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SOURCE TEST CASCADE IMPACTOR

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Abstract—The source test cascade impactor has been developed for measuring the size distribution of particles in stacks and ducts at air pollutant emission sources. This impactor is inserted inside the duct or stack to minimize tubing wall losses and water condensation problems. The new source test cascade impactors have been used to measure the size distribution of particles emitted from a Kraft pulp mill recovery furnace, a coal fired power boiler, a fluidized bed sewage sludge incinerator, a plywood veneer drier, and an aluminum reduction cell.

Nomenclature

C = Cunningham correction factor
d = particle diameter
d_{50} = particle diameter collected with 50% efficiency
D = diameter of jet (hole in impactor stage)
M = molecular weight of gas
N = number of jets per impactor stage
P = gas pressure
Q = gas volumetric flow rate through impactor
Re_j = Reynolds number of jet
T = gas temperature
V_j = velocity of gas in jet

Greek symbols

λ = mean free path of gas molecules
μ = gas viscosity
π = 3.14159
ρ_p = density of particle
ψ = inertial impaction parameter
ψ_{50} = inertial impaction parameter at 50 per cent particle collection efficiency.

1. INTRODUCTION

THE SIZE distributions of aerosol particles at air pollutant emission sources are needed to:

(1) design new particulate air pollutant removal equipment;
(2) evaluate the performance of existing particulate control systems; and
(3) characterize the aerosol emissions of various sources.

Unfortunately a satisfactory technique for obtaining the size distribution of aerosols at emission sources has not been available. The requirements of a source test particle size measuring system include isokinetic sampling capabilities, prevention of wall losses and vapor condensation, representative sampling, structural ruggedness, low cost and ability to determine the aerosol size distribution. A cascade impactor which can be inserted inside a duct or stack appears to most closely fulfil the above requirements. By operating the impactor inside the duct, true isokinetic sampling can be achieved with a minimum of wall losses and condensation problems. Fortunately the theory of inertial separation of particles by cascade impactors has been developed and verified. Also cascade impactors have been used extensively and a substantial amount of performance data is available.

MAY (1945) reported particle size separation data measured with a cascade impactor having rectangular shaped jets and presented a dimensional analysis relating the impactor stage collection efficiencies to the impactor design variables. LASKIN (1949) added a filter to May's impactor design to collect the particles passing the last impaction stage. FIRST *et al.* (1952) and GUSSMAN and GORDON (1966) reported on a modification of a Casella impactor such that the first impactor stage was located in the probe elbow, thus preventing the loss of large particles to the elbow wall. BRINK (1958, 1963) used a five stage in-line impactor to size particles in the 0.3–3 μm size range. The development of a six stage in-line cascade impactor was reported by MITCHELL and PILCHER (1957). COHEN and MONTAN (1967) evaluated an eight stage multi-jet cascade impactor which they designed for operating flexibility (variable air flow rate and number of stages), sturdiness and fabrication simplicity. ANDERSEN (1958) reported on the development of a six stage multi-jet impactor for sizing airborne bacteria. LIPPMANN (1961) developed a four stage rectangular jet cascade impactor for field survey sampling. PARKER *et al.* (1968) used a low pressure cascade impactor designed for measuring particles in the 0.01 to several micron size range.

Two approaches for interpreting cascade impactor data (effective cut-off diameter and mass mean diameter) have been discussed by MERCER (1965). COUCHMAN and MOSELY (1967) reported a simplified method for determining cascade impactor stage efficiencies.

The theory of inertial impaction of particles has been studied extensively. SELL (1931) determined velocity profiles experimentally and calculated particle trajectories around various shaped objects. ALBRECHT (1931) calculated the particle collection efficiency of simple bodies assuming a potential fluid velocity flow field. Since then inertial impaction studies have been mainly involved with simple body geometries (cylinders, spheres and rectangles) and jets. Theoretical particle collection efficiencies for bodies have been reported by a number of investigators including LANGMUIR and BLODGETT (1945), RANZ and WONG (1952), WONG *et al.* (1955), LEWIS and BRUN (1956) and GOLOVIA and PUTMAN (1962). A concise review of the solution of the equation of motion for particles flowing around an object has been presented by NOLL and PILAT (1970). Theoretical particle collection efficiencies for jet impactors have been reported by DAVIES and AYLWARD (1951) and RANZ and WONG (1952).

