Although fireproof Absolute filters of limited capacity are currently available, those having sufficient capacity for large-scale applications are impractical at this time, due primarily to the technological stage of development. Nevertheless, continued development and research will in time produce filters that are sufficiently fire-resistant to confine most ventilation system fires to the filter assembly with minimal loss or damage. This will permit a considerable saving to industry by minimizing fire losses and will be a noteworthy milestone, particularly, from the standpoint of air cleaning systems for radioactive substances.

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DESIGN AND CALIBRATION OF AN IMPROVED CASCADE IMPACTOR FOR SIZE ANALYSIS OF AEROSOLS

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1 INTRODUCTION

A rapid and reliable method for determining the particle-size distribution and concentration of aerosols is essential for general aerosol and air cleaning studies. Although the physical properties and effectiveness of sprays and aerosols are determined by their particle-size distribution, accurate data on size are seldom available. Some of the numerous experimental methods of determining size distributions of aerosols are: (1) microscopic examination of particles collected on slides or in cells, (2) freezing of drops in a spray followed by sieving, (3) direct photographic methods, (4) other optical methods based on the scattering or absorption of light, (5) electronic and radioautographic techniques, and (6) impaction methods. Each of these methods has its advantages and disadvantages and none is entirely satisfactory.

The most commonly used of the six above mentioned methods is the microscopic technique. A sample of an aerosol is collected by passing a slide through the aerosol. Each individual particle on the slide is then measured. Not only is this method tedious and time consuming, but it is also biased in favor of the larger particles because the smaller particles will tend to pass around the slide.

The purpose of this paper is to describe an improved cascade impactor for the size analysis of aerosols and the methods by which it was calibrated.

2 PRINCIPLE OF THE CASCADE IMPACTOR

A cascade impactor is a device which separates aerosols into various size classes. The impactor operates on the principle that particles in a moving air stream will impact upon a slide placed in their path provided that the inertia of the particles is sufficient to overcome the drag exerted by the air stream that must pass around the slide. One of the pioneers to use this principle to classify aerosols was K. R. May.[1]

Figure 1 is a schematic drawing showing how the cascade impactor classifies particles of different sizes. As the moving particles approach the slide in the impactor, the larger

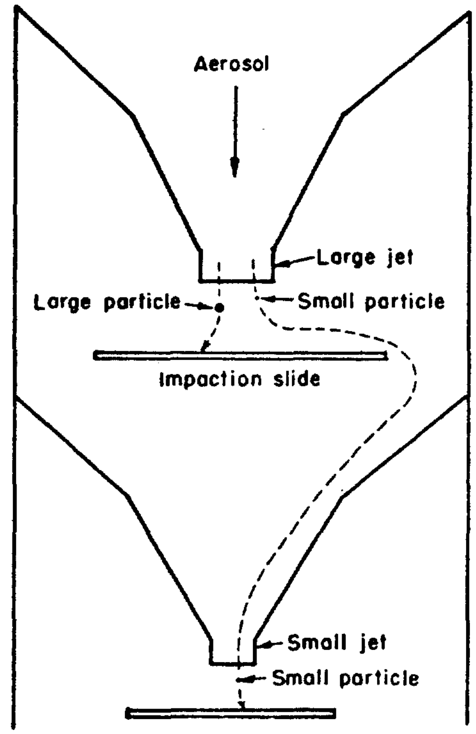

Fig. 1—Schematic diagram showing principle of the cascade impactor.

particles will impact on the slide while the smaller particles are carried around the slide by the drag force of the air stream. Since each jet is smaller than the preceding one, the velocity of the air stream is increased as the aerosol passes through various stages of the impactor. Consequently, smaller size fractions of particles are impacted on each successive slide, and a complete size classification of the particles is obtained.

3 IMPACTOR THEORY RELATING TO THE DESIGN

The design of the previous Battelle impactors was based on the assumption that the jet-to-slide clearance is infinite, and that impaction takes place on a slide of infinite extent. Moreover, it was assumed that gravitational and electrical effects are small compared with the inertia effects. Under these assumptions, the impaction process may be characterized by a single impaction parameter.

$$\psi = \frac{\rho_p V D_p^2}{18 \mu D_j}$$

where ρ_p denotes the density of the aerosol particle, V the velocity of the particle relative to the surrounding fluid, D_p the diameter of the particle, μ the viscosity of the fluid, and D_j the diameter of the jet. The impaction parameter is easily derived by the techniques of dimensional analysis. Moreover, the derivation shows that the impaction process may be expected to be characterized by a single parameter only if the jet-to-slide clearance is infinite, and if the impaction slide is infinite in extent. Otherwise, the efficiency of impaction may be a function of the usual impaction parameter and an additional dimensionless ratio of lengths.

A theoretical study by Davies and Alyward[2] has shown that jet-to-slide clearance less than the jet diameter may be expected to yield a more desirable classification with a rectangular jet.

It was suggested that the design of new impactors should be based on a narrow jet-to-slide clearance to obtain better separation of sizes. As shown in a technical report for Fort Detrick prepared by Einbinder,[3] each stage of the impactor may be designed based upon the value of the impactor parameter corresponding to 50 per cent impaction. Ranz and Wong[4] found that the impaction parameter (ψ), corresponding to 50 per cent impaction for round jets, was about 0.14. However, this value holds for a jet-to-slide clearance which is effectively infinite. For smaller jet-to-slide clearances, the value of the impaction parameter would be expected to decrease appreciably.

4 EXPERIMENTAL DETERMINATION OF IMPACTION EFFICIENCIES

As a result of a study of the impaction theory, the effects of varying the jet-to-slide distance for round jets were studied. Round jets were used because of their ease of fabrication.

Figure 2 is a plot of the experimental impaction efficiencies, η, for round jets as a function of the impaction parameter, $\psi^{1/2}$. The figure shows how the sharpness of classification was improved by reducing the jet-to-slide clearance from approximately three to three-eights of the jet diameter. These data for the small jet-to-slide clearance were obtained by microscopic count and by colorimetric analysis of the material collected on the slides. Essentially monodispersed aerosols were produced by the atomization of dyed dibutyl phthalate with a spinning disk operating at 80,000 rpm. The impaction parameter was varied by changing the volume flow rate while holding the other factors constant. Because of the low volume flow rate required to make the curve asymptotic with zero efficiency of impaction, it is believed that gravitational effects caused particles to impact on the slide for the low values of the impaction parameter.

The results of these tests indicated that it would be desirable to design an impactor with small jet-to-slide clearances. Because the wall losses for these tests were higher than desired, tests were run to determine the effects of wall-to-slide distance on wall loss.

5 EFFECT OF WALL-TO-SLIDE DISTANCE

An aerosol particle that is slightly too small to impact on a slide and, consequently, passes around and near the edge of the slide, tends to strike the inner wall of the cascade impactor. This phenomenon, which is called aerodynamic wall loss, becomes more probable when the diameter of the impaction slide approaches the inside diameter of the cascade impactor. The distance between the inner wall of the impactor and edge of the slide is equal to the difference in the radii of the inner wall and of the slide, and is called the wall-to-slide distance, D_{WS}.

Figure 3 is a plot of the amount of aerodynamic wall loss as a function of the wall-to-slide distance. Circular jets and circular slides were used, and the sampling rate was 12.5 liters/min. The impactor was mounted in a vertical position during these tests to reduce the likelihood of fall-out on the walls by gravity. These tests were run with particles 12 and 16 μ in diameter, which is the suggested cutoff diameter, D_p, for the first stage of the small-scale impactor.

Figure 4 is a replot of the same data showing the relation between the efficiency of impaction on the walls, η_w, and the wall-to-slide distance. The term, η_w, is defined as that fraction of the total weight of particles of a given size which passes around a slide and deposits on the wall.

The following empirical equation was developed to fit the bulk of the data obtained in these experiments.

$$\eta_w = \left[e^{-(0.00428\, D_{ws} \times D_s^2 \times Q^{1/2})}\right]\left[\frac{D_p^2 Q^2}{10800\, D_j^3}\right]$$

where D_{WS} denotes the wall-to-slide distance in centimeters, D_S denotes slide diameter in centimeters, Q denotes the volume flow rate in liters per minute, D_p denotes the particle diameter in microns, and D_j denotes the jet diameter in centimeters.

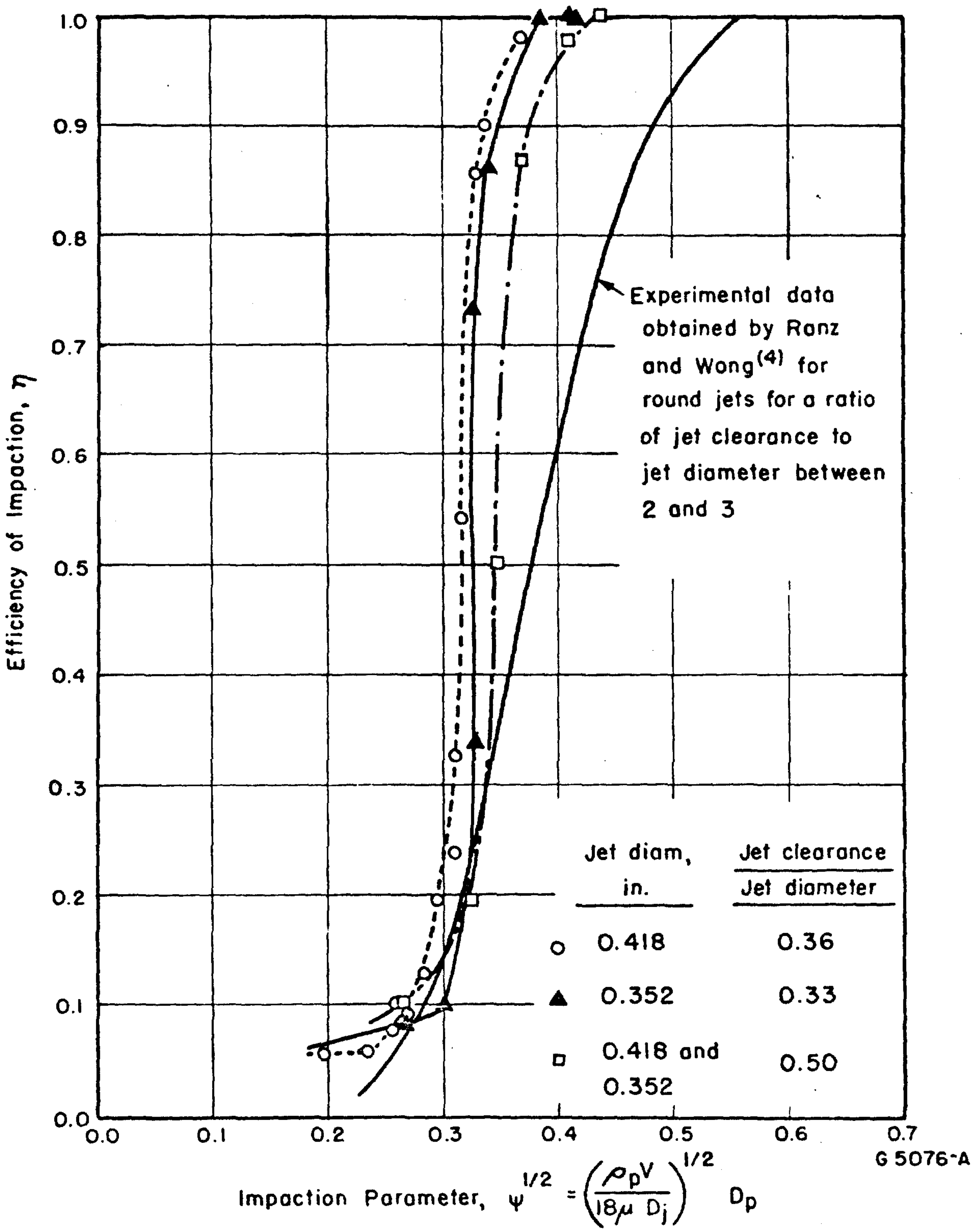

Fig. 2—Impaction efficiency as a function of the impaction parameter for circular aerosol jets impinging on flat 25 mm slides.

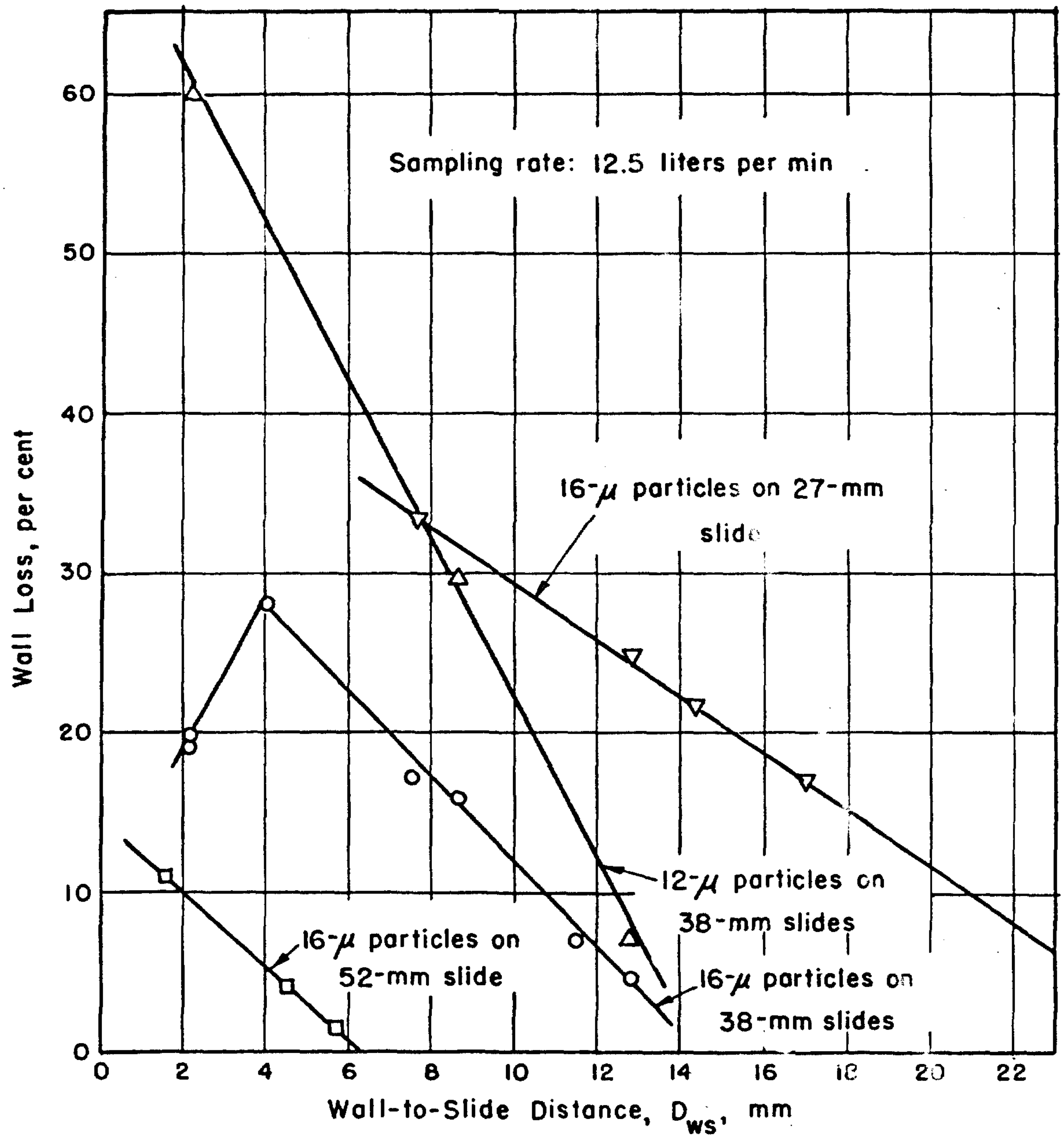

Fig. 3—Aerodynamic wall loss as a function of wall-to-slide distance (D_{WS}) for circular jets.

