0
2	8.6 - 13.6	16.3	≤ .2	≥ 99.0
3	5.6 - 8.6	34.6	.4	99.0
4	4.0 - 5.6	67.1	1.0	98.5
5	2.5 - 4.0	124.	3.8	96.9
6	1.3 - 2.5	188.	14.6	92.3
7	0.80 - 1.3	146.	21.4	85.3
8	0.54 - 0.80	25.4	18.2	28.5
Final filter	≤0.54	≤ 2.1	6.4	≤ 0.0
TOTAL, Andersen Impactor		605.	65.9	89.1

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 13

AEROSOL Iron oxide

INLET CONCENTRATION .33 gr/ft^3 = 747 mg/m^3

OUTLET CONCENTRATION .059 gr/ft^3 = 135 mg/m^3

TOTAL MASS EFFICIENCY .818

FLOW: 1000 ft^3/min = 28.3 m^3/min Total Spray: 9.2 gal/min = $.58 \times 10^{-3}$ m^3/sec

TEMPERATURE: 80 °F = 27 °C

REMARKS: Nozzles used at 100 p.s.i.g. = 6.9×10^5 N/M^2

SAMPLING DEVICE	FLOW RATE (ft^3/min)		FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		TOTAL VOLUME (m^3)
INLET TOTAL FILTER	2.0	=	.057	4.0	8.0	=	.23
INLET IMPACTOR	.5	=	.014	4.0	2.0	=	.057
OUTLET TOTAL FILTER	2.0	=	.057	40.	80.	=	2.3
OUTLET IMPACTOR	.5	=	.014	40.	20.	=	.57

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	≤ 5.3	1.6	≥ 77.5
2	8.6 - 13.6	7.1	1.6	77.5
3	5.6 - 8.6	33.6	2.3	93.2
4	4.0 - 5.6	54.8	5.3	90.3
5	2.5 - 4.0	124.	15.4	87.6
6	1.3 - 2.5	210.	45.4	78.4
7	0.80 - 1.3	147.	59.	60.0
8	0.54 - 0.80	15.9	15.9	0.0
Final filter	≤0.54	≤ 5.3	5.5	≤ 0.0
TOTAL, Andersen Impactor		599.	152.	74.6

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 14 | INLET CONCENTRATION .118 gr/ft^3 = 271 mg/m^3

AEROSOL Iron oxide | OUTLET CONCENTRATION .016 gr/ft^3 = 36.6mg/m^3

TOTAL MASS EFFICIENCY .866

FLOW: 1000 ft^3/min = 28.3 m^3/min Total Spray: 18.4 gal/min = 1.16 x 10^{-3} m^3/sec

TEMPERATURE: 203 °F = 95 °C

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)		FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		TOTAL VOLUME (m^3)
INLET TOTAL FILTER	2.0	=	.057	4.	8.	=	.226
INLET IMPACTOR	0.5	=	.014	4.	2.	=	.057
OUTLET TOTAL FILTER	2.0	=	.057	40.	80.	=	2.26
OUTLET IMPACTOR	0.5	=	.014	40.	20.	=	.566

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	≤ 5.2	≤ .5	≥ 95.3
2	8.6 - 13.6	≤ 5.2	≤ .5	≥ 95.3
3	5.6 - 8.6	7.1	≤ .5	≥ 95.3
4	4.0 - 5.6	10.6	≤ .5	≥ 95.3
5	2.5 - 4.0	30.0	1.4	95.3
6	1.3 - 2.5	97.2	10.4	89.3
7	0.80 - 1.3	67.1	15.9	76.3
8	0.54 - 0.80	≤ 5.2	8.1	≤ 0
Final filter	≤ 0.54	≤ 5.2	≤ .5	-
TOTAL, Andersen Impactor		215.5	36.0	83.3

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 16 — INLET CONCENTRATION 1.01 gr/ft^3 = 2311 mg/m^3