2. DEVELOPMENT OF SOURCE TEST CASCADE IMPACTOR

(a) *Recommended design for predictable performance*

After a detailed analysis of cascade impactors, COHEN and MONTAN (1967) recommended that for predictable performance of a round hole multi-jet impactor the design parameters should be in the following range:

1. $Re_{jet} > 100$ (hole length/hole diameter).
2. $V_{jet} > 10$ (terminal settling velocity of particles at stage cut-off of 50 per cent collection efficiency).
3. $Re_{jet} < 3200$ (to remain in Stokes region for particle).
4. $V_{jet} < 1.1 \times 10^4$ cm s^{-1} (incompressible flow region).

5. Hole to plate clearance/hole diameter in 1–3 range.
6. Hole depth/hole diameter ≥ 1.

(b) *Design of source test cascade impactor*

A cascade impactor for use in measuring the particulate size distribution in ducts and stacks at air pollutant sources was designed and constructed at the University of Washington in November 1968. The first model of the source test cascade impactor (Mark I) is a multi-jet six stage impactor which can be inserted inside of a duct or stack through a 3 in. dia. sampling port. A sectional schematic view of the cascade impactor (Mark I model) is illustrated in FIG. 1. A 2 in. diameter filter holder is

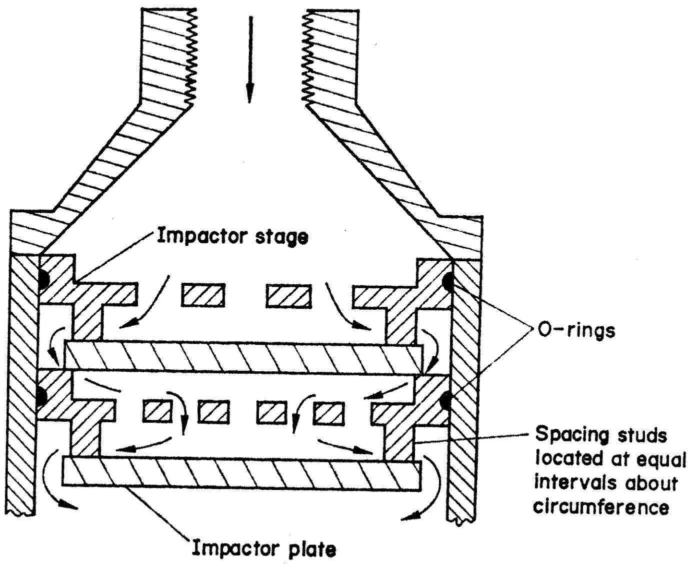

FIG. 1. Schematic of source test cascade impactor (Mark I).

located immediately following the impactor, as shown in FIG. 2. The stages, particle collection plates, impactor inlet section with nozzle, impactor cylindrical shell, and the outlet section are shown in FIG. 3. For each stage the jet depth is 0.05 in. and the hole to plate clearance 0.1 in. The number of jets and the jet diameter for each stage is listed in TABLE 1.

TABLE 1. JET DIMENSIONS OF SOURCE TEST CASCADE IMPACTOR

Stage	Jet diameter (in.)	Number of jets
1	0.120	103
2	0.0595	102
3	0.0370	102
4	0.0280	102
5	0.0210	102
6	0.0135	102

The source test cascade impactor was machined out of aluminum. Seals were maintained around the perimeter of the stages with o-rings.

(c) *Calibration*

The collection efficiency of each impactor stage was calculated in terms of the particle size collected with 50 per cent collection efficiency, d_{50}. d_{50} was assumed to be only a function of the inertial parameter ψ which is defined as:

$$\psi = \frac{C\rho_p d^2 V_j}{18\mu D}. \tag{1}$$

The magnitude of the inertial parameter at the particle size of 50 per cent collection efficiency, ψ_{50} has been reported to range between 0.12 and 0.17 for circular jets based on theoretical and experimental studies. ψ_{50} was assumed to be 0.145 for calibration of the source test cascade impactor. The velocity of the gas in the jets of each stage is calculated by

$$V_j = \frac{4Q}{\pi D^2 N} \tag{2}$$

where Q is the gas volumetric sampling rate, D the jet diameter, and N the number of jets in the stage.