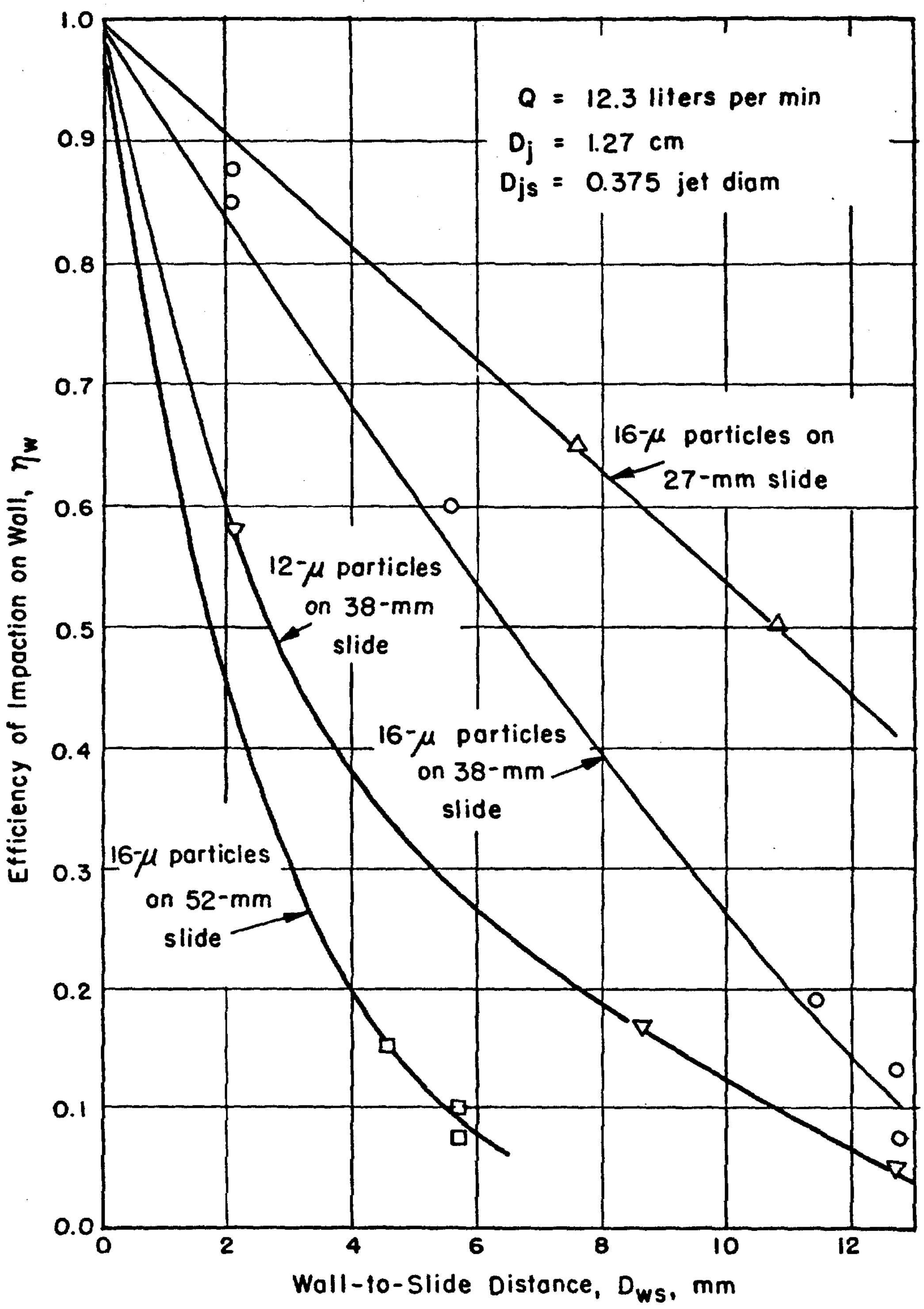

Fig. 4—Impaction efficiency on the wall as a function of wall-to-slide distance (D_{ws}) for circular jets.

Table 1 is a comparison of observed and calculated values of the impaction efficiencies for the wall. The results of these tests indicate that the empirical equation holds well over the entire range studied.

Table 1—COMPARISON OF OBSERVED AND CALCULATED VALUES OF WALL-IMPACTION EFFICIENCIES

η_w (observed)	η_w (calculated)	D_p	D_s	D_{ws}	D_j	Q
0.05	0.06	12	3.8	1.27	1.27	12.3
0.16	0.16	12	3.8	0.86	1.27	12.3
0.60	0.63	12	3.8	0.21	1.27	12.3
0.10	0.11	16	5.2	0.56	1.27	12.3
0.15	0.19	16	5.2	0.45	1.27	12.3
0.22	0.18	16	2.7	1.70	1.27	12.3
0.65	0.64	16	2.7	0.76	1.27	12.3
0.12	0.09	16	3.8	1.27	1.27	12.3
0.70	0.80	12	2.5	0.67	1.06	12.3
0.31	0.26	12	2.5	0.67	1.06	8.3
0.08	0.08	12	2.5	0.67	1.06	4.0
0.21	0.21	12	2.5	0.67	1.06	7.2
0.29	0.33	12	2.5	0.67	1.43	12.3
0.11	0.15	12	2.5	0.67	1.43	7.2
0.02	0.05	12	2.5	0.67	1.27	4.0
0.28	0.29	12	3.8	0.56	1.27	12.3
0.23	0.20	10	3.8	0.56	1.27	12.3
0.15	0.14	8.4	3.8	0.56	1.27	12.3
0.03	0.04	10	3.8	1.27	1.27	12.3
0.45	0.46	14	3.8	0.56	1.27	12.3
0.77	0.75	18	3.8	0.56	1.27	12.3
0.07	0.08	14	3.8	1.27	1.27	12.3
0.14	0.13	18	3.8	1.27	1.27	12.3

6 IMPACTION EFFICIENCIES UNDER CONDITIONS FAVORABLE TO LOWER WALL LOSS

Because the wall loss was high for the data presented in Fig. 2, impaction-efficiency curves were obtained for an experimental two-stage impactor in which the slide diameter and wall-to-slide distance could be varied. The main object of these tests was to determine the optimum size of slide and to evaluate the effect of the increased wall-to-slide distance on the impaction-efficiency curve.

Figure 5 is a plot of the experimental impaction efficiency, η, for round jets as a function of the impaction parameter. These results show that both the jet-to-slide distance and the diameter of the slide affect the impaction efficiency. The aerosols for these tests were produced by the disk atomization of dyed dibutyl phthalate. The impaction parameter was varied by changing the sampling rate and the jet diameter.

These tests indicated that the first stage of the new impactor should have a slide of about 38 mm in diameter, a D_{js} of approximately three-eighths of the jet diameter, and a D_{ws} of 12.7 mm. A prototype impactor was made with an increased D_{ws} value of 22 mm.

7 CONSTRUCTION OF THE BATTELLE NO. 6 PROTOTYPE IMPACTOR

A transparent small-scale impactor having a volume flow rate of 12.5 liters/min was constructed to determine the over-all feasibility of such a design. The slides for this impactor are 38 mm in diameter, the jet-to-slide distance is 0.375 times the jet diameter, the length is 17 in., and the wall-to-slide distance is 22 mm.

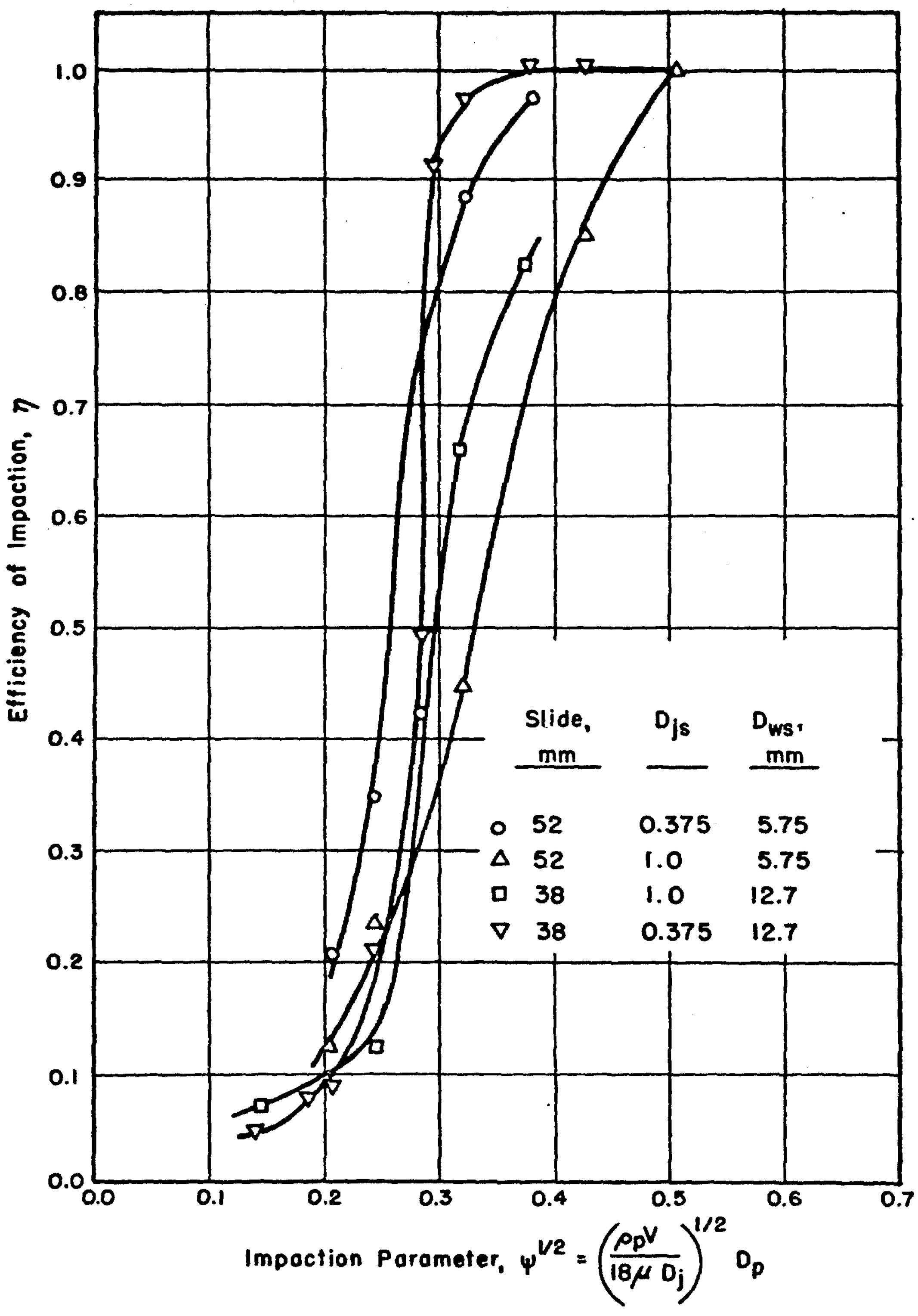

Fig. 5—Impaction efficiency as a function of the impaction parameter for circular aerosol jets impinging on flat circular slides.

Figure 6 is a photograph of the transparent impactor in which the slide supports and retaining springs are attached directly to the lucite jets. The walls are made of cylindrical sections of 87 mm glass tubing. Leaks are prevented by means of O-rings at each joint. Wall loss tests were run with this impactor and the results, which are reported in a later section, indicate that the wall loss was substantially eliminated.

Additional impaction-efficiency curves were run with this impactor to determine the effect of increasing the wall-to-slide distance from 12.7 to 22 mm. Since there was no appreciable change in the impaction efficiency curve, additional impactors were fabricated of metal.

8 CONSTRUCTION OF THE BATTELLE NO. 6 METAL IMPACTOR

Figure 7 is an assembly drawing of the Battelle No. 6 cascade impactor. The six jets of the impactor are made of monel metal and the cylindrical walls are made of Type 316 stainless steel to reduce corrosion. All joints are sealed with O-rings to prevent leakage. Three tie rods hold the stages together for operation in a vertical position.

The No. 6 cascade impactor was designed to sample aerosols composed of particles less than 25 μ in diameter; however, the largest size which impacts on the first stage depends on the maximum size present in the aerosol. The cutoff sizes for each of the six jet stages are approximately 16, 8, 4, 2, 1, and 0.5 μ. The seventh stage of the impactor consists of a filter which removes nearly all of the particles which fail to impact on the sixth stage.

Table 2 shows the jet diameter and the particle-size cutoff diameters, D_p^*, for each of the six stages. During fabrication the variation in jet diameters is confined to less than ± 0.001 in.

A critical-flow orifice, downstream from the filter, maintains a flow rate of 12.5 liters/min provided a sufficient vacuum is applied at the impactor outlet.

Slides which are 38 mm in diameter were used for all stages of the No. 6 impactor. The slides in the latter stages of the impactor could be made smaller in diameter; however, a uniform slide size was maintained for convenience and ease of handling.

Upon the completion of fabrication of the metal impactors they were calibrated.

9 CALIBRATION OF THE BATELLE NO. 6 CASCADE IMPACTOR

Before the cascade impactor can be used for rapid determination of the particle-size distribution of an aerosol, the various stages of the impactor must be calibrated. The Battelle No. 6 impactor was calibrated by the following methods.

1. The first method consisted of sampling aerosols of nearly uniformly sized particles and determining the distribution on the various stages by mass analysis.

2. The second method consisted of sampling uniformly sized particles and determining the size distribution by microscopic counting.

3. The third and most tedious method was to determine the particle-size distribution of a sampled heterogeneous aerosol by microscopic measurement of each particle.

9.1 Calibration of the Impactor by Mass Analysis

The most rapid method of calibration consists of sampling a nearly uniformly sized aerosol produced by means of a spinning disk. The impaction efficiency was determined by evaluating the mass fraction of the aerosol particles collected on two successive stages. Because of the difficulty of obtaining particles smaller than 7.8 μ, this technique could only be used to calibrate the cutoff sizes for Stages 1, 2, and 3 of the Battelle No. 6 impactor. To reduce to a minimum the effect of evaporation of the liquid droplets, dibutyl phthalate which had been dyed with 10 per cent DuPont oil yellow dye was chosen as the test liquid. The purpose of the dye was to provide a tracer so that the mass of the collected droplets could be determined colorimetrically. The collected droplets were washed from the slide with ethyl alcohol, and the amount of dye present was determined with a Beckman Model DU spectrophotometer.

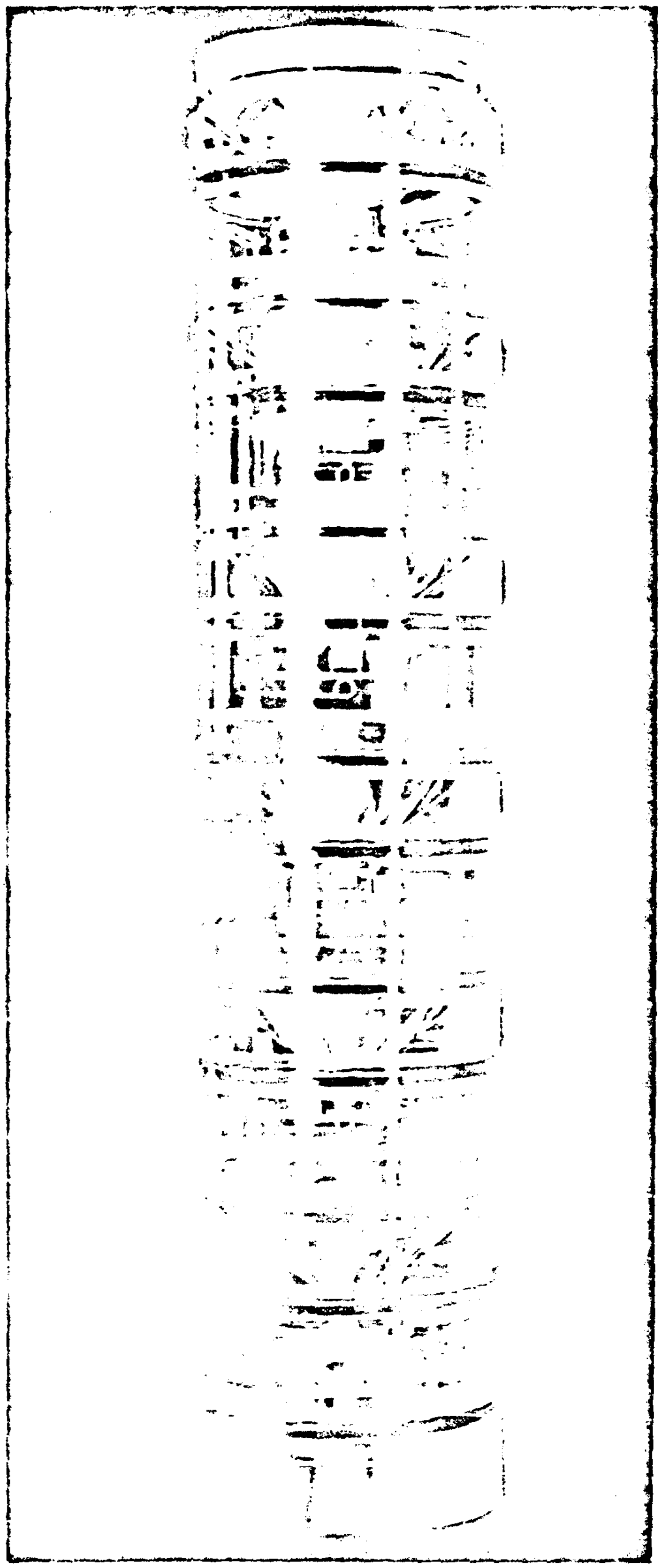

Fig. 6—Transparent small-scale impactor.