AEROSOL Iron oxide — OUTLET CONCENTRATION .047 gr/ft^3 = 107 mg/m^3

TOTAL MASS EFFICIENCY .954

FLOW: 1000 ft^3/min = 28.3 m^3/min Total Spray: 18.4 gal/min = 1.16 x 10^{-3} m^3/sec

TEMPERATURE: 63 °F = 17 °C

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)		(m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		(m^3)
INLET TOTAL FILTER	2.0	=	.057	1.0	2.0	=	.057
INLET IMPACTOR	0.5	=	.014	2.0	1.0	=	.028
OUTLET TOTAL FILTER	2.0	=	.057	4.5	9.0	=	.255
OUTLET IMPACTOR	0.5	=	.014	15.0	7.5	=	.212

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	49.5	≤ 1.4	≥ 99.2
2	8.6 - 13.6	70.7	≤ 1.4	≥ 99.2
3	5.6 - 8.6	159.	≤ 1.4	≥ 99.2
4	4.0 - 5.6	180.	≤ 1.4	≥ 99.2
5	2.5 - 4.0	254.	4.7	98.1
6	1.3 - 2.5	375.	25.4	93.2
7	0.80 - 1.3	258.	33.0	87.2
8	0.54 - 0.80	60.1	17.4	71.0
Final filter	≤0.54	17.7	≤ 1.4	≥ 92.0
TOTAL, Andersen Impactor		1424.	81.5	94.3

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 17

AEROSOL Iron oxide

INLET CONCENTRATION .84 gr/ft^3 = 1922 mg/m^3

OUTLET CONCENTRATION .042 gr/ft^3 = 96 mg/m^3

TOTAL MASS EFFICIENCY .950

FLOW: 1000 ft^3/min = 28.3 m^3/min Total Spray: 18.4 gal/min = 1.16×10^{-3} m^3/sec

TEMPERATURE: 70 °F = 21 °C

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)		(m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		(m^3)
INLET TOTAL FILTER	2.0	=	.057	1.	2.0	=	.057
INLET IMPACTOR	0.5	=	.014	2.	1.0	=	.028
OUTLET TOTAL FILTER	2.0	=	.057	15.	30.	=	.85
OUTLET IMPACTOR	0.5	=	.014	15.	7.5	=	.21

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	24.7	≤ 1.4	≥ 99.0
2	8.6 - 13.6	53.0	≤ 1.4	≥ 99.0
3	5.6 - 8.6	148.	≤ 1.4	≥ 99.0
4	4.0 - 5.6	187.	1.9	99.0
5	2.5 - 4.0	307.	5.2	98.3
6	1.3 - 2.5	382.	25.9	93.2
7	0.80 - 1.3	205.	39.1	80.9
8	0.54 - 0.80	21.2	18.4	13.3
Final filter	≤ 0.54	≤ 10.7	2.8	≤ 73.3
TOTAL, Andersen Impactor		1336.	95.2	92.9

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 18 — INLET CONCENTRATION .872 gr/ft^3 = 1996 mg/m^3

AEROSOL Iron oxide — OUTLET CONCENTRATION .038 gr/ft^3 = 86.6 mg/m^3

TOTAL MASS EFFICIENCY .957

FLOW: 1000 ft^3/min = 28.3 m^3/min — Total Spray: 18.4 gal/min = 1.16×10^{-3} m^3/sec

TEMPERATURE: 70 °F = 21 °C

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)		FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		TOTAL VOLUME (m^3)
INLET TOTAL FILTER	2.0	=	.057	1.0	2.0	=	.057
INLET IMPACTOR	0.5	=	.014	2.0	1.0	=	.028
OUTLET TOTAL FILTER	2.0	=	.057	15.0	30.	=	.85
OUTLET IMPACTOR	0.5	=	.014	15.0	7.5	=	.21