Substituting into equation 1 for V_j gives

$$\psi = \frac{2C\rho_p d^2 Q}{9\pi\mu D^3 N}. \tag{3}$$

Solving for the particle diameter d

$$d = \left[\frac{9\pi\mu D^3 N\psi}{2C\rho_p Q}\right]^{1/2}. \tag{4}$$

Substituting 0.145 for the inertial parameter ψ at 50 per cent collection efficiency gives

$$d_{50} = \left[\frac{2.05\mu D^3 N}{C\rho_p Q}\right]^{1/2}. \tag{5}$$

The Cunningham correction factor C is calculated from the equation by DAVIES (1945)

$$C = 1 + \frac{2\lambda}{d_{50}}[1.257 + 0.40 \exp(-1.10 d_{50}/2\lambda)] \tag{6}$$

where λ is the mean free path of the gas molecules and is given by

$$\lambda = \frac{\mu RT}{0.499 pM \left(\frac{8RT}{\pi M}\right)^{1/2}}. \tag{7}$$

Graphs of calculated d_{50} vs. the gas flow rate Q at various gas temperatures (20 and 400°C) are presented for each of the impactor stages in FIGS. 4 and 5. The variables recorded during a measurement of the aerosol size distribution include the gas sampling flow rate, gas temperature, and gas pressure at the impactor outlet. As the gas pressure drop through the impactor did not exceed 4 in. of mercury and was usually about 10 in. of water, no corrections for pressure changes were made in the calibration calculations. The design and operation parameters of this impactor are

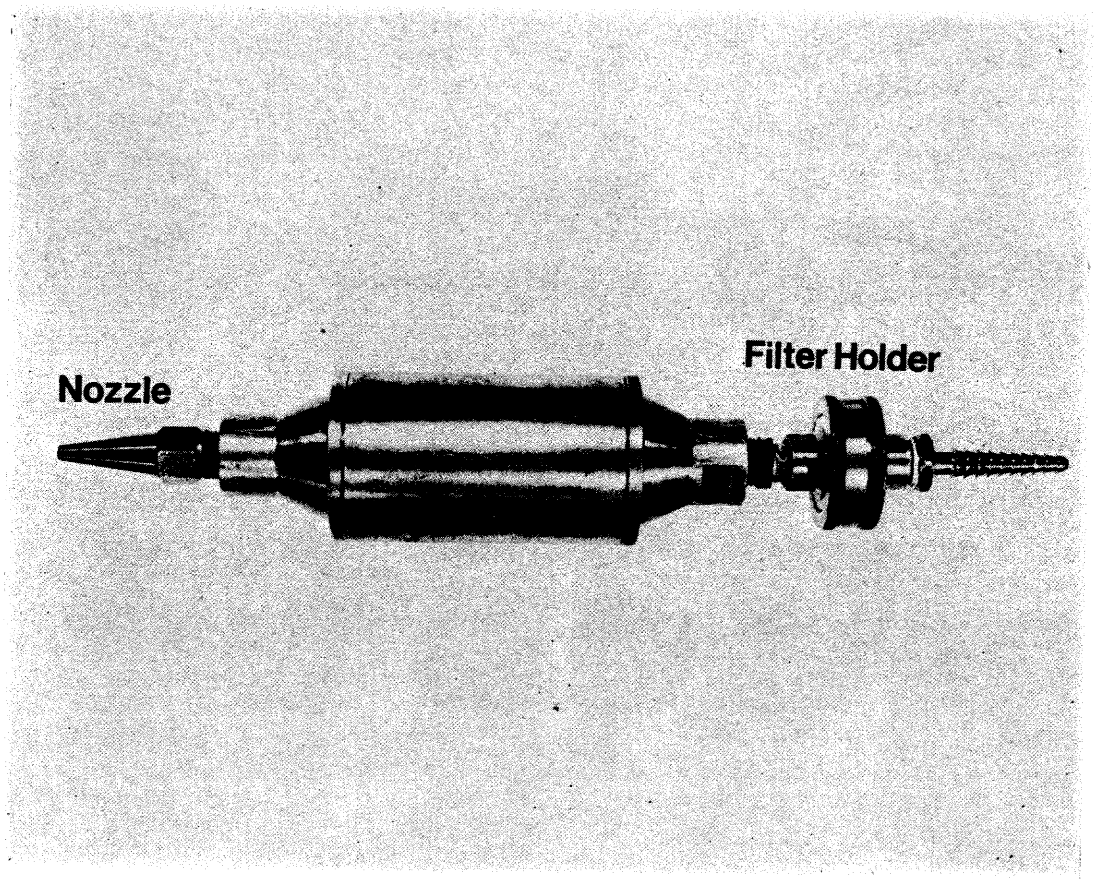

FIG. 2. Source test cascade impactor (Mark I).