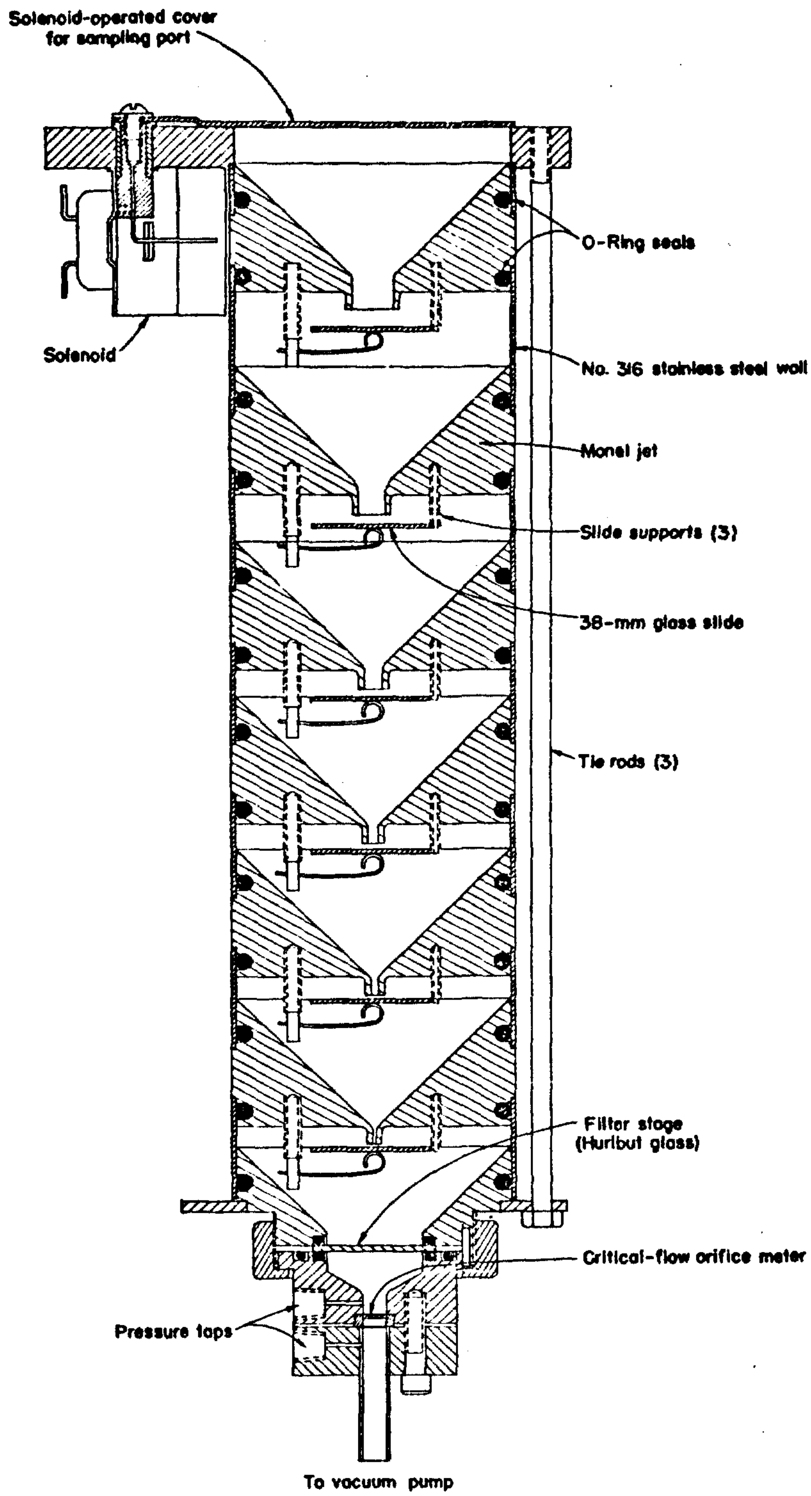

Fig. 7—Assembly drawing of the Battelle No. 6 cascade impactor.

Table 2—JET DIAMETER AND CUTOFF SIZES FOR THE BATTELLE NO. 6 CASCADE IMPACTOR WHEN SAMPLING AEROSOLS AT A RATE OF 12 5 LITERS/MIN

Stage No.	Jet diameter, mm	Cutoff size (D_p^*)† uncorrected,‡ μ	Cutoff size (D_p^*) corrected,§ μ
1	13.64	16	16
2	8.59	8	7.9
3	5.41	4	3.9
4	3.41	2	1.9
5	2.16	1	0.92
6	1.41	0.5	0.42

†D_p^* is the diameter of spherical particles of unit density for which 50 per cent will impact on the given slide and 50 per cent will pass on to the succeeding slide.

‡ Uncorrected for Cunningham effect.

§ Corrected for Cunningham effect.

Figure 8 shows the impaction-efficiency curve obtained by sampling dibutyl phthalate aerosols composed of nearly uniform droplets having mean diameters of either 7.8 or 10.0 μ. The numerical value of the impaction parameter was varied by changing the volume flow rate of the aerosol through the impactor. The numerical value of the impaction parameter, $\psi^{1/2}$, which results in an impaction efficiency of 50 per cent is approximately 0.29. Knowing the viscosity of air, the density of the particles, the diameter of the jet, and the velocity of the air within the jet, the cutoff particle size for each jet can be calculated.

9.2 Calibration of the Impactor by Microscopic Counting of Uniformly Sized Particles

The last three stages of the impactors were partially calibrated by a method in which uniformly sized polystyrene beads, 1.172 and 1.73 μ in diameter, were collected in the cascade impactor and the efficiency of impaction determined by making a microscopic count. The aerosols were produced by ultrasonic atomization in a 1700-liter plastic capsule. Before atomization the polystyrene latexes, which were supplied by the Dow Chemical Company, were diluted by a factor of 10^5.

After the suspending medium had evaporated completely, the aerosol was sampled on clean glass slides placed in the six stages of the cascade impactor. The impaction slides were then shadowed with gold in a vacuum evaporator so that the particles had a shadow length of six times their height. Errors resulting from the presence of extraneous particles on the slide were avoided by counting only those particles with shadows of the right length.

9.3 Calibration of the Impactor by Microscopic Measurement of Each Particle

One of the most tedious methods of calibrating an impactor is to measure each collected particle microscopically. This method of analysis was used to calibrate some of the stages of the cascade impactor.

The main disadvantages of microscopic measurement are the limitation of accuracy when measuring particles less than three microns in diameter, and the rapid evaporation of small liquid droplets.

Figure 9 is a size-frequency distribution curve of polystyrene beads collected on sticky slides in the first three stages of the transparent impactor. The sampled aerosol was produced by the aerosolization of heterogeneous polystyrene beads. A microscopic examination showed that the beads were spherical; however, some of the outer surfaces were covered with plate-shaped particles less than one micron in length. The plate-like material on the surface of some of the spherical particles was ignored when the diameter was measured.

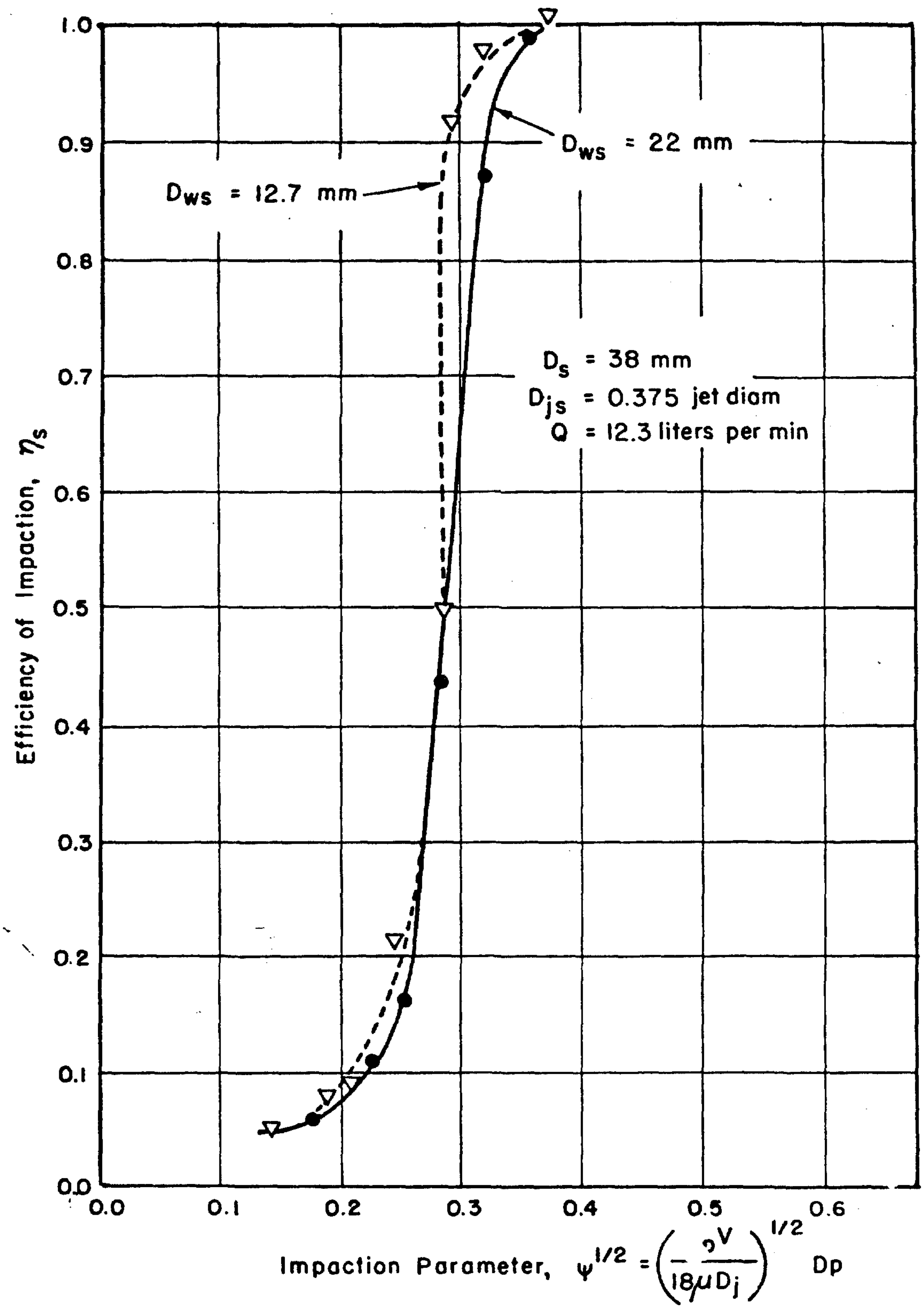

Fig. 8—Impaction efficiency as a function of the impaction parameter for circular aerosol jets impinging on flat circular slides.

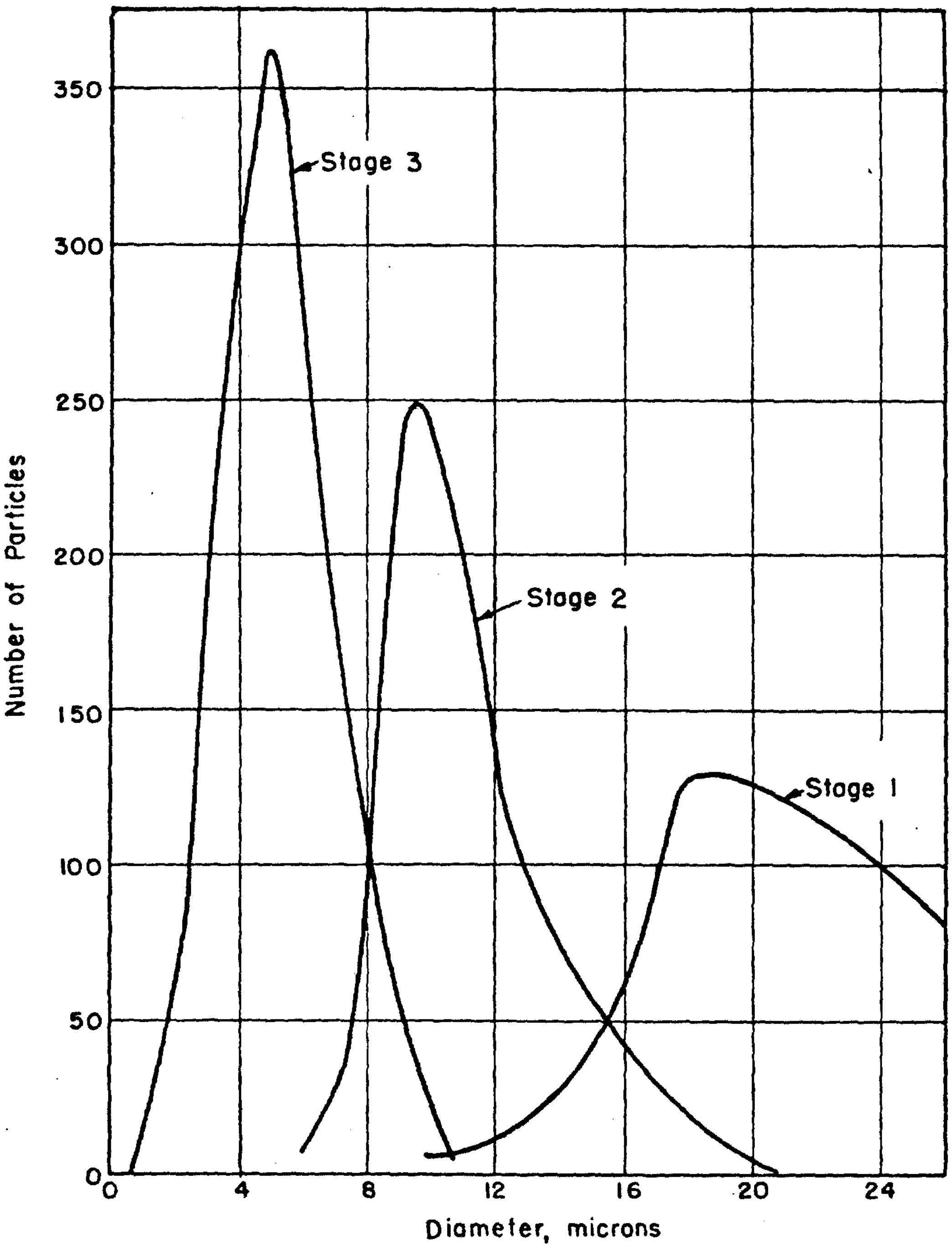

Fig. 9—Size distribution of polystyrene beads collected on three stages of the small-scale prototype cascade impactor.

The polystyrene particles were well classified according to size, and the cutoff sizes for Stages 1 and 2 were close to the calculated values of 16 and 8 μ, respectively. The cutoff size D_p^* for the first stage was about 1 μ lower than the designed size of 16 μ. A probable explanation is that the effective diameter of the particles covered with plates was slightly greater than the measured spherical diameter.