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	21.2	≤ 1.4	≥ 99.3
2	8.6 - 13.6	53.0	≤ 1.4	≥ 99.3
3	5.6 - 8.6	198.	≤ 1.4	≥ 99.3
4	4.0 - 5.6	205.	≤ 1.4	≥ 99.3
5	2.5 - 4.0	322.	2.8	99.1
6	1.3 - 2.5	343.	24.0	93.0
7	0.80 - 1.3	198.	33.5	83.1
8	0.54 - 0.80	28.3	12.7	55.0
Final filter	≤ 0.54	≤ 10.7	1.9	≤ 82.2
TOTAL, Andersen Impactor		1378.	74.9	94.6

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 19 INLET CONCENTRATION .679 gr/ft^3 = 1553 mg/m^3

AEROSOL Iron oxide OUTLET CONCENTRATION .035 gr/ft^3 = 79.1 mg/m^3

TOTAL MASS EFFICIENCY .949

FLOW: 1000 ft^3/min = 28.3 m^3/min Total Spray: 18.4 gal/min = 1.16×10^{-3} m^3/sec

TEMPERATURE: 203 °F = 95 °C

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)		(m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		(m^3)
INLET TOTAL FILTER	2.0	=	.057	1.0	2.0	=	.057
INLET IMPACTOR	0.5	=	.014	2.0	1.0	=	.028
OUTLET TOTAL FILTER	2.0	=	.057	14.0	28.	=	.792
OUTLET IMPACTOR	0.5	=	.014	14.0	7.	=	.198

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	24.7	≤ 1.5	≥ 99.2
2	8.6 - 13.6	56.5	≤ 1.5	≥ 99.2
3	5.6 - 8.6	191.	≤ 1.5	≥ 99.2
4	4.0 - 5.6	166.	≤ 1.5	≥ 99.1
5	2.5 - 4.0	272.	6.6	97.6
6	1.3 - 2.5	286.	28.8	89.9
7	0.80 - 1.3	170.	40.9	75.9
8	0.54 - 0.80	17.7	15.6	11.4
Final filter	≤ 0.54	≤ 10.7	3.5	≤ 66.7
TOTAL, Andersen Impactor		1194.	98.9	91.7

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 21

AEROSOL Fly ash

INLET CONCENTRATION .955 gr/ft^3 = 2186 mg/m^3

OUTLET CONCENTRATION .011 gr/ft^3 = 25.3 mg/m^3

TOTAL MASS EFFICIENCY .988

FLOW: 1000 ft^3/min = 28.3 m^3/min Total Spray: 18.4 gal/min = 1.16×10^{-3} m^3/sec

TEMPERATURE: 70 °F = 21 °C

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)		(m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		(m^3)
INLET TOTAL FILTER	2.0	=	.057	3.0	6.0	=	.171
INLET IMPACTOR	0.5	=	.014	3.0	1.5	=	.042
OUTLET TOTAL FILTER	2.0	=	.057	57.5	115.	=	3.25
OUTLET IMPACTOR	0.5	=	.014	60.0	30.	=	.84

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	40.0	≤ .4	≥ 99.8
2	8.6 - 13.6	75.4	≤ .4	≥ 99.8
3	5.6 - 8.6	153.	≤ .4	≥ 99.8
4	4.0 - 5.6	115.	≤ .4	≥ 99.7
5	2.5 - 4.0	80.1	1.2	98.5
6	1.3 - 2.5	73.0	6.8	90.6
7	0.80 - 1.3	28.3	11.0	61.3
8	0.54 - 0.80	≤ 7.1	5.9	≤ 16.7
Final filter	≤0.54	≤ 7.1	1.1	≤ 85.0
TOTAL, Andersen Impactor		575.	26.4	99.4