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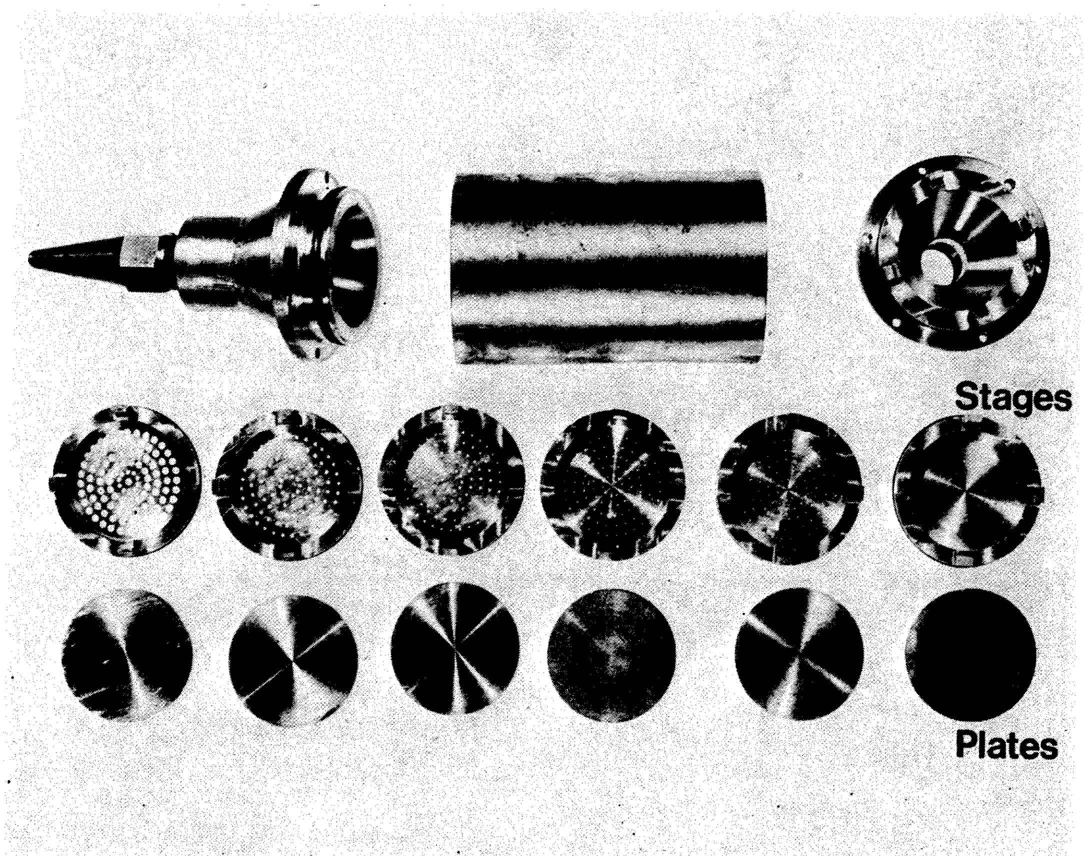

FIG. 3. Impactor parts (Mark I).