Figure 10 is a plot of the theoretical impaction efficiency curves as a function of particle size for each of the seven stages of the impactor. The points on the curves are experimental results obtained by all three methods of calibration.

The sharpness of cutoff of the impaction efficiency curve permits the impactor to be designed so that the cutoff size for each stage is approximately one half that of the preceding stage. Consequently, particles of a given size will not impact on more than two stages.

10 WALL LOSS STUDIES WITH THE BATTELLE NO. 6 CASCADE IMPACTORS

Several tests have been run with the Battelle No. 6 cascade impactor to determine the extent of wall loss. Because the wall loss on the latter impactor stages is usually below the limit of detection of most light measuring instruments, radiochemical methods of analysis were used. The aerosols sampled were produced by the atomization of biological slurries tagged with radioactive phosphorous-32, using a standard two-fluid nozzle, into a 1700-liter plastic capsule. For the first series of tests a glass "L" was used to transport the aerosol from the chamber to the transparent impactor. The slides of the impactor were porous metal moistened with a glycerin-water solution to make them sticky. For two of the three trials, the walls of the impactor were also treated with the same coating. The relative humidity was kept low to assure that the aerosol particles would be substantially dry.

Table 3 shows wall loss for each stage expressed as a percentage of the sum of the material collected on the wall and on the succeeding slides.

These results indicate that the wall loss is extremely small for this type of aerosol. Wall loss for the entire impactor for this series amounted to less than 1 per cent of the material sampled.

Recently a series of tests were run in which the wall loss of a metal impactor was compared with the wall loss of a transparent impactor. Although both impactors were of the series six design, the jet diameters were slightly different. The design of jet diameters of the metal impactor was adjusted for the particle-size deviation caused by the Cunningham effect.

The aerosols for this series of trials were identical to those of the previous series. However, both impactors were mounted inside the center of a 1700-liter plastic capsule. Porous slides which had been moistened with glycerine were used to collect the aerosol particles. The impacted particles were removed from the slides by passing a wash solution containing a wetting and chelating agent through the slides while held over the mouth of a filter flask. Material that collected on the walls was removed by scrubbing each wall with a brush using the same kind of wash solution.

Table 4 is a tabulation of the counts obtained on the walls and slides for two typical tests. These results indicate that the wall loss for Stages 4, 5, and 6 of the metal impactor is less than 1.5 per cent of the material which collects on the stage, and the wall loss for Stage 3 is less than 4 per cent. The particle size of the aerosol sampled at the high humidity was increased considerably by the addition of a large amount of glycerine before atomization, so that the amount of material which collected on Stage 2 would be significant. The results of this test indicated that the wall loss for Stage 2 is less than 15 per cent. An interesting point to note is that this wall loss apparently was not caused by aerodynamic factors which force particles to impact on the cylindrical portion of the stage, but by gravitational settling of the particles as they entered the second jet. The total wall loss for this particular test amounted to 6.5 per cent. In most of the tests in which wall loss was determined it was less than 2 per cent of the total aerosol sampled.

Radiochemical methods of determining wall loss have an advantage over light-measuring method in that a blank need not be run because most contaminents do not contain any radio-

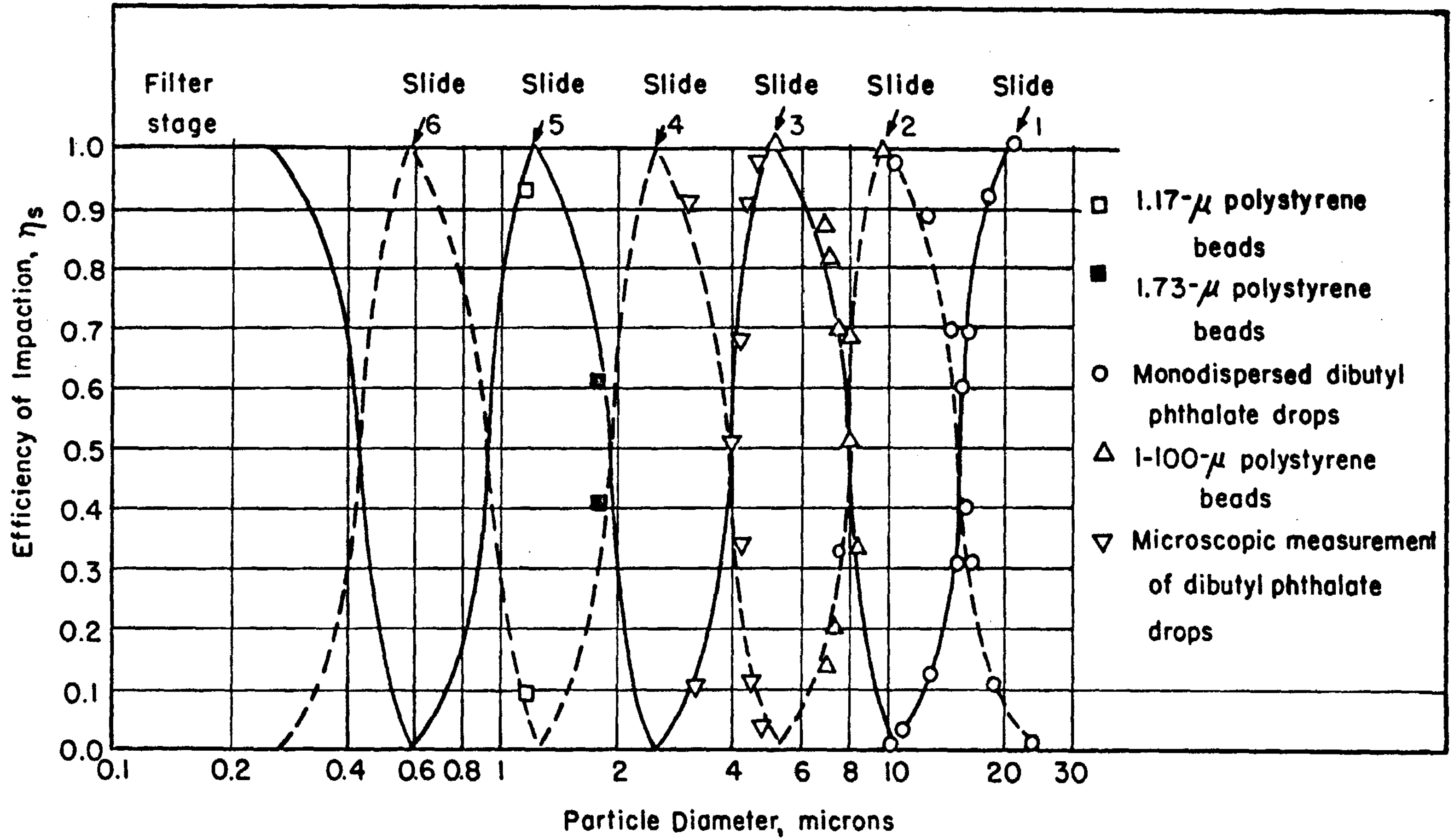

Fig. 10—Impaction efficiency as a function of particle size for each stage of No. 6 cascade impactor.

Table 3—WALL LOSS WHEN SAMPLING BACTERIAL AEROSOLS WITH THE TRANSPARENT IMPACTOR

Test No.	Temp, C	RH, per cent	Wall loss*				
			Wall 2	Wall 3	Wall 4	Wall 5	Wall 6
1	25	25	1.43	0.38	0.09	0.36	0.22
2	26	46	3.09	0.71	0.23	0.22	0.14
3†	28	30	3.18	0.78	0.18	0.30	2.63‡

$$* \text{Wall loss} = \frac{\text{material impacted on wall}}{\text{material impacted on wall} + \text{material impacted on succeeding slide.}}$$

† The walls of the impactor were not treated with gylcerine for Test No. 3.

‡ It is believed that the relatively high value of 2.63 per cent is correct and is due to electrostatics. The operator held the impactor by placing his hands on Stage No. 5 which may account for the higher wall loss.

Table 4—CASCADE IMPACTOR WALL-LOSS TESTS

Test	RH, %	Stage	Brass impactor: Counts on slide	Brass impactor: Counts on wall	Brass impactor: Wall loss, %	Transparent impactor: Counts on slide	Transparent impactor: Counts on wall	Transparent impactor: Wall loss, %	Remarks
3	40	1	18,528	750	*	372	2,077	*	Bacterial standard slurry
		2	2,514	727	22.44	752	2,091	73.54	
		3	9,573	652	6.37	12,281	1,417	10.34	
		4	190,085	1,002	0.52	129,326	1,644	1.25	
		5	241,780	564	0.23	310,487	2,267	0.72	
		6	172,669	418	0.24	181,947	2,941	1.59	
		7	72,138			42,695			
		Total	707,290	3,365	0.47	677,863	10,362	1.50	
7	98	1	15,201	16,946	*	11,436	19,957	*	Bacterial slurry containing 50 per cent glycerine
		2	73,583	12,875	14.89	64,019	12,333	16.15	
		3	92,642	3,578	3.72	92,786	4,363	4.49	
		4	47,004	730	1.53	48,844	531	1.07	
		5	14,289	28	0.19	18,469	17	0.12	
		6	4,994	0	0	2,417	0	0	
		7	756			222			
		Total	248,469	17,211	6.48	238,193	17,244	6.75	

* By definition the material which settled on the inlet cone before the sample of aerosol entered the impactor is not considered as part of the sample. Consequently there is no wall loss for Stage 1.

activity. Unless extreme care is taken, the blank readings can amount to a high portion of a reading obtained on a light-measuring device, causing a large error in the final analysis.

11 CONCLUSIONS

The size distribution of an aerosol can be determined rapidly and accurately with the cascade impactor. After one instrument has been calibrated additional impactors with identical dimensions can be fabricated, and no further calibrations are required.

Because of its inherent versatility for the sampling of either solid or liquid particles over a wide range of conditions, the cascade impactor meets most of the requirements of an instrument for general studies of aerosols.

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A MULTIBED LOW VELOCITY AIR CLEANER

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1 INTRODUCTION

It is estimated that the civilian power reactor program will have accumulated by 1970, 10^7 gallons of waste containing 2×10^{10} curies.[1] The disposal of this large volume of wastes, without danger to the public, presents a unique problem in industrial waste treatment. While the exact composition of these wastes will vary widely, an off-gas problem will always exist in their storage or ultimate disposal. The multibed air cleaner is designed to decontaminate the off-gases from one waste disposal method, the fixation of radioactive wastes in a sintered clinker.

2 DISPOSAL SCHEMES

Processes for the ultimate disposal of acid aluminum nitrate wastes fall into two broad categories based on temperature. Medium-temperature processes are defined as those which operate in the range of 400°C to 600°C. High-temperature processes are those which operate at temperatures greater than 800°C.

Examples of medium-temperature processes are the fluidized bed reactor[2] and the fused salt calciner.[3] The fluidized bed reactor utilizes a seed bed of alumina to form a product of alumina particles containing the fission products. These particles can be placed in containers for storage.

The fused salt calcination process uses sodium nitrate (produced by sodium hydroxide neutralization of acid aluminum nitrate waste) as a flux to produce a melt which can be cast into a convenient form for storage.

There are two different techniques of high-temperature fixation under development. In the first method acid aluminum nitrate wastes are calcined to give a granular product from which leachable fission products are removed by water or mild acid. The fission products are absorbed from the leachate by montmorillonite clay which is then fired in a kiln at 1000°C. This fixes all the fission products except ruthenium. The ruthenium is leached from the fired clay for separate disposal.[2]

A second method of high-temperature fixation is under development at the Oak Ridge National Laboratory. Raw acid aluminum nitrate waste is processed with Conasauga shale and fluxing agents at temperatures greater than 800°C to form a sintered clinker which immobilizes the fission products. The fluxing agents are limestone and sodium carbonate. The heat required for the sintering process may be obtained by (1) self-heating, heat of fission product decay, or (2) self-heating plus external heating.[2]

3 ANALYSIS OF OFF-GASES

The processes outlined above produce radioactive aerosols of several types. The fluidized bed and fused salt calcination will produce an aerosol of solid particles in a hot gas stream. The sintering process produces a complex of particulates ranging from approximately gas molecule size 1 A to 10 μ. The nature of the aerosol will vary with the changing temperature of the sintering material. As the sintering material heats, water vapor and water droplets are evolved. Radioactive materials begin to appear in the aerosol when the mass reaches 86°C (see Table 1). After the boiling temperature is reached, the aerosol contains water droplets carrying both dissolved and insoluble particles.

Table 1—ENTRAINMENT BY EVAPORATION-ENTRAINMENT WELL

Temp., °C	Well Count, counts/min/ml	Cond. count, counts/min/ml	Decontamination factor
90–100	856	1.340	6.39×10^2
86	8514	1.35	6.3×10^3
91	8514	2.47	3.44×10^3
95	8514	63.	1.35×10^2

The nature of the aerosol particulates evolved from the sintering material at temperatures greater than 100°C is not presently known. On the basis of experiments with sodium chloride it is expected that a copious number of crystalline particles of about 0.05 μ are evolved at temperatures greater than 300°C. The particle size of the NaCl aerosol increases as the temperature of the solid salt material increases to 800°C.[4] Particulates from the sintering material are expected to follow this pattern.

Reactive and nonreactive gases will be present throughout the sintering process. Of the reactive gases the first to be released is carbon dioxide, released during the mixing operation. Radioiodine will be present in the off-gases during the entire sintering operation, though the major part of the iodine will be volatilized below 200°C. Nitrate salts begin to decompose at 150°C, and oxides of nitrogen persist at 800°C.

The important nonreactive gases present in the waste solution are Kr^{85} and Xe^{133}. The more important of the two biologically is Kr^{85} because of its long half life, 9.5 years.

4 EXPERIMENTAL EQUIPMENT AND DATA

It is recognized that no single filtering agent can effectively remove this multiplicity of contaminants. The variety of contaminants suggested a multibed air cleaner (see Fig. 1). The components of the multibed air cleaner are sand, soda lime, and activated carbon.

Dry sand is an effective filter for particulates. Figures 2 and 3 show that the efficiency of a sand filter depends upon (1) sand grain size and shape, (2) superficial air velocity (volumetric flow divided by filter cross sectional area), and (3) sand bed depth.

At a superficial gas velocity of 0.1 cm/sec (0.2 ft/min) the most penetrating aerosol particle size is in the 0.25 to 0.45 μ radius range.[5] The efficiency of a sand filter increases exponentially with depth of the sand bed. Thus, if a sand filter 4 in. in depth passes 2 per cent of an aerosol, a filter 8 in. deep will pass only 0.04 per cent of the same aerosol.

If very moist aerosols are passed through a sand filter, water condenses in the filter voids and clogs the filter. Figure 4 shows the build-up of pressure at the inlet to a sand filter as it

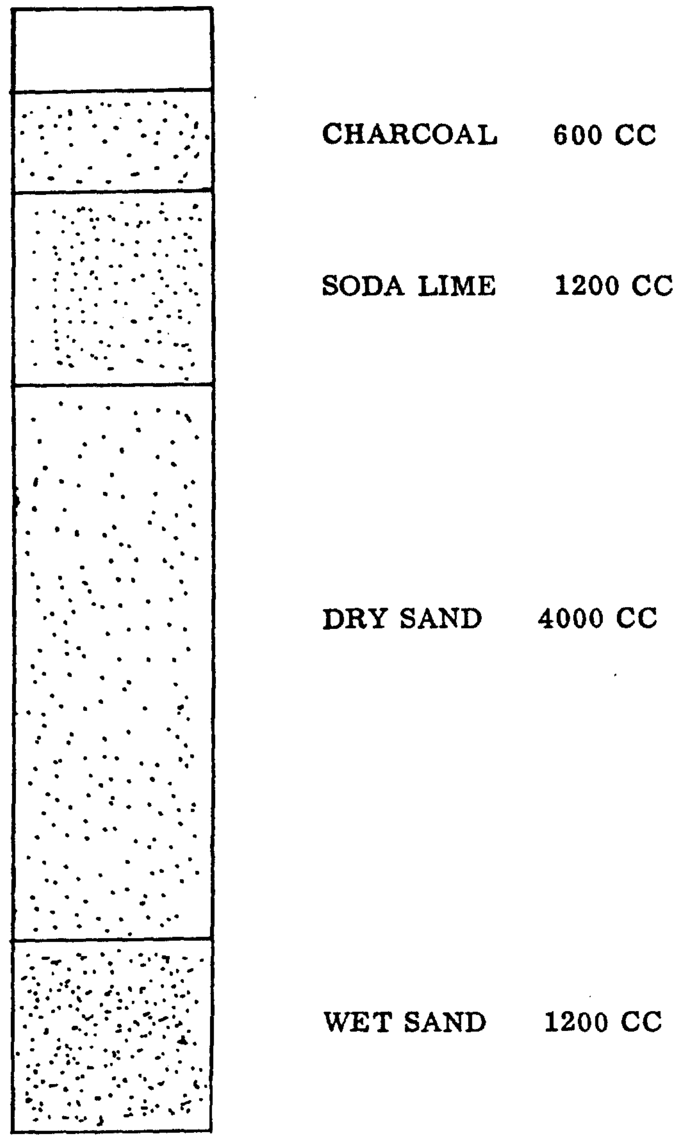

Fig. 1—Compound sand filter. Column diameter, 9 cm; flow rate, 500 cc/min.