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 22

AEROSOL Fly ash

INLET CONCENTRATION 1.30 gr/ft^3 = 2984 mg/m^3

OUTLET CONCENTRATION .012 gr/ft^3 = 27.4 mg/m^3

TOTAL MASS EFFICIENCY .991

FLOW: 1000 ft^3/min = 28.3 m^3/min

Total Spray: 18.4 gal/min = 1.16×10^{-3} m^3/sec

TEMPERATURE: 203 °F = 95 °C

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)		FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		TOTAL VOLUME (m^3)
INLET TOTAL FILTER	2.0	=	.057	3.0	6.0	=	.171
INLET IMPACTOR	0.5	=	.014	3.0	1.5	=	.042
OUTLET TOTAL FILTER	2.0	=	.057	58.0	116.	=	3.28
OUTLET IMPACTOR	0.5	=	.014	60.0	30.	=	.84

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	84.8	≤ .4	≥ 99.8
2	8.6 - 13.6	155.	≤ .4	≥ 99.8
3	5.6 - 8.6	229.	≤ .4	≥ 99.8
4	4.0 - 5.6	127.	≤ .4	≥ 99.7
5	2.5 - 4.0	115.	1.4	98.8
6	1.3 - 2.5	80.1	9.2	88.5
7	0.80 - 1.3	30.6	9.2	70.0
8	0.54 - 0.80	≤ 7.1	4.6	≤ 35.0
Final filter	≤ 0.54	≤ 7.1	1.8	≤ 75.0
TOTAL, Andersen Impactor		822.	26.9	96.7

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 23

AEROSOL Iron oxide

INLET CONCENTRATION .178 gr/ft^3 = 408 mg/m^3

OUTLET CONCENTRATION .010 gr/ft^3 = 23.2 mg/m^3

TOTAL MASS EFFICIENCY .943

FLOW: 500 ft^3/min = 14.2 m^3/min Total Spray: 18.4 gal/min = 1.16×10^{-3} m^3/sec

TEMPERATURE: 66 °F = 19 °C

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)		FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		TOTAL VOLUME (m^3)
INLET TOTAL FILTER	1.0	=	.028	15	15.0	=	.424
INLET IMPACTOR	0.5	=	.014	15	7.5	=	.212
OUTLET TOTAL FILTER	1.0	=	.028	118	118	=	3.34
OUTLET IMPACTOR	0.5	=	.014	120	60	=	1.70

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	≤ 1.4	≤ .2	≥ 98.6
2	8.6 - 13.6	≤ 1.4	≤ .2	≥ 98.6
3	5.6 - 8.6	6.1	≤ .2	≥ 98.6
4	4.0 - 5.6	12.2	≤ .2	≥ 98.6
5	2.5 - 4.0	27.3	.6	97.8
6	1.3 - 2.5	48.5	4.4	91.0
7	0.80 - 1.3	32.5	7.6	76.6
8	0.54 - 0.80	1.9	4.9	≤ 0
Final filter	≤ 0.54	≤ 1.4	1.1	≤ 25.0
TOTAL, Andersen Impactor		131.	18.7	85.6

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 24

AEROSOL Iron oxide

INLET CONCENTRATION .187 gr/ft^3 = 428 mg/m^3

OUTLET CONCENTRATION .014 gr/ft^3 = 32.6 mg/m^3

TOTAL MASS EFFICIENCY .924

FLOW: 500 ft^3/min = 14.2 m^3/min Total Spray: 18.4 gal/min = 1.16×10^{-3} m^3/sec

TEMPERATURE: 203 °F = 95 °C

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)		FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		TOTAL VOLUME (m^3)
INLET TOTAL FILTER	1.0	=	.028	15	15.0	=	.424
INLET IMPACTOR	0.5	=	.014	15	7.5	=	.212
OUTLET TOTAL FILTER	1.0	=	.028	84	84	=	2.38
OUTLET IMPACTOR	0.5	=	.014	120	60	=	1.70