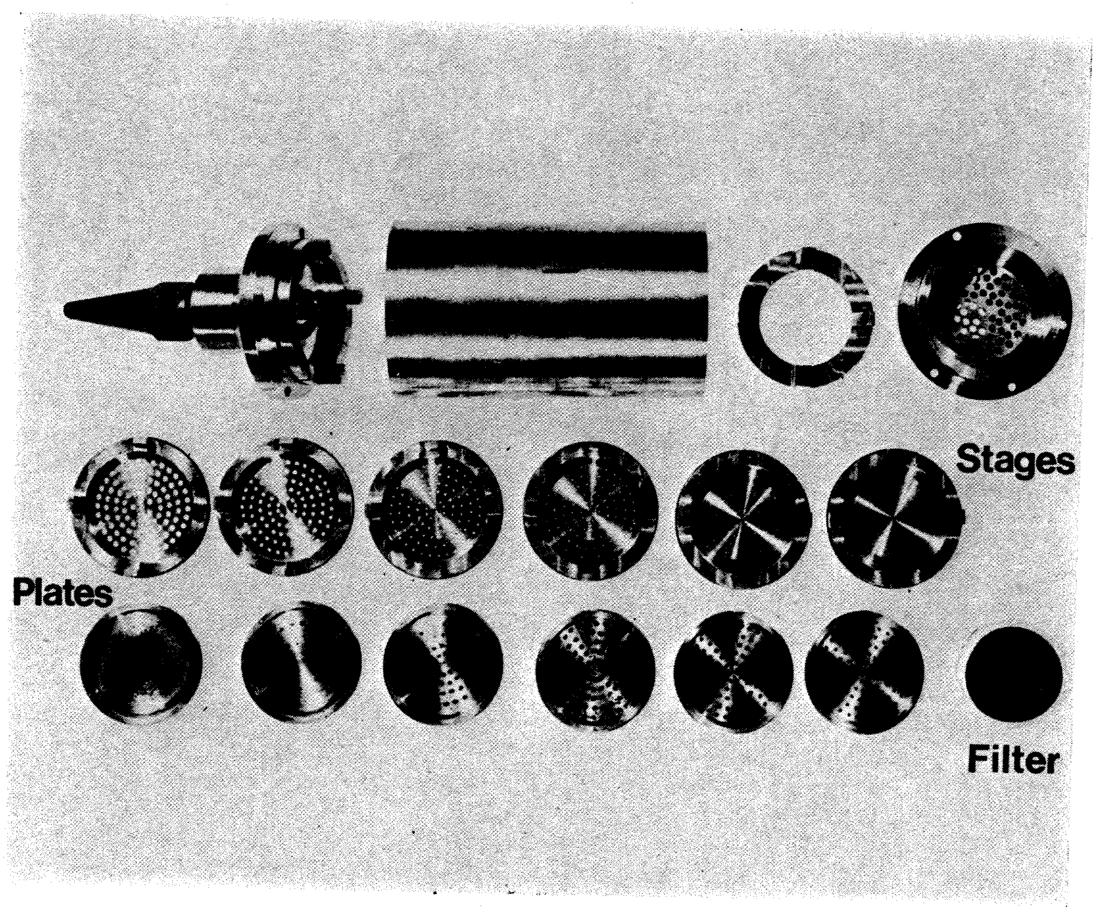

FIG. 9. Mark II source test cascade impactor.

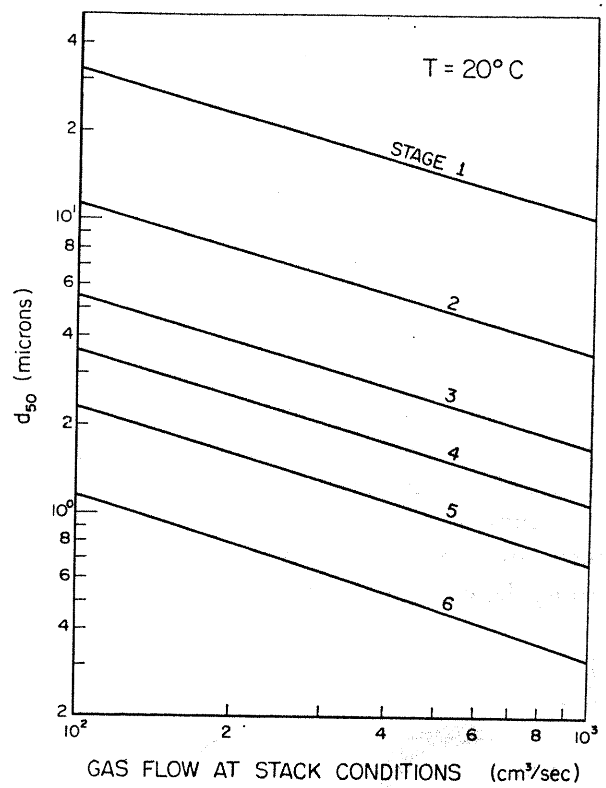

FIG. 4. Calculated d_{50} of stages at 20°C (Mark I).