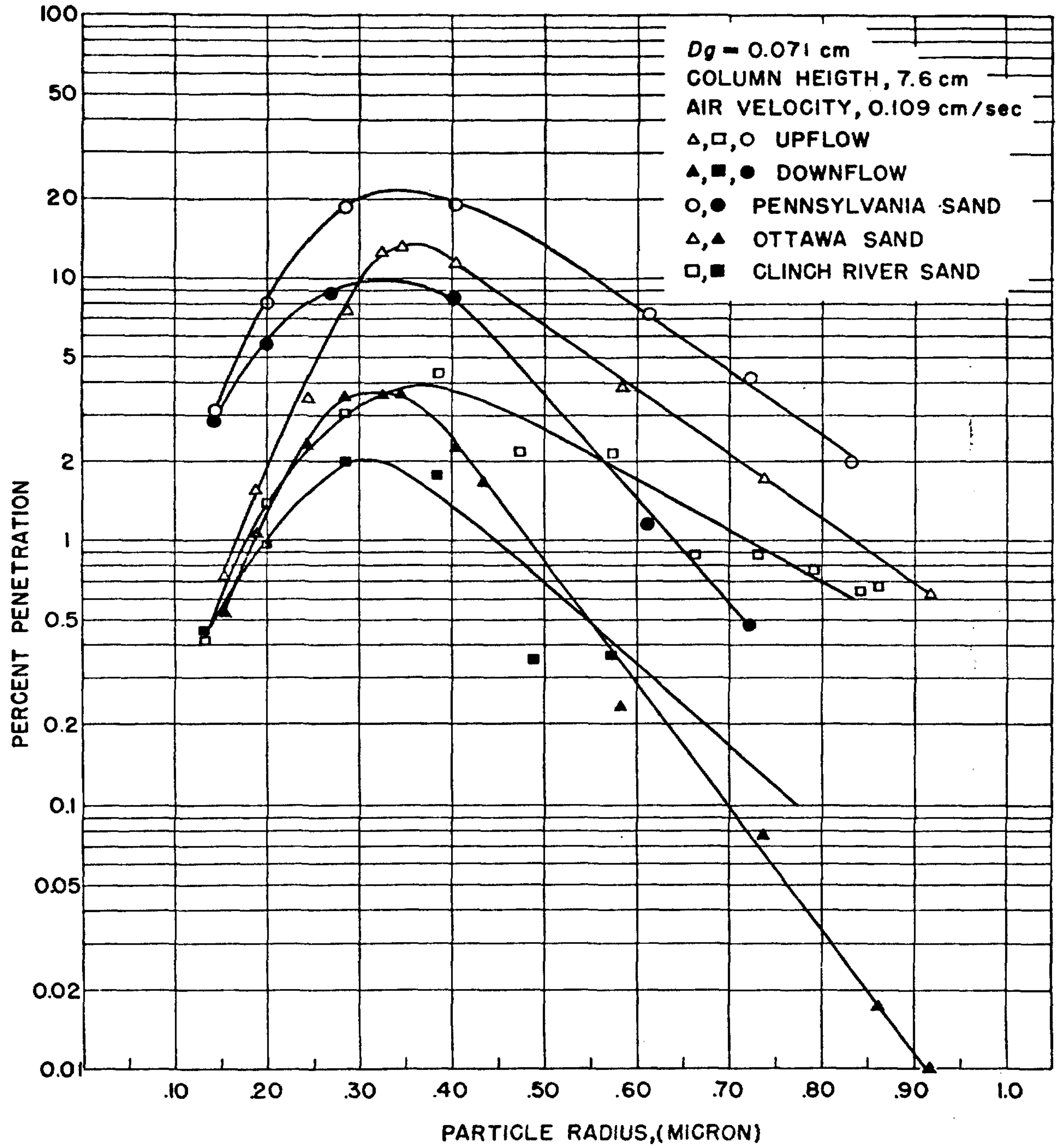

Fig. 2—Penetration in filters of Pennsylvania, Ottawa, and Clinch River sands.

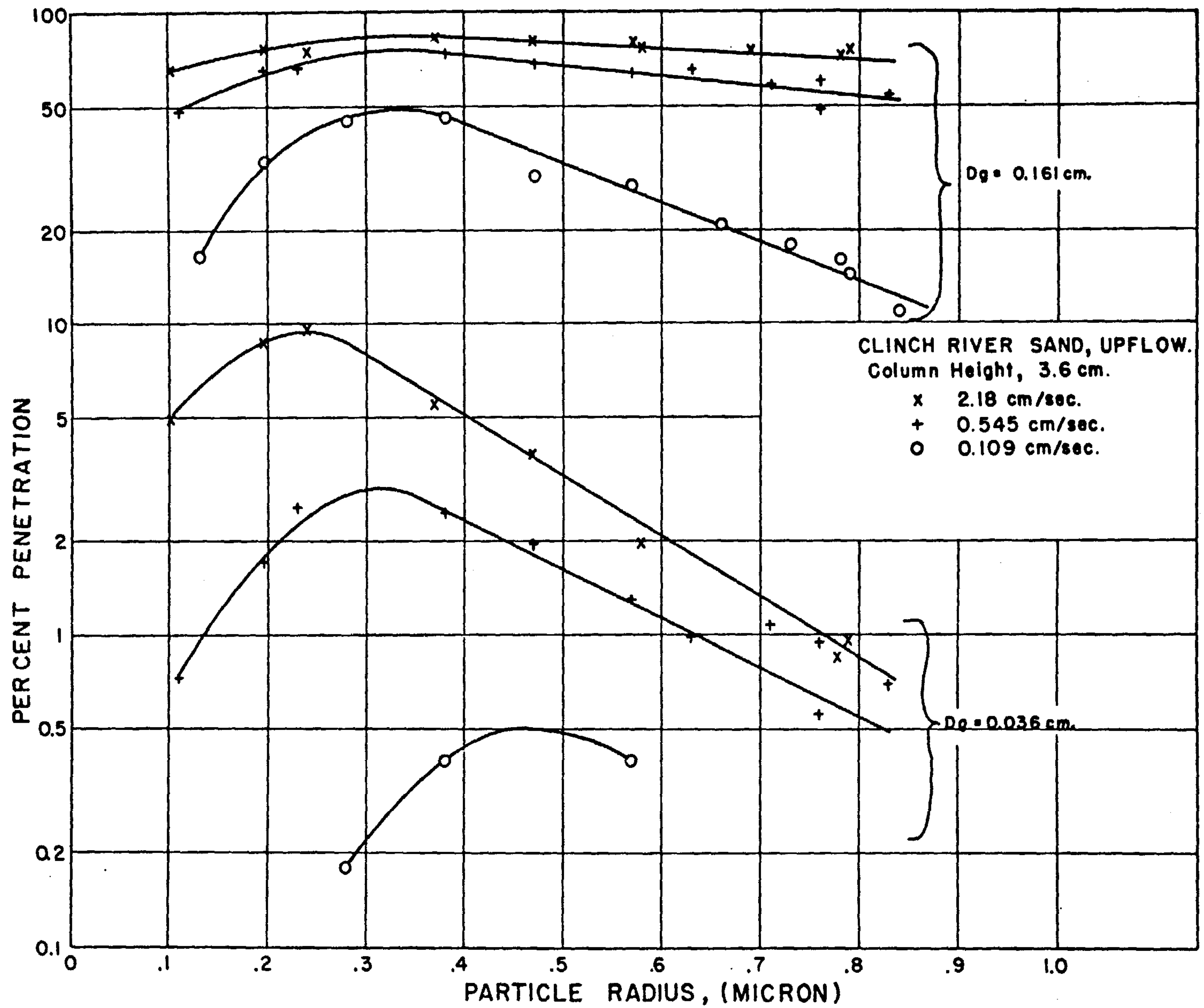

Fig. 3—Penetration in Clinch River sand filter.

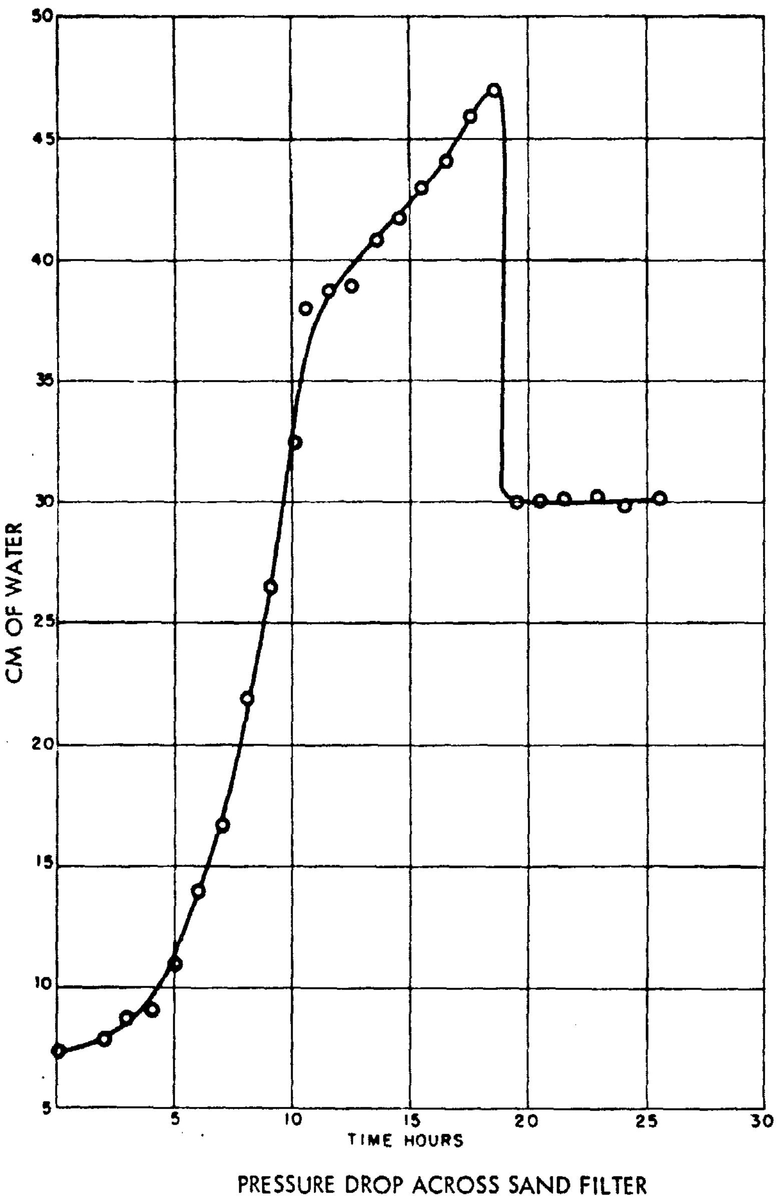

Fig. 4—Build-up of pressure in sand filter from saturation with water.

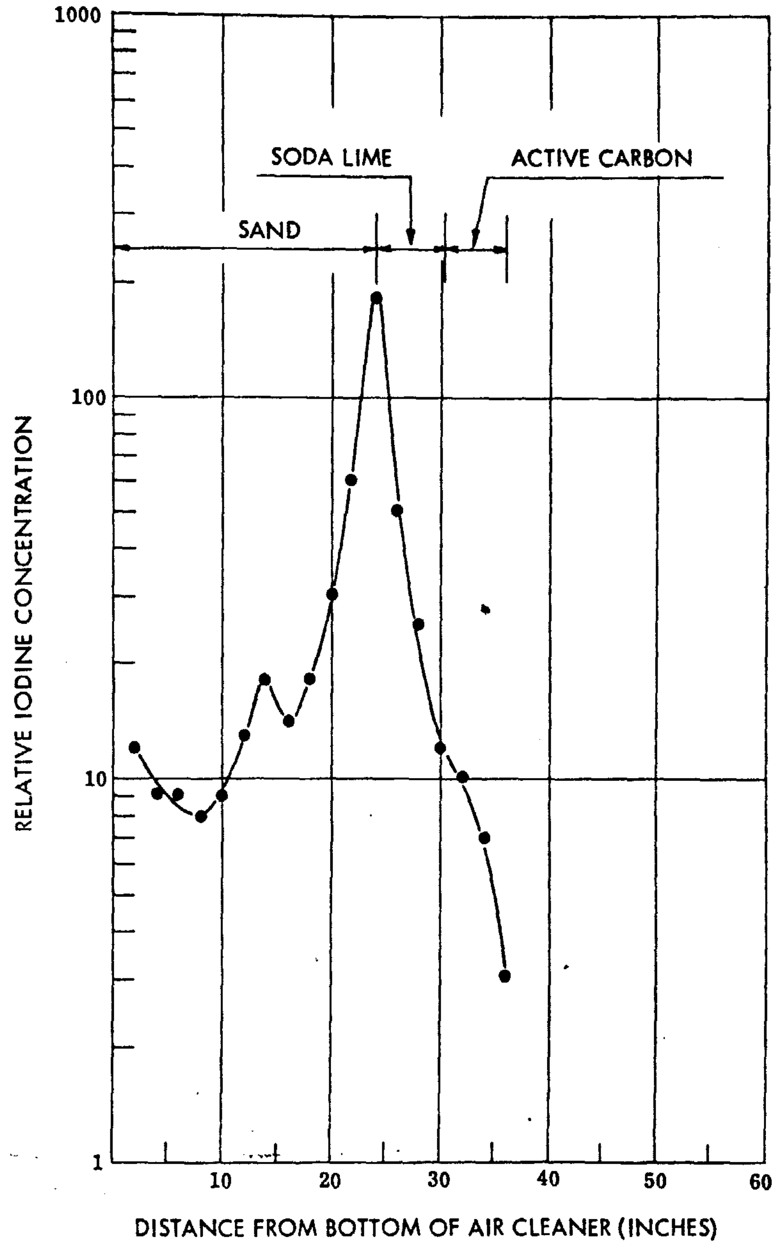

Fig. 5—Distribution of I^{131} within the multibed air cleaner.

becomes saturated with water. The sharp drop is indicative of channeling. The data show that for wet aerosols, sand is a poor filter but an effective condenser. By proper filter design the condensed water can be drained from the filter thus maintaining the sand in an unsaturated (and efficient) condition.

Laboratory sintering experiments using Ru^{106} tracer show that the sand filter functions as described above. Water condenses in the lower few inches of the filter and is drained to a sump beneath the filter. Most of the evolved ruthenium is found in the condensate and in the filter, although some is found plated on the surface of the tubing leading to the filter. No activity is found in the off-gas system after the filter. Table 2 presents the data for these experiments.

Table 2—FATE OF RUTHENIUM IN THE MULTIBED AIR CLEANER

	Activity, counts/min
Initial waste	5.6×10^7
Final waste	4.4×10^7
Condensate	3.3×10^6
Ruthenium scrubber	0
Air cleaner	5.8×10^6
Tubing	2.9×10^6

Soda lime is known to be an effective agent for removal of nitrogen oxides from gas streams. A soda lime bed (8-mesh) placed on the sand filter reduced the oxides of nitrogen concentration (nitrite) to approximately 10 ppm as determined by bubbling through dimethylaniline. A 12-in. bed of soda lime was not measurably more effective than a 4-in. bed. The 4-in. bed of soda lime was one sixth the depth of the sand filter.