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	2.8	≤ .18	≥ 93.8
2	8.6 - 13.6	3.3	.24	92.9
3	5.6 - 8.6	10.8	.29	97.3
4	4.0 - 5.6	16.5	.35	97.9
5	2.5 - 4.0	39.6	1.5	96.3
6	1.3 - 2.5	71.1	7.2	89.9
7	0.80 - 1.3	56.5	9.8	82.7
8	0.54 - 0.80	12.7	6.5	49.1
Final filter	≤0.54	≤ 1.4	2.4	≤ 0
TOTAL, Andersen Impactor		213.	28.3	86.7

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 25 INLET CONCENTRATION .615 gr/ft^3 = 1406 mg/m^3

AEROSOL Iron oxide OUTLET CONCENTRATION .027 gr/ft^3 = 62.9 mg/m^3

TOTAL MASS EFFICIENCY .955

FLOW: 1000 ft^3/min = 28.3 m^3/min Total Spray: 18.4 gal/min = 1.16×10^{-3} m^3/sec

TEMPERATURE: 70 °F = 21 °C

REMARKS: Approximately 10 ppm surfactant added to spray water.

SAMPLING DEVICE	FLOW RATE (ft^3/min)		(m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		(m^3)
INLET TOTAL FILTER	2.0	=	.057	1.	2.0	=	.057
INLET IMPACTOR	0.5	=	.014	2.	1.0	=	.028
OUTLET TOTAL FILTER	2.0	=	.057	15.	30.	=	1.71
OUTLET IMPACTOR	0.5	=	.014	15.	7.5	=	.21

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	14.1	≤ 1.43	≥ 99.2
2	8.6 - 13.6	24.7	≤ 1.43	≥ 99.2
3	5.6 - 8.6	117.	≤ 1.43	≥ 99.2
4	4.0 - 5.6	141.	≤ 1.43	≥ 99.2
5	2.5 - 4.0	223.	1.89	99.2
6	1.3 - 2.5	307.	17.9	94.2
7	0.80 - 1.3	187.	28.3	84.9
8	0.54 - 0.80	21.2	8.0	62.2
Final filter	≤0.54	≤ 10.7	1.89	≤ 82.2
TOTAL, Andersen Impactor		1039.	58.0	94.4

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 26

AEROSOL Fly ash

INLET CONCENTRATION .121 gr/ft^3 = 276 mg/m^3

OUTLET CONCENTRATION .002 gr/ft^3 = 3.9 mg/m^3

TOTAL MASS EFFICIENCY 98.6

FLOW: 500 ft^3/min = 14.2 m^3/min

Total Spray: 18.4 gal/min; 1.16 x 10^{-3} m^3/sec

TEMPERATURE: 85 ^oF = 29 ^oC

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)		FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		TOTAL VOLUME (m^3)
INLET TOTAL FILTER	1.0	=	.028	25.	25.0	=	.708
INLET IMPACTOR	0.5	=	.014	25.	12.5	=	.354
OUTLET TOTAL FILTER	1.0	=	.028	268.	268.	=	7.58
OUTLET IMPACTOR	0.5	=	.014	270.	135.	=	3.82

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	$\geq$13.6	12.7	$\leq$ .1	$\geq$ 99.8
2	8.6 - 13.6	26.0	$\leq$ .1	$\geq$ 99.8
3	5.6 - 8.6	41.8	$\leq$ .1	$\geq$ 99.8
4	4.0 - 5.6	24.3	$\leq$ .1	$\geq$ 99.7
5	2.5 - 4.0	24.0	$\leq$ .1	$\geq$ 99.7
6	1.3 - 2.5	17.5	.7	96.0
7	0.80 - 1.3	10.5	1.4	86.7
8	0.54 - 0.80	$\leq$ .8	.9	$\leq$ 0
Final filter	$\leq$0.54	$\leq$ .8	.3	$\leq$ 62.5
TOTAL, Andersen Impactor		158.	3.4	97.8

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 27

AEROSOL Fly Ash

INLET CONCENTRATION .136 gr/ft^3 = 311 mg/m^3

OUTLET CONCENTRATION .002 gr/ft^3 = 4.2 mg/m^3

TOTAL MASS EFFICIENCY .986

FLOW: 500 ft^3/min = 14.2 m^3/min Total Spray: 18.4 gal/min = 1.16×10^{-3} m^3/sec