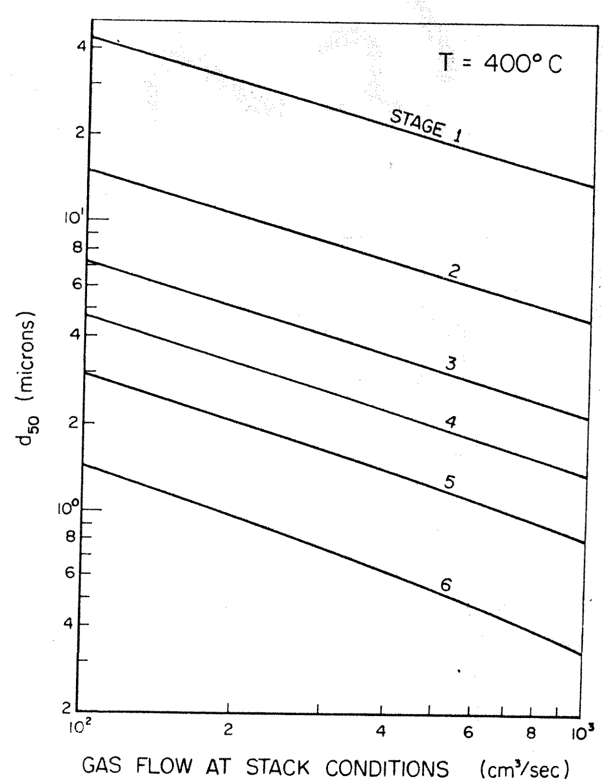

FIG. 5. Calculated d_{50} of stages at 400°C (Mark I).

approximately in the range suggested by COHEN and MONTAN (1967) for predictable performance. For fabrication simplicity the hole to plate clearance and hole depth are the same for all stages which causes the hole to plate clearance/hole diameter ratio to range from 0.8 to 7.3 and the hole depth/hole diameter ratio to range from 0.42 to 3.7. The source test cascade impactor calibration was experimentally verified using aerosols of 1.9 and 3.5 μm dia. Dow latex spheres sampled at various flow rates (all at room temperature).

3. FIELD USE EXPERIENCE

(a) *Sampling procedure*

The entire size distribution measurement includes three phases; pre-test preparation, source test sampling of the particulates, and the analysis of the collected samples. The pre-test preparation includes cleaning the impactor, placing a thin layer of grease (Dow Corning high vacuum silicone grease) on the impactor plates if solid particulates are to be sampled, and weighing the plates (to about 0.1 mg). The source test involves first determining the gas velocity profile in the duct (measure gas temperature

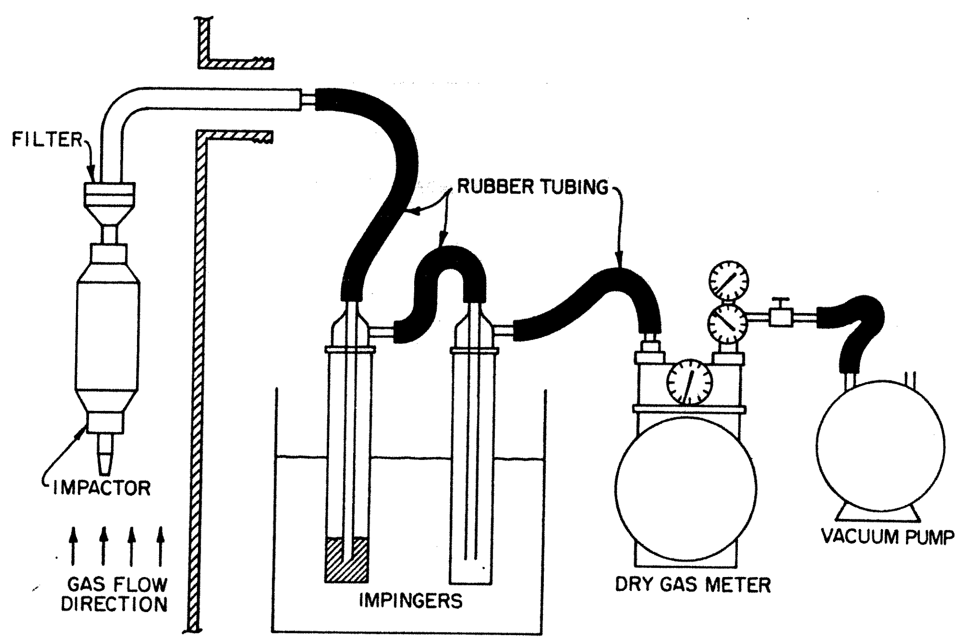

FIG. 6. Impactor sampling train.