Radioiodine, when used as a tracer, condensed on the sand. As the sand was heated by the condensing water vapor, the iodine sublimed, moving slowly up the filter to the sand-soda lime interface where it remained. The distribution of iodine within the filter is shown in Fig. 5.

Activated carbon was included in the multibed air cleaner primarily to remove the initial surge of iodine and was placed immediately above the soda lime. Since the iodine did not reach the activated carbon, its inclusion for iodine removal was not justified. However, the activated carbon did reduce the nitrogen oxides passing the soda lime to less than 1 ppm nitrites. For this reason the activated carbon was included in the air cleaner.

It is known that noble gases are retained by activated carbon at low temperatures. Because their retention is low at room temperature, this factor has not been considered in the design of the air cleaner.

5 SUMMARY AND CONCLUSIONS

One solution to the air cleaning problems presented by the self-sintering method of reactor waste disposal is the multibed air cleaner. This air cleaner will remove greater than 99.995 per cent of the evolved particulates and all the fission product gases except xenon and krypton.

The air cleaner is applicable to the cleaning of off-gases from any similar operation. It must be remembered, however, that the superficial air velocity should not exceed 0.1 cm/sec.

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AIR CLEANING OPERATIONS AT UCRL

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Air cleaning and other controls of radioisotopes to prevent their dispersion into the environment entrained in air continue to receive both operating and applied research attention.

In processing off-gases from chemical manipulation of reactor irradiated materials, containing multicuries of alpha emitters and associated fission products, increased emphasis on containment in physical systems of very low exhaust volume is noted. In such operations dependence on AEC type filters for cleanup has been abandoned; these now act as forefilters for Millipore filters handling the total exhaust, which lies in the 200 to 300 ml/min range. In the past, radioactive fission product gases passed to the stack from such equipment. We are now set up to capture this fraction nearly quantitatively from our so-called closed dissolver design reported at the 1957 Nuclear Congress in Philadelphia.

For the past several years considerable effort has been devoted by UCRL Berkeley to processing kilocuries of alpha emitters of classified interest for our Livermore laboratory. It is with considerable gratification we observe they are now eminently capable of staffing their own responsibility under Mr. Jack Murrow. This has made possible Berkeley's increasing attention to projects of foreseeable magnitude for the near future. Among these will be the development of equipment and techniques for the suppression and capture of aerosols arising in small-scale, but high-level activity, evaporations necessary as a preliminary to ion exchange separation processes.

Another problem of some interest will be the perfection of gas cleaning methods for circulating helium blankets in accelerator target systems.

Vacuum furnace operations involving vaporizing transuranics as well as certain fission products are posing increasing difficulty in decontaminating the pump effluent. This problem is aggravated by the oil mist commonly associated therewith.

Our room air sampling program continues to increase with laboratory expansion of programs, personnel, and work areas. We now routinely handle 1500 separate samples monthly, On the average less than two per month approach Handbook 52 concentrations. The major problem existing in this field is an old one, namely, finding a practical way to get early or immediate warning of above background alpha emitter pollutants dispersed in air or stack gases. A portion of our air sampling effort is devoted to periodic collaboration in assessing fallout from nuclear device tests.

On the increase is attention to individual stack emissions of very low level, as from fume hoods where local policy dictates handling maxima of less than 0.1 μc.

Substantial but intermittent work has been performed on control of radioactive air pollutants arising from biological experimentation, both plant and animal. In the middle range view this will demand a perhaps disproportionate expenditure of time and expense per curie handled because of the often almost bizarre requirements superimposed on good air cleaning fundamentals by the objects worked on.

A hidden cost of continuous nature resides in the lack of trained available personnel. Perhaps 15 per cent, as a guess, of available trained man-hours is devoted to indoctrination and training of those new to the ranks. Since costs of air cleaning and surveillance, after initial expenditures are made for capital equipment, are largely those for salaries, it would appear an AEC effort to support instruction of specialists in the professional and technical aspects of air cleaning might well be considered.

ECONOMIC SURVEY OF AIR AND GAS CLEANING OPERATIONS WITHIN THE AEC

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At the request of the Division of Reactor Development, U. S. Atomic Energy Commission, the Harvard University Air Cleaning Laboratory is conducting an economic survey of air and gas cleaning operations within the AEC. The concept of such a program is not new, the basic purposes and requirements of the current survey having been outlined in a memorandum to AEC site management over two years ago. However, this laboratory and personnel responsible for handling air cleaning operations throughout the Commission have not yet succeeded in obtaining comparative data. The shortage of technical manpower and the increase in air cleaning problems and their complexities probably represent the best arguments for reviewing air and gas cleaning experience at the major AEC sites.

Certainly the most practical approach to engineering problems is immediate reference to a guide or manual which suggests reliable solutions in accordance with economic factors. In limited cases, the experience of individuals or a single facility may furnish the desired information. On the other hand, it may be necessary to perpetuate uneconomical methods of gas cleaning to meet production schedules.

It seems reasonable to assume that a detailed inspection of the several AEC sites would reveal (1) that each plant has developed gas cleaning procedures for certain operations which could well be adopted as "standard methods" and (2) that each plant has collector problems which are still unsolved. A composite of successful AEC plant experience on air cleaning methods and costs would provide a useful guide in approaching new problems and re-evaluating present techniques.

Compilation of representative data on the cost and performance of air and gas cleaning apparatus is a major objective of this survey. Since the hazards associated with the handling of fissionable materials demand emphasis first on proper control measures and second on the economics involved, the tremendous industry developed by the AEC is burdened with far greater air cleaning costs than those encountered outside the atomic energy field. The only possible way to assess these costs is to identify them, find out how much and what degree of air cleaning is represented by them, and what bookkeeping methods have led to the cost estimates.

Basically, these are straightforward questions whose answers should permit advancement of design and cost criteria which can provide more economical solutions to air and gas cleaning problems. However, it is recognized immediately that obtaining the necessary data from the various sites is going to require that several persons at each plant be contacted in person or by letter. It will be necessary to define precisely the reasons for the survey and the type of information wanted. If preliminary visits to several of the major AEC sites can be used as guideposts it will be discovered that the over-all handling of one air cleaning operation may involve several departments and individuals. Capital, freight, maintenance, repair, inspection, monitoring, replacement, and disposal charges may be dispersed through several departments with nearly as broad a spectra for equipment performance data, such as power requirements, efficiency, air handling capacity, pressure loss, and filter life. Obviously, considerable labor will be required to ferret out the facts and many plants will be hard put to cooperate, manpower and budgetwise.

This laboratory and the Division of Reactor Development realize that the success of the economic survey depends in large part upon the response of the various AEC sites. The fact that several papers have been presented at the AEC Air Cleaning Seminars discussing specific site air cleaning methods and problems demonstrates a positive interest in the subject. Information furnished by Van Valzah[1] on filtration costs at the Argonne National Laboratory and by Harris and Mason[2] on bag filtering costs at the Mallinckrodt Chemical Company represents a substantial contribution to the economic survey. References to these papers and others have helped to determine what factors should be given major consideration.

Results of preliminary visits to AEC plants have indicated the need for a detailed questionnaire which summarizes the information required for the survey. This would serve the following purposes: (1) provide a compact outline of program objectives and thereby minimize extraneous effort in pursuit of data, (2) ensure that information from the various sites may be properly correlated.

A tentative outline of the basic material which this laboratory believes should be included in the survey questionnaire is presented in this paper. It is recognized that there may be serious omissions and that the general arrangement of material may be disputed. Therefore, it is planned to distribute the questionnaire in essentially the same form as that appearing in this report to site management and personnel who are directly concerned with air cleaning operations. It is strongly urged that the outline be reviewed critically so that its final form will represent the composite expression of those individuals requested to use it as a guide.

The outline has been arranged in two parts which cover (1) pertinent descriptive and operational data and (2) air and/or gas cleaning costs. Section I should furnish a complete picture of the dust collecting device, i.e., identification, classification and type. If the cleaner represents a site development, detailed design and testing data should be supplied giving literature references wherever possible.

Under the category of Operational data, Section II, the following items are considered important: A. Site application, such as prefilter for supply or exhaust air, and high efficiency collector for laboratory or process areas. B. Cleaning requirement and process, which should describe aerosol composition, concentration, and efficiency requirements within practical security boundaries. C. Space requirements, which frequently may be a decisive factor in collector selection. D. Operating characteristics, which should permit a thorough evaluation of collector performance. E. Method of replacement or cleaning of media. Recent data reported by the Hanford plant show that for certain operations vacuum cleaning of Absolute filters and washing of glass fiber filters have extended service life significantly. Site procedures of this type are particularly worthy of dissemination since they may lead to substantial savings in air cleaning costs. F. Criteria for cleaner changes. Reasons for filter changes may vary from one plant to another even for identical operations. Only by a thorough analysis of plant procedures can an optimum system be devised. G. Handling and disposal methods. Incineration techniques have been discarded in favor of baling and storage or burial at some installations on a basis of cost. However, problems relative to storage or burial capacity point toward re-evaluation of incineration processes. Item H. is reserved for comments on previous subjects which should reflect the personal experience of plant personnel.

Gas cleanings costs have been divided into two main classifications, Section III Equipment Charges and Section IV Labor Costs. Generally speaking, it has been assumed that initial collector costs (separated from freight charges) would not differ materially from one place in the country to another insofar as commercially available collectors are concerned. It is very possible, however, that duct and fan installations may be quite different and therefore should not be considered as part of the integral collector cost. In reporting initial cost on a basis of dollars per 1000 cfm capacity per year, the total cleaning capacity should be furnished, since average cost will decrease with large volume installations. Write-off figures which serve to prorate equipment costs over the period of useful life may vary considerably. Reasons for a particular time should be explained if these data are to be used for future design criteria. A five year write-off period, for example, may be justified from a financial point of view, but may actually be five to ten years short in describing collector life.

Labor charges on the whole are practically meaningless unless defined in terms of man-hours and labor classification. Here an attempt should be made to distinguish between charges associated with equipment installation and those connected with routine procedures, i.e., maintenance, inspection, cleaning, filter replacement, decontamination, and several miscellaneous operations. All of the items listed in Sections III and IV represent costs that should be charged directly to air cleaning operations although individual plant bookkeeping systems may not so indicate. From the statistical viewpoint, they show in true perspective the economic consideration associated with a proposed air cleaning system.

Assessment of operations that simultaneously represent air cleaning procedures and product recovery processes should be judged on their individual characteristics. If the intrinsic value of the material to be recovered coincidentally dictates a degree of cleaning equal to or more than that required from the hazard viewpoint, the costs associated with the operation should be considered a basic production charge. On the other hand any part of the air cleaning system whose sole function is to prevent dissemination of toxic materials should be considered separately.

However, regardless of charge classification, a cost analysis should be attempted since these figures would apply equally well to another system where everything but the recovery value of the dust is the same.

It is proposed that each site investigate only representative air and gas cleaning systems for typical operations. However, if one particular installation appears to be well out of line with respect to both average cost and performance, the unusual features should be described.

Insofar as possible, results of the survey will be presented by the nature of the operation upon which the collector is installed without reference to location.

At present there appears to be a universal agreement on the necessity for an economic survey of air and gas cleaning operations within the AEC. However, the problem of time and manpower allocations at the various sites still presents a stumbling block.

Since authorization from plant management will be required in most cases for extensive participation, the Division of Reactor Development is planning to contact site managers and operators to formulate a practical approach.

The benefits to be derived from a comprehensive survey are summarized below.

1. The AEC and contractor groups will obtain a clearcut picture on the actual cost of air and gas cleaning operations.

2. Evaluation of cost and performance data will permit selection of optimum cleaning techniques for new operations and elimination of unsatisfactory methods for existing operations.

3. Compilation of survey results in the form of a manual will permit a reasonable estimate of the cost and air cleaning problems associated with the forthcoming application of nuclear engineering in the field of private industry.

4. Examination of total costs may indicate that a centralization of responsibility for the handling of air cleaning problems may in itself lead to considerable savings.

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BASIC INFORMATION REQUIREMENTS FOR
ECONOMIC SURVEY OF AIR AND GAS CLEANING
OPERATIONS WITHIN THE ATOMIC ENERGY COMMISSION
(Tentative Outline)

Descriptive and Operational Data

I Descriptive data

- A Manufacturer
- B Trade name
- C Cleaner classification and type
  - 1 Roughing or precleaning
    - a Oil coated metal screens, ribbon, expanded metal
    - b Coarse fiber-bulk or preformed glass, mineral, metal, synthetic
    - c Low efficiency paper
    - d Electrified fiber media
    - e Wet cell washers
    - f Wet scrubbers, water or chemical
    - g Others
  - 2 High efficiency precleaner or final cleaner
    - a Low voltage, 2 stage electrostatic precipitator
    - b High voltage electrostatic precipitator
    - c Fiber bed, bulk or preformed
    - d Woven and felted fabrics
    - e Deep bed sand or fiber filters
  - 3 Ultra (Absolute) filter, CWS or AEC types
    - a Cellulose asbestos
    - b All glass

II Operational data

- A Site application
  - 1 Prefilter, supply air
    - a General ventilation
    - b Special hoods
    - c Process air (cooling)
    - d Other
  - 2 Precleaning, exhaust air
    - a Laboratory, level, isotope
    - b Production areas
    - c Other
  - 3 Final cleaning, exhaust air
    - a Laboratory, level, isotope
    - b Production area
    - c Other
  - 4 After cleaning, exhaust air
    - a Emergency system
    - b Special applications
  - 5 Product recovery
- B Cleaning requirement and process
  - 1 Dust, mist, fume, vapor removal, also rare gases
  - 2 Aerosol composition

3 Particle size characteristics
4 Concentration, weight or activity/unit volume of gas

C Space requirements

1 Over-all dimensions (unit collectors) and capacity, cfm, or with parallel or banked units
2 Cubic feet per cfm cleaning capacity
3 Face area per 1000 cfm cleaning capacity

D Operating characteristics

1 Filtering velocity, fpm
2 Pressure loss, inches water

a Initial (clean filter)
b Maximum allowable before removal or cleaning

3 Power requirements, hp per 1000 cfm air

a Fan system
(1) Based on cleaner pressure loss only
(2) Based on entire system, including other cleaning devices and hood, duct, and stack system
b Water sprays or scrubbing liquid, pump hp per 1000 cfm air
c Electrical power, electrostatic precipitators kw per 1000 cfm air

4 Cleaner service life

a Before cleaning or replacement, or
b Mechanical overhaul

5 Operating temperatures and humidities

6 Water or scrubbing liquid volume, gallons per 1000 cfm air

a Spray nozzle type and pressure, lb per sq in., gage
b Per cent recycle
c Chemical requirements, lb of reagent per 1000 cfm air

7 Collection efficiency, weight and activity basis

E Method of replacement or cleaning of media

1 Washing, steam cleaning
2 Washing and reoiling
3 Replacement of filter media, i.e., airmat paper, felt bags
4 Replacement of complete package unit, i.e., Dust Stop, AEC filter
5 Vacuum cleaning
6 Other

F Criteria for cleaner changes

1 Pressure loss
2 Activity
3 Time cycle
4 Other, including mechanical failure due to erosion, corrosion, or chemical attack, or due to faulty design or application
5 Who determines criteria for maintenance? Health Physics Dept., Engineering Dept., Industrial Hygiene Dept., Maintenance Dept., or other

G Handling and disposal methods

1 Personnel protection
2 Packaging
3 Baling
4 Incineration
5 Burial or storage

H Comments, relative to above items

1 Reason for selection of any one type of cleaner
2 Is this device satisfactory as to quality of cleaning, over-all cost?

3 Suggestions for improving performance based on field experience
4 Recommended research

Gas Cleaning Costs

Note: Equipment and replacement parts should be defined in terms of purchase price. Freight charges should be given separately. Installation charges, if not included in collector price, and all labor costs arising from maintenance repair, inspection, etc., should be expressed in terms of man-hours per 1000 cfm/yr. Indicate labor category, such as laborer, millwright, technician, and health physicist.