TEMPERATURE: 200 °F = 95 °C

REMARKS:

SAMPLING DEVICE	FLOW RATE (ft^3/min)		FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)		TOTAL VOLUME (m^3)
INLET TOTAL FILTER	1.0	=	.028	25	25	=	.708
INLET IMPACTOR	0.5	=	.014	25	12.5	=	.354
OUTLET TOTAL FILTER	1.0	=	.028	243	243	=	6.88
OUTLET IMPACTOR	0.5	=	.014	293	146.5	=	4.15

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	10.2	≤ .07	≥ 99.8
2	8.6 - 13.6	22.9	≤ .07	≥ 99.8
3	5.6 - 8.6	36.5	≤ .07	≥ 99.8
4	4.0 - 5.6	24.0	≤ .07	≥ 99.7
5	2.5 - 4.0	21.2	≤ .07	≥ 99.7
6	1.3 - 2.5	16.7	.58	96.5
7	0.80 - 1.3	11.6	1.4	87.7
8	0.54 - 0.80	1.7	.89	47.5
Final filter	≤0.54	≤ .8	.46	≤ 45.8
TOTAL, Andersen Impactor		145	3.4	97.7

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 28

AEROSOL IRON OXIDE (steam)

INLET CONCENTRATION gr/ft^3 = mg/m^3

OUTLET CONCENTRATION .021 gr/ft^3 = 47.8 mg/m^3

TOTAL MASS EFFICIENCY

FLOW: 500 ft^3/min = 14.2 m^3/min Total Spray: 18.4 gal/min

TEMPERATURE: ^{o}F = ^{o}C = 1.16 x 10^{-3} m^3/sec

REMARKS: Spray introduced in inlet duct. Humidity ratio of approximately .044.

SAMPLING DEVICE	FLOW RATE (ft^3/min)	FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)	TOTAL VOLUME (m^3)
INLET TOTAL FILTER	Broken	= line, sample void			=
INLET IMPACTOR	0.5	= .014	2	1	= .028
OUTLET TOTAL FILTER	1.0	= .028	15	15	= .42
OUTLET IMPACTOR	0.5	= .014	15	7.5	= .21

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	67.1	≤ 1.41	≥ 99.3
2	8.6 - 13.6	110	≤ 1.41	≥ 99.3
3	5.6 - 8.6	216	≤ 1.41	≥ 99.3
4	4.0 - 5.6	216	≤ 1.41	≥ 99.3
5	2.5 - 4.0	251	1.88	99.3
6	1.3 - 2.5	318	16.0	95.0
7	0.80 - 1.3	198	28.3	85.7
8	0.54 - 0.80	28.3	14.6	48.4
Final filter	≤0.54	≤ 10.6	3.77	≤ 64.4
TOTAL, Andersen Impactor		1403	64.5	95.4

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 29 INLET CONCENTRATION .581 gr/ft^3 =1329 mg/m^3

AEROSOL Iron Oxide OUTLET CONCENTRATION .025 gr/ft^3 = 57.1mg/m^3

TOTAL MASS EFFICIENCY .948

FLOW: 1500 ft^3/min = 42.5 m^3/min Total Spray: 18.4 gal/min

TEMPERATURE: 70°F = 21°C = 1.16 x 10^{-3} m^3/sec

REMARKS:

Data corrected for leakage between inlet and outlet.