and pressure drop profile with type S pitot tube) and then calculating the nozzle size for isokinetic sampling. The sampling train is set-up including the cascade impactor followed by a 2 in. diameter glass fiber filter, a sampling probe, 2 ice-cooled Greenburg–Smith impingers, a dry gas meter, and a vacuum pump, as shown in FIG. 6. The source test cascade impactor followed by the filter was pre-heated to prevent condensation problems by placing it into the stack with the nozzle faced downstream for about 10 min prior to sampling. Then a particulate sample was obtained by facing the impactor nozzle upstream and turning on the vacuum pump. The sampling time, the air temperature and static pressure at the dry gas meter, and the gas volumetric readings were recorded. After obtaining the particulate sample the impactor was disassembled and the impactor plates weighed. The weights of the particles collected on each stage are used to calculate a cumulative particle size distribution.

(b) *Particle size distribution measured*

The Mark I six stage source test cascade impactors have been used to measure the size distribution of particles emitted by a coal fired power boiler, a kraft pulp mill recovery furnace, and a plywood veneer drier. The particle size distributions measured at the University of Washington Power Plant are presented in FIG. 7. The tests were

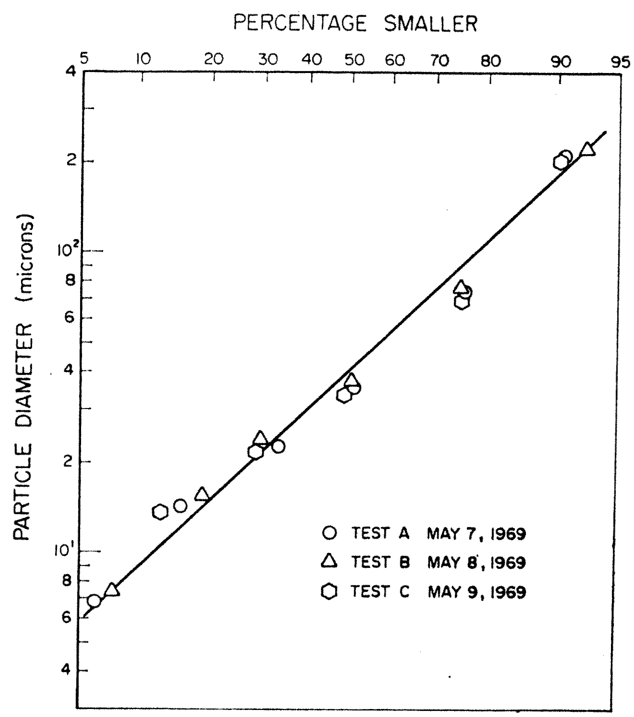

FIG. 7. Size distribution of emissions from coal fired power boiler at University of Washington.

conducted in a 4 by 5 ft duct downstream of a primary settling chamber and near the entrance to an electrostatic precipitator. The flue gases in this duct consisted of the emissions from boiler 4 (natural gas fired) and boiler 3 (pulverized coal). The particle density was assumed to be 2 g cm^{-3} which is approximately the magnitude reported by SMITH and GRUBER (1966) for flyash.

The particulate size distribution measured at the inlet and outlet of an electrostatic precipitator on a kraft pulp mill recovery furnace (St. Regis Paper Company, Tacoma, Washington) is shown in FIG. 8. Note that the particles are larger in the precipitator outlet than the inlet. WHITE (1963) reported that this phenomenon is due to the re-entrainment of particles off the precipitator collection plates, the larger particles being re-entrained preferentially because of their greater aerodynamic drag.