III Equipment charges, average yearly costs

A Initial collector cost (separate from freight costs), including filter frames, \$'s/1000 cfm not including fan, or duct work, or installation; unless some special factors involved such as sprays in duct system, special materials or linings, etc., - explain

B Item A based on 5- to 10-year write-off, \$'s/1000 cfm/yr. Indicate write-off period and explain

C Replacement parts, over-all yearly cost, \$'s/1000 cfm/yr

1 "Throwaway" filters, roughing type
2 "Ultra" filters, AEC type
3 Replacement media
4 Filter bags
5 Other

D Replacement parts, item C cost/standard replacement unit

IV Labor charges, over-all yearly cost

A Installation over and above equipment cost, based on equipment write-off period, man-hours/ 1000 cfm/yr

B Routine maintenance and inspection, man-hours/1000 cfm/yr

C Cleaning or replacing filter media, man-hours/1000 cfm/yr

D Handling and disposal, man-hours/1000 cfm/yr

E Labor charges, individual filter replacement, man-hours/1000 cfm/yr

1 Cloth bags
2 Absolute filters
3 Other

F Costs associated with clean out and repair of hoods, duct work decontamination pertaining to maintenance, etc., man-hours/1000 cfm/yr

G Miscellaneous costs

1 Average cost of lost production due to equipment downtime or exhauster
2 Fan maintenance
3 Costs of air cleaning as per cent of total plant maintenance cost
4 Indirect costs: How much of the time and/or labor in equipment's failure or maintenance is hidden in other departments and not directly charged to the collector maintenance: for example engineering, health physics, maintenance, etc.

AIR CLEANING COSTS—A STUDY OF THREE SYSTEMS

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1 INTRODUCTION

It is evident that, as experience is gained in all phases of handling radioactive materials, the expense of experimentation can no longer be justified in the cost of a basic facility. This is true of air cleaning facilities, but if unsatisfactory experiments are not to be repeated, the operating experience with the air cleaning facilities installed in the early days of the atomic energy industry must be reported. The purpose of this paper, therefore, is to detail experiences and costs in operating three of the earlier air cleaning facilities that were designed for the Los Alamos Scientific Laboratory for DP West Site, CMR Building, and Ten Site. These systems, with some modifications which will be discussed, are still in use, and they cover air cleaning problems of aerosols from plutonium oxides and salts, chemical and metallurgical research, and beta-gamma activity.

2 METHOD OF PRESENTATION

Each system is described in detail and the nature of the original problem discussed. The cost of air cleaning per cubic foot per minute per year is developed from three factors: depreciation, operation, and maintenance.

The depreciation factor consists of two items: (1) the estimated depreciation of the air cleaning system, and (2) the depreciation of the building housing the unit. These figures are estimates but will indicate two important features of the systems, namely, the expected life of the system based on close observation and the floor area provided for housing the units.

The operating cost item includes computations for the cost of renewing the air cleaning media; utilities, including waste disposal; and health services. The labor cost shown will be the actual cost of labor chargeable to the item by the service company serving the town of Los Alamos and the Laboratory. Because most servicing and repair must be done after the regular working hours, much of the labor is overtime, plus hazard pay for the skilled crafts.

Utilities are charged at the established rates for the Los Alamos Scientific Laboratory: \$0.27 per 1,000 gallons of water; \$0.007 per kilowatt-hour of electrical energy; \$0.90 per cubic foot for collection and burial of radioactive dry trash;[1] \$0.009 per gallon[1] in the case of CMR Building, and \$0.01 per gallon in the case of Ten Site for disposal of radioactive liquid waste.

The cost of health services is based on the number of man-hours, estimated from experience, necessary to cover each individual job. This item obviously will be largely dependent upon the number of workers employed to accomplish the task and the manner in which it is done, but the time estimate should be reasonably correct for any reasonable approach to the job. The cost per man-hour of monitoring has been set at \$5 by LASL, under the cost allocation system used here.

The maintenance item is the cost of repairing pumps, water lines, and other apparatus connected with the air cleaning system. It is the maintenance engineer's best estimate based on actual operating experience. The cost may appear high but, again, overtime and hazard pay is a consideration.

Table 1 summarizes costs for all three systems which are also discussed individually.

3 AIR CLEANING FACILITY FOR DP WEST

DP West is the LASL's plutonium facility engaged in the formation of plutonium metal from its salts, fabrication of the metal, and recovery of the metal. Consequently, the aerosol consists of plutonium oxides and salts. The air cleaning system to handle this plutonium aerosol was designed, however, at a time when the designer could not be told it was to remove plutonium from the air. It is reasonably certain that the design criterion was for a metal fume of extreme toxicity. When the threshold limits for nonradioactive poisonous materials, which are in the 1×10^{-1} mg/m^3 range, are compared to that for plutonium of 1×10^{-8} mg/m^3, it is reasonable to suppose that the thinking of the designer could have been wrong by several orders of magnitude in this respect.

Table 1—SUMMARIZED ANNUAL COSTS OF AIR CLEANING

System	Depreciation	Operation	Maintenance	Total cost	Flow rate, cfm	Cost per cfm
DPW						
Electro-Matic	$15,690	$4,450	$10,700	$30,840	184,000	$0.17
PL-24	1,760	10,250	1,500	13,510	184,000	0.07
Combined	17,450	14,700	11,700	43,850	184,000	0.24
CMR	6,830	12,660	4,140	23,630	35,000	0.68
Ten Site	9,970	8,820	6,040	24,830	27,600	0.90

The system as originally installed consisted of the American Air Filter Electro-Matic unit followed by PL-24, 10-ply paper filters. Sufficient units were installed to handle 184,000 cfm at half of rate air cleaning capacity. (See Fig. 1.)

Inasmuch as the Electro-Matic units were taken out of service in 1949, very little data on their operation are available. The units were discontinued, because of the required maintenance, when Absolute type filters became available for air filtration at the source of contamination. The PL-24 filters have been continued in service, however, to serve as a backup for prefiltered air and a minimum filtration for exhaust air that is not prefiltered. The efficiency of the PL-24 filters is approximately 60 per cent for the plutonium aerosol which ranges in median size from 0.3 to 1.0 μ with a standard deviation of 1.5 to 3.

4 DP WEST AIR CLEANING COSTS

The cost figures for the air cleaning systems at DP West are summarized in Table 1 and detailed below.

4.1 Depreciation

For the purpose of establishing the influence of the initial costs in the cost for air cleaning per cubic foot of air per minute, the initial cost of the air cleaning equipment has been estimated. The American Air Filter Electro-Matic unit's initial cost was estimated[2] at $400 per 1,000 cubic feet per minute rated capacity and the useful life set at 10 years. For a system of 184,000 cfm at one-half capacity, the total initial cost would be $147,200 and the annual depreciation $14,720.

The initial cost for the PL-24 filters was computed on the basis of $50 per cell installed. Thus, the annual cost of 315 cells with an estimated system life of 20 years is $790.

4.2 Occupancy Charge

The occupancy charge is based on the square foot of building space that logically could be assigned to the air cleaning units. The cost of such space is estimated at $10 per square foot with a 20-year depreciation period. In this case, the Electro-Matic and PL-24 units each occupy a space 97 by 20 ft. The annual occupancy charge is, therefore, estimated at $970.

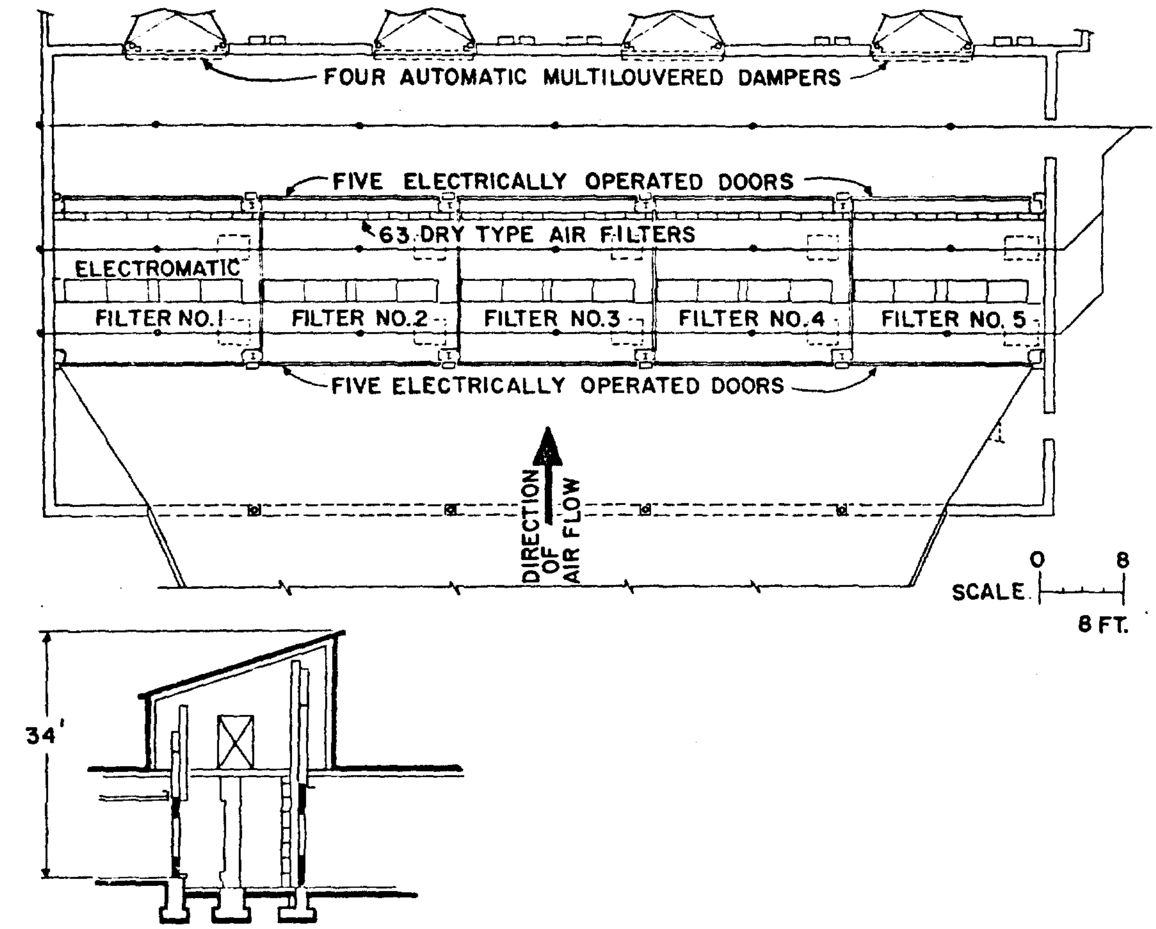


Fig. 1—DP West air cleaning facility.

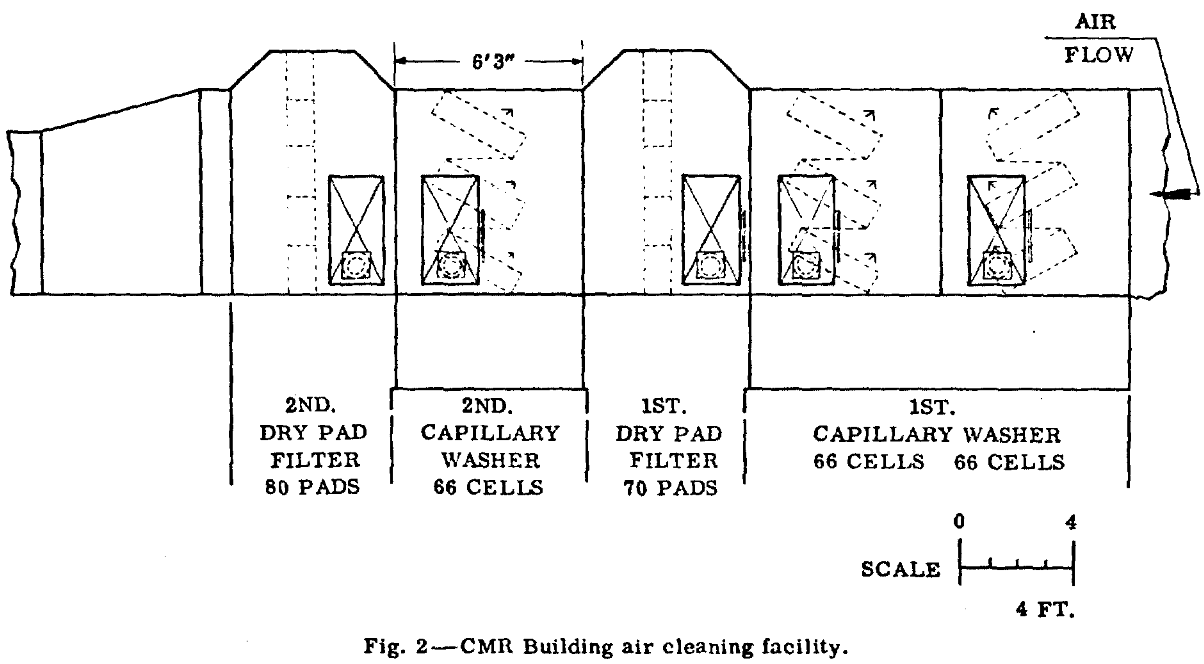


Fig. 2—CMR Building air cleaning facility.

4.3 Operating Costs

The operating cost for the Electro-Matic units has to be estimated since the units were taken out of service in 1949. The estimated annual electrical operating cost, including the power pack, of $450 is derived from the Handbook on Air Cleaning[2] and adjusted for power costs of $0.007 per kilowatt-hour, 8,760 hours per year operating time, and 184,000 cfm. The last year in which the Electro-Matic units were operated, the total cost of maintenance and operation was $13,135. Of this amount it is estimated that about $4,000 could be charged to operation.

The operating costs for the PL-24 filters operating without the Electro-Matic units are available in detail. It has been found that for operating reasons the filters must be changed three times a year. The cost of each filter change at present Los Alamos prices is as follows:

1. Material	
40 rolls of PL-24 10-ply paper, at $7 per roll	$ 280
2. Labor	
32 man-hr at straight time	
143 man-hr at hazard pay (straight time + 10 per cent)	
113 man-hr at double time	
Total labor	1,912
Zia Company overhead charge at 7 per cent	152
3. Health services	
Equipment (coveralls, boxes, etc.)	300
Monitoring, 130 man-hr at $5 per hour	650
4. Waste disposal	
100 cu ft, at $0.90 per cubic foot	90
Total	$ 3,384
5. Total annual cost	
(3 filter changes per year)	$10,152

The electrical operating cost computed on the basis of a pressure drop of 0.05 in. water, exhaust rate of 184,000 cfm, 8,760 hr of operation per year and $0.007 per kilowatt-hour, amounts to $100 per year. Total annual operating cost for the PL-24 filters alone is, therefore, $10,250.

4.4 Maintenance

As stated above the total cost of maintenance and operation for the Electro-Matic units was $13,135. Approximately $9,200 of this amount could be attributed to maintenance. Health services for this amount of maintenance have been estimated at approximately $1,500. The total annual maintenance, therefore, amounts of $10,700.

Maintenance on the PL-24 filters would be limited to maintenance of the filter housing and appurtenances. After 10 years about 100 frames need replacing, and it is estimated that 400 frames will be replaced in the 20-year life of the system. Actual cost of the frames is $31.27 and the estimated cost per frame installed in place is $50. The annual cost of replacing frames, therefore, could be set at $1,000. The cost of miscellaneous maintenance together with necessary health services would also approximate $500 and the total cost of maintenance would be $1,500 per year.

In summary, it can be stated that the figures for the PL-24 filters accurately reflect the cost of operating ($10,250) and maintaining ($1,500) the filters. The figures for depreciation ($790) and occupancy ($970) are believed to be reasonable estimates. The total annual cost for the PL-24 filters, therefore, is $0.07 per cubic foot per minute, and of this the operation and maintenance cost is $0.06 per cubic foot per minute.

If the estimates and known costs for operating the Electro-Matic units are added to the PL-24 filter cost, the total annual cost is $0.24 per cubic foot per minute.