SAMPLING DEVICE	FLOW RATE (ft^3/min)	FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)	TOTAL VOLUME (m^3)
INLET TOTAL FILTER	1.0 =	.028	2	2.0 =	.056
INLET IMPACTOR	0.5 =	.014	2	1.0 =	.028
OUTLET TOTAL FILTER	2.0 =	.056	15	30 =	.85
OUTLET IMPACTOR	0.5 =	.014	15	7.5 =	.21

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	10.6	≤ 1.41	≥ 97.9
2	8.6 - 13.6	28.3	≤ 1.41	≥ 97.9
3	5.6 - 8.6	81.3	≤ 1.41	≥ 97.9
4	4.0 - 5.6	67.1	≤ 1.41	≥ 97.5
5	2.5 - 4.0	134	3.30	97.0
6	1.3 - 2.5	177	18.8	87.1
7	0.80 - 1.3	134	27.8	75.0
8	0.54 - 0.80	≤ 10.6	7.07	≤ 19.4
Final filter	≤0.54	≤ 10.6	≤ 1.41	
TOTAL, Andersen Impactor		633	58.4	88.9

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 30

AEROSOL Iron Oxide

INLET CONCENTRATION .571 gr/ft^3 = 1306 mg/m^3

OUTLET CONCENTRATION .025 gr/ft^3 = 57.6 mg/m^3

TOTAL MASS EFFICIENCY .947

FLOW: 1500 ft^3/min = 42.5 m^3/min Total Spray: 18.4 gal/min

TEMPERATURE: 190°F = 88°C = 1.16 x 10^{-3} m^3/sec

REMARKS:

Data corrected for leakage between inlet and outlet.

SAMPLING DEVICE	FLOW RATE (ft^3/min)	FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)	TOTAL VOLUME (m^3)
INLET TOTAL FILTER	1.0	= .028	2	2.0	= .056
INLET IMPACTOR	0.5	= .014	2	1.0	= .028
OUTLET TOTAL FILTER	2.0	= .056	15	30	= .85
OUTLET IMPACTOR	0.5	= .014	15	7.5	= .21

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	35.3	≤ 1.41	≥ 98.7
2	8.6 - 13.6	63.6	≤ 1.41	≥ 98.7
3	5.6 - 8.6	124	≤ 1.41	≥ 98.7
4	4.0 - 5.6	106	≤ 1.41	≥ 98.6
5	2.5 - 4.0	163	1.9	98.6
6	1.3 - 2.5	198	17.4	89.4
7	0.80 - 1.3	148	20.7	83.1
8	0.54 - 0.80	14.1	2.8	75.8
Final filter	≤0.54	≤ 10.6	≤ 1.41	-
TOTAL, Andersen Impactor		852	43.3	93.8

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 31 — INLET CONCENTRATION .504 gr/ft^3 = 1153 mg/m^3

AEROSOL Iron Oxide (steam) — OUTLET CONCENTRATION .019 gr/ft^3 = 44.4 mg/m^3

TOTAL MASS EFFICIENCY .962

FLOW: 500 ft^3/min = 14.2 m^3/min Total Spray: 18.4 gal/min

TEMPERATURE: - °F = - °C =1.16 x 10^{-3} m^3/sec

REMARKS: Spray in inlet duct humidity ratio of approximately .072.

SAMPLING DEVICE	FLOW RATE (ft^3/min)	FLOW RATE (m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)	TOTAL VOLUME (m^3)
INLET TOTAL FILTER	1.0	= .028	5	5.0	= .14
INLET IMPACTOR	0.5	= .014	5	2.5	= .07
OUTLET TOTAL FILTER	1.0	= .028	25	25	= .70
OUTLET IMPACTOR	0.5	= .014	25	12.5	= .35

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	11.8	≤ .8	≥ 98.9
2	8.6 - 13.6	17.0	≤ .8	≥ 98.9
3	5.6 - 8.6	41.0	≤ .8	≥ 98.9
4	4.0 - 5.6	48.1	≤ .8	≥ 98.9
5	2.5 - 4.0	102	1.1	98.9
6	1.3 - 2.5	184	11.0	94.0
7	0.80 - 1.3	90.5	17.8	80.3
8	0.54 - 0.80	17.0	5.1	70.0
Final filter	≤0.54	≤ 4.2	≤ .8	-
TOTAL, Andersen Impactor		510	35.9	93.0