5 CMR BUILDING

The CMR Building is a large laboratory devoted to radioactive chemical and metallurgical research. It was originally thought that the air cleaning systems would have to handle exhaust air containing plutonium and uranium (U^{235}) in every possible dispersoidal form and in such quantity as to be economically feasible to recover. There was also considerable concern that the anticipated quantity of acid fumes in the effluent might create a nuisance. It was believed, therefore, that a wet air cleaning system would aid in the recovery of fissionable metals, prevent the emission of acid fumes, and be more economical to operate and maintain. Unfortunately, none of these presumptions has been borne out. The increased supply of fissionable material has reduced the value of recovery operations, and the advantages of wet recovery over dry recovery are not pronounced. The amount of acid fumes released to exhaust air did not create a nuisance problem, nor is it anticipated that it will. Actual operation of the systems has indicated that the original estimate of operation and maintenance costs was completely unrealistic.

The system as designed for the CMR Building is shown in Fig. 2. The air first passes through two wet pads. The wet pads consist of a random pack of 300-μ glass fibers packed 6 lb/cu ft in a 20- by 20- by 8-in. cell. The first bank of cells is sprayed countercurrent and the second bank sprayed concurrent at the rate of 8 gal/min/cell. The air next passes through zigzag water eliminator plates before being filtered by dry pads. The dry filters consist of $1\frac{1}{2}$ in. of 100-μ glass fiber pad plus a $\frac{1}{2}$-in. pad of 10-μ glass fibers. The air then passes through another wet washer of 300-μ glass fiber sprayed concurrently, then eliminator plates, and finally another dry pad identical to first dry filters.

6 CMR BUILDING AIR CLEANING COSTS

The cost figures for a CMR Building air cleaning system are summarized in Table 1 and detailed below.

6.1 Depreciation

In 1950 the installation cost of the CMR Building system was $2.40 per cubic foot per minute and each system exhausted 35,000 cfm. Total cost, therefore, was $84,000 for each of the ten systems. The estimated useful life of the system, if operated as designed, is 15 years. The depreciation per year, therefore, would be $5,600.

6.2 Occupancy Charge

The amount of floor space that logically could be assigned to the air cleaning unit is 56 by 44 ft, or 2,464 sq ft. At $10 per square foot depreciated over a 20-year period, the occupancy charge per year is $1,232.

6.3 Operating Costs per System

The unit costs for changing the air cleaning media are as follows:

1. Wet cells		
Cost per cell for changing (material $12, labor $3)	$15	
Total number wet pads per system	198	
Expected life of wet pads	2 years	
Annual cost for changing wet pads		$1,485
2. Dry pads		
Cost per pad for changing (material $2, labor $2)	$4	
Total number pads	150	

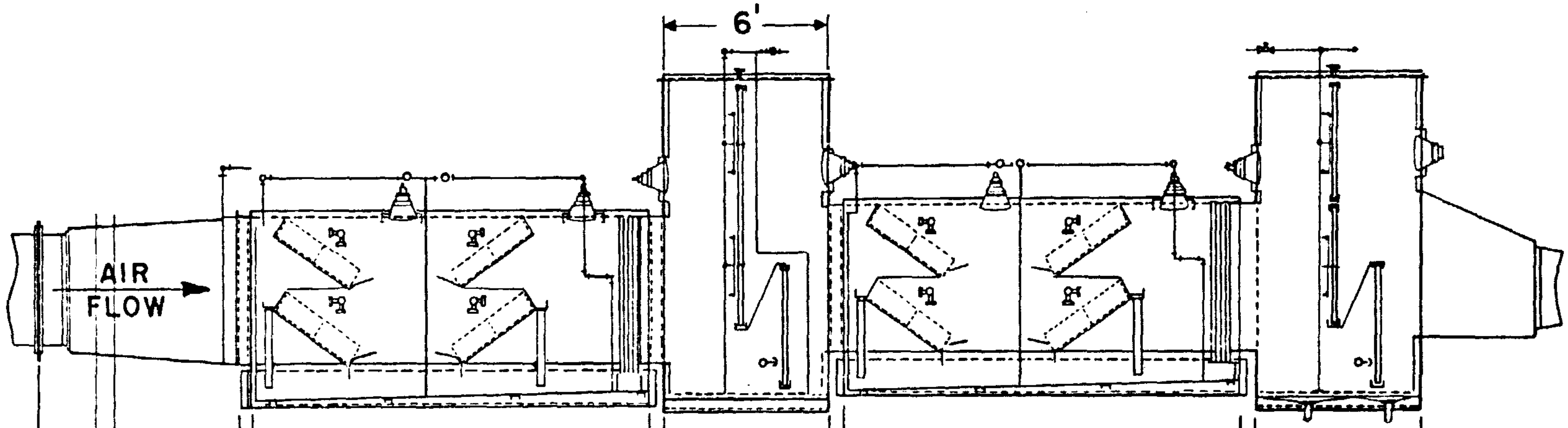
Expected life of pads, 1st bank (70)	1 year	
2nd bank (80)	2 years	
Annual cost for changing dry pads		$ 440
3. Utilities		
a. Water		
Evaporation, 1.5 gpm	8,760 hr/year	
Bleed off, 1.5 gpm	8,760 hr/year	
Cost of water	$0.27 per 1,000 gallons	
Annual cost of water		$ 425
b. Electrical		
3 pumps, 15 hp	8,760 hr/year	
Pressure drop through system	1.75 in. water	
Air flow rate	35,000 cfm	
Fan efficiency	65 per cent assumed	
Cost of electrical power	$0.007 per kilowatt-hour	
Annual cost of electrical power pumps	$2,050	
Pressure drop	$ 690	
Total annual electrical cost		$2,740
c. Waste disposal		
Liquid waste volume, 1.5 gpm	8,760 hr/year	
Cost of waste treatment	$0.0093 per gallon	
Annual cost of liquid waste	$7,332	
Dry waste volume	200 cu ft	
Cost of collection and burial	$0.90 per cubic foot	
Annual cost of dry waste disposal	$180	
Total annual cost of waste disposal		$7,512
4. Health services		
Wet pad changes	8 man-hr/year	
Dry pad changes	4 man-hr/year	
Cost of health services	$5 per man-hour	
Total annual operating health costs		$ 60
5. Total annual cost of operation		$12,662

6.4 Maintenance Cost per System

1. Water nozzle cleaning	6 times/year	
Labor	$3,000	
Water – 8,000 gal draw and fill 6 times per year	$20	
Waste disposal, 48,000 gal	$450	
Health services, 24 man-hr at $5 per hour	$120	
Total		$3,590
2. Miscellaneous maintenance		
Cost per year		$ 500
Health services		$ 50
3. Total annual cost of maintenance		$4,140

It should be mentioned that the actual annual cost of operation and maintenance per system is $16,800 or $0.48 per cubic foot per minute as compared to an original estimated cost of $1,730 or $0.05 per cubic foot per minute.

The total annual cost per system including depreciation is $23,630 or $0.68 per cubic foot per minute.



	INTAKE DUCT	CAPILLARY NO. 1		DRY PAD FILTER 1	CAPILLARY NO. 2		DRY PAD FILTER 2
SYSTEM NO.	EXHAUST VOLUME	NO. OF WET PADS		NO. OF DRY PADS	NO. OF WET PADS		NO. OF DRY PADS
E-11	12,000 CFM	24	24	18	24	24	12
E14, E15	4,800 "	8	8	6	8	8	6
E12, E13	3,000 "	5	5	4	5	5	4

Fig. 3—Ten Site air cleaning facility.

The main operating problem in connection with this system was the plugging of the nozzles. This was caused by short lengths of the 300-μ glass filaments becoming suspended in the recycled spray water, and eventually sealing the nozzles completely. As noted in the analysis of cost, this difficulty required draining the system and cleaning the nozzles every 2 months. Efforts to strain the glass fibers were never very successful, since the fibers would become so oriented as to pass coarse filters and would mat over a fine filtering device. The water supply for Los Alamos contains 200 ppm total dissolved solids, but even with this relatively low percentage of solids, the recycled water became highly concentrated. It became evident that to prevent undue plugging of the wet washers and faster plugging of the spray nozzles owing to salt buildup, it would be necessary to bleed off the concentrated water at the same rate the water was evaporated. Preliminary design considerations indicated that ion exchange system for treating the water would cost $50,000 plus the cost of operation. Because of the cost of operating the wet system, it has been decided to replace all the systems with a type of dry filtration specifically designed to handle the aerosol produced in each specific area of the building.

7 TEN SITE AIR CLEANING SYSTEM

The entire air cleaning facility for Ten Site consists of five separate systems that are identical except for their capacity. The Ten Site air cleaning system as shown in Fig. 3 is essentially the same as the air cleaning system for CMR Building, with the major exception that laboratory liquid waste and the exhaust air are carried in the same duct. There is also an additional bank of wet washers. The waste water is used as the source of spray water for the air washers. This necessitates the incorporation into the combined system of four 50,000-gal storage tanks. In the following cost analysis the depreciation of only one of the tanks is charged to the cost of the air cleaning system, since the other three could logically be charged to liquid-waste disposal.

The system was designed to handle an aerosol with beta-gamma activity, predominantly one resulting from handling barium-lanthanum equilibrium mixture. Thus, although there was no recovery problem in connection with the aerosol, it was thought that the wet washer would be more effective in collecting the Ba-La aerosol which is evolved in an acid fume and, by washing the filter media, reduce the time the air cleaning system would be a source of gamma radiation. The system has accomplished these objectives reasonably well. The main problem in connection with this system was the rather belated discovery that the Ba-La mixture contained small variable amounts of strontium (Sr^{90}) and that the concentration of Sr^{90} present in the waste water was too high for discharge. This meant that a waste-water treatment facility had to be added to the liquid waste-exhaust air system. A proportionate part of the cost of this facility has been assigned to the air cleaning system.

8 TEN SITE AIR CLEANING COST

The air cleaning costs for Ten Site are summarized in Table 1 and detailed below.

8.1 Depreciation

The installation cost for this system has been set at $3 per cubic foot per minute. The total exhaust capacity of all the systems is 27,600 cfm and the expected life is 15 years. The total cost, therefore, would be $82,800 and the annual depreciation $5,520. The cost of the storage tanks has been estimated at $1 per gallon capacity plus $4,000 per tank for appurtenances. The total cost per tank would be $54,000 and, with an expected life of 20 years, the annual depreciation would amount to $2,700.

8.2 Occupancy

The floor area necessary to house the systems is 66 by 53 ft, or about 3,500 sq ft. At $10 per square foot and a 20-year life the annual occupancy charge is $1,750.

8.3 Operating Costs

1. Wet cells		
Cost per pad for changing media (material $12, labor $3)	$15	
Total number of wet pads all systems	200	
Expected life of wet pads	2 years	
Annual cost for changing wet pads		$1,500
2. Dry pads		
Cost per pad for changing (material $2, labor $15)	$17	
Total number of pads all systems	70	
Expected life	2 years	
Annual cost for changing dry pads		$ 595
3. Utilities		
a. Electrical		
9 pumps, 3 hp	8,760 hr/year	
2 pumps, 8 hp	8,760 hr/year	
1 pump, $1\frac{1}{2}$ hp	8,760 hr/year	
Total horsepower hours per year	384,500	
Air flow rate	27,600 cfm	
Pressure drop	2 in. water	
Fan and efficiency	65 per cent assumed	
Annual cost of electrical power		
Pumps	$2,000	
Pressure drop	$ 600	
Total		$2,600
b. Waste disposal		
Liquid waste volume	1,000 gal/day	
Cost of waste treatment	$0.01 per gallon	
Annual cost liquid waste		$3,650
Dry waste volume per year	250 cu ft	
Cost of collection and burial	$0.90 per cubic foot	
Annual cost of dry waste		$ 225
4. Health services		
Wet cell changes	20 man-hr/year	
Dry pad changes	30 man-hr/year	
Cost of health services	$5 per man-hour	
Annual cost of operating health services		$ 250
5. Total annual cost of operating		$8,820

8.4 Maintenance Cost

1. Nozzle cleaning		
Labor per year	$2,000	
Health services (48 man-hr)	$240	
Total	$2,240	
2. Miscellaneous maintenance	$3,500	
Health services	$300	
3. Total annual maintenance cost		$6,040

The annual cost of operating and maintenance for the Ten Site air cleaning facility is $14,820 or $0.54 per cubic foot per minute. The total annual cost, including depreciation, is $24,790 or $0.90 per cubic foot per minute.

9 SUMMARY

In connection with these three systems, it should be mentioned that their efficiencies and loadings are comparable and that the dry filtration system is serviced more often than normal, while the wet system would be in definite need of servicing at the end of the time intervals noted for changing pads and nozzles. Consequently, there is some danger that the cost variation between the wet systems and the dry system, detailed above, might be construed as more significant than is really justified. It should be stressed, therefore, that the cost analysis presented in this paper only compares one type of wet air cleaning with one type of dry air cleaning.

The variations in cost between the wet and dry systems, and the discrepancy between the original estimate of expected operating and maintenance cost and the actual cost of these factors does indicate that there are factors of cost involved in a wet air cleaning system that should receive careful consideration prior to adopting such a system. At Los Alamos, we feel that wet methods of air cleaning are inherently more expensive than dry filtration and that, unless the unique properties of wet collection are required by the nature of the aerosol, dry filtration is generally preferable.

The desirability of designing the air cleaning system so that air cleaning media can be readily changed is emphasized by the $15 labor charge per dry pad change in the Ten Site system. In this case, the dry pads are held in place by an unduly complicated method. The matter of requiring men to enter highly contaminated areas in protective equipment to change filter media should also receive more attention. The men generally earn hazard pay and must work at a slower rate in such a situation.

ACKNOWLEDGMENT

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STUDY OF THE FUNDAMENTAL PEROPERTIES OF AEROSOLS

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The work on the project has been retarded during the past year because of illness of the Director who has been on disability leave from the University since September 1956. He has, however, been able to direct the work of three part-time research assistants and some things have been accomplished that may be of practical interest and value in the control of aerosol problems in nuclear energy plants. These will be described briefly here and reported in detail in forthcoming technical reports.

A complete theoretical analysis has been made of the effect of electrostatic charges on the deposition of aerosols on cylindrical collectors. The work supplements that reported two years ago on spherical collectors which was published in a paper by H. F. Kraemer and H. F. Johnstone.[1] The cases studied include those in which an electrostatic charge exists on the aerosol particles or on the collector, or both. Experimental studies were made which verify the theoretical conclusions. These included measurements on the filtration of charged aerosol particles and filtration by tangled wire dipole mats and by charged filter mats. These devices have been suggested as means of improving the filtration of very small aerosol particles. The results show that the existence of a charge either on the particles, or on the filter mat, increases the filtration efficiency, but the charge on the mat must be maintained in some way. Several methods of doing this have been suggested and still others are suggested by the work.

It has been interesting to find that when charged aerosol particles are collected on glass fiber filter mats the efficiency increases at first, passes through a maximum, and gradually decreases with time.

A brief study was made on the removal of aerosol particles from gases by means of pellets charged electrostatically by pneumatic conveyance through a duct. The work was done on a small 18-in. cyclone equipped with means for introducing the charged pellets at the center of the rotating gas stream. Aerosols of ammonium sulfite and ammonium chloride particles with mean diameters of 1.3 and 0.4 μ, respectively, were used. The pellets were 30- to 100-mesh glass or plastic beads which were circulated at the rate of only 3 to 20 g/cu ft of gas. While the efficiency of the collection of the particles was low, the results show that the device might be developed for large scale use in the filtration of submicron particles in large cyclones. Under such conditions the efficiency appears to increase with larger gas flow and smaller particles. The AEC has indicated interest in filing a patent application on the device.

Experiments were made under similar conditions using charged droplets of water fed to the center of the rotating gas stream. This required high potential and careful insulation of the water system. The device gave higher efficiency of collection of small aerosol particles than either a dry cyclone or a wet cyclone with uncharged droplets.

Further work has been done on the nature of agglomerated aerosol particles consisting of aggregates of unitary particles. Several distinctly different aerosols were used, including uniform spherical primary particles and needle shape particles. The principal result of this work has been the adaptation of the Millikan cell for measurements which provide information on the settling and impactability properties of aerosols which are often encountered in practice. Certain generalizations have been found that may serve as a rough correlation of the properties of aerosol agglomerates.

Brief studies were made on the self-nucleation of the formation of the liquid phase in the condensation of water and alcohol. These studies are important as a basis of using selective nucleation for the control of massive reactions in the atmosphere.

REFERENCE

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