DYNACTOR SCRUBBER EFFICIENCY EVALUATION DATA

TEST # 32 — INLET CONCENTRATION .286 gr/ft^3 = 654 mg/m^3

AEROSOL Iron Oxide (1st Stage Test) — OUTLET CONCENTRATION - gr/ft^3 = - mg/m^3

TOTAL MASS EFFICIENCY -

FLOW: 1000 ft^3/min = 28.3 m^3/min Total Spray: 18.4 gal/min = 1.16 x 10^{-3} m^3/sec

TEMPERATURE: 80^{o}F = 27^{o}C

REMARKS: Downstream sampling done between the first and second Dynactor stages.

SAMPLING DEVICE	FLOW RATE (ft^3/min)	(m^3/min)	DURATION (min)	TOTAL VOLUME (ft^3)	(m^3)
INLET TOTAL FILTER	1.0 =	.028	3	3.0 =	.084
INLET IMPACTOR	0.5 =	.014	3	1.5 =	.042
OUTLET TOTAL FILTER	- =	-	-	- =	-
OUTLET IMPACTOR	0.5 =	.014	10	5.0 =	.14

FRACTIONAL EFFICIENCY DATA, ANDERSEN IMPACTOR, MODEL III

STAGE	AERODYNAMIC DIAMETER (μm)	INLET CONCENTRATION (mg/m^3)	OUTLET CONCENTRATION (mg/m^3)	FRACTIONAL MASS EFFICIENCY (percent)
1	≥13.6	14.1	≤ 2.1	≥ 96.0
2	8.6 - 13.6	28.3	≤ 2.1	≥ 96.0
3	5.6 - 8.6	70.7	2.8	96.0
4	4.0 - 5.6	80.1	6.4	92.1
5	2.5 - 4.0	127	19.1	85.0
6	1.3 - 2.5	184	53.7	70.8
7	0.80 - 1.3	130	38.9	70.0
8	0.54 - 0.80	16.5	6.4	61.4
Final filter ≤ 0.54		≤ 7.1	≤ 2.1	-
TOTAL, Andersen Impactor		650	129	80.1

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-650/2-74-083	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Dynactor Scrubber Evaluation		5. REPORT DATE September 1974
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Douglas W. Cooper and Daniel P. Anderson		8. PERFORMING ORGANIZATION REPORT NO. GCA-TR-74-21-G
9. PERFORMING ORGANIZATION NAME AND ADDRESS GCA Corporation GCA/Technology Division Bedford, Massachusetts 01730		10. PROGRAM ELEMENT NO. 1AB012; ROAP 21ADL-004
		11. CONTRACT/GRANT NO. 68-02-1316 Task 6
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development NERC-RTP, Control Systems Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; Through 7/26/74
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT The report gives results of testing the Dynactor spray scrubber for power consumption and collection efficiency at three flow rates, two temperatures, and two dust loading levels, using two dusts. Total filter samplers and cascade impactors were used upstream and downstream from the collector. Power was determined from voltage, current, and phase-angle measurements. A factorial design series of tests at two levels of flow, concentration, temperature, and dust type gave these average mass efficiencies: 99.0% for 4.0-5.6 μm aerodynamic diameter, 98.4% for 2.5-4.0 μm, 93.0% for 1.3-2.5 μm, 75.4% for 0.8-1.3 μm, 27.4% for 0.54-0.80 μm, and 47.4% for < 0.54 μm. Higher efficiency was fostered by: lower flow rate, lower inlet temperature, and higher mass loading. Power consumption was about one-third of that expected from a venturi scrubber with equivalent collection efficiency, but collection efficiency decreased dramatically for fine particles, those smaller than 1 μm.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Air Pollution Control	13B
Scrubbers	Stationary Sources	07A
Performance Tests	Dynactor Scrubber	14B
Dust Collectors	Fine Particulate	13A
Efficiency	Collection Efficiency	
	Power Consumption	

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