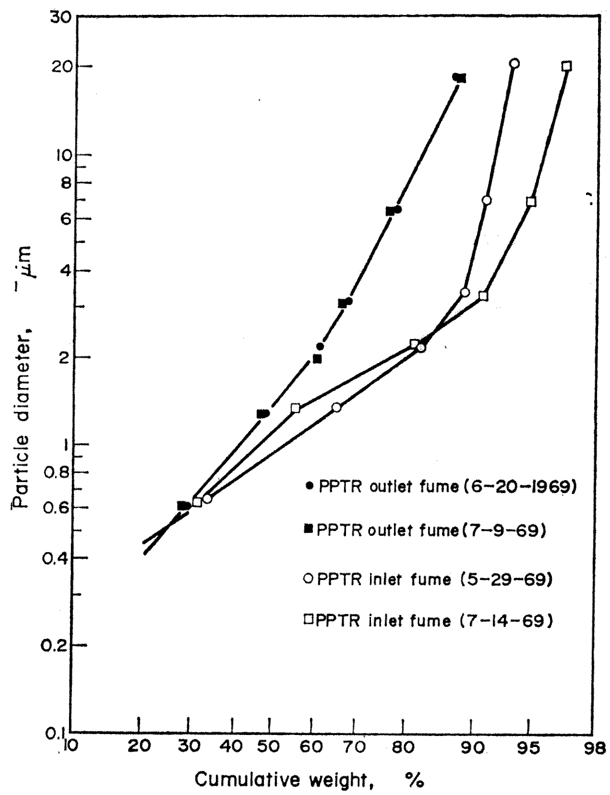

FIG. 8. Size distribution of particles at inlet and outlet of electrostatic precipitation on a kraft pulp mill recovery furnace.

4. DISCUSSION

The performance of the Mark I Source Test Cascade Impactor appears to be satisfactory. However, with the Mark I models there is some problem with the loss of particles onto the top of the first stage of jets (particles too large to follow the gas streamlines through the jet holes in the first stage) and with wall losses between the stages. The particle weight concentration measured by the Mark I Source Test Cascade Impactors and by sampling with a fiberglass lined alundum thimble filter at a coal fired power plant (upstream of an electrostatic precipitator) were approximately the same if the particles on the first jet stage and the impactor walls were included (the losses to the first plate and the walls ranged from 17 to 40 per cent by weight).

A Mark II source test cascade impactor has been constructed which includes placing the filter inside the impactor and a first stage consisting of a single jet. As shown in Fig. 9 the Mark II impactor includes seven stages (a single inlet jet stage, six multi-jet stages) followed by a filter. The single jet of the inlet nozzle (first stage) eliminates the problem of particle loss upon the top of the first multi-jet stage. The impactor plates for Mark II have been modified to include a 1/8 in. high rim around the perimeter of the plates to prevent the particles from falling from the plate to the wall. It appeared that a major part of the Mark I wall losses were due to migration of the particles (after impaction during sampling) caused by the bumping around of the impactor during removal from the duct or stack and transportation to the laboratory.

It is concluded that with the source test cascade impactor the introduction of errors due to water condensation and probe, nozzle, and tubing wall losses has been minimized with the straight line gas flow at the impactor inlet, preheating of the impactor, and by eliminating the need to transport the aerosol outside of the duct or stack before the particles are sized.

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REFERENCES

Albrecht F. (1931) Theoretical investigations of dust deposition from flowing air and its application to the theory of the dust filter. *Physik. Z.* **32,** 48; *Tech. Rep.* No. 3, Univ. of Illinois, Urbana, Ill. (1951).

Anderson A. A. (1958) A new sampler for the collection, sizing, and enumerating of viable airborne bacteria. *J. Bacteriol* **76,** 471–484.

Brink J. A. (1958) Cascade impactors for adiabatic measurements. *Ind. Engng Chem.* **50,** 645–648.

Brink J. A. and Patton W. F. (1963) New equipment and techniques for sampling chemical process gases, *J. Air Pollut. Control Ass.* **13,** 162–166.

Cohen J. J. and Montan D. M. (1967) Theoretical considerations, design, and evaluation of a cascade impactor. *Am. Ind. Hyg. Ass. J.* **28,** 95–104.

Couchman J. C. and Moseley H. M. (1967) Simplified method for determining cascade impactor stage efficiencies. *Am. Ind. Hyg. Ass. J.* **28,** 62–67.

Davies C. N. (1945) Definitive equations for the fluid resistance of spheres. *Proc. phys. Soc.* **57,** 259–270.

Davies C. N. and Aylward M. (1951) The trajectories of heavy solid particles in a two-dimensional jet of ideal fluid impinging normally upon a plate. *Proc. phys. Soc.* **B64,** 889–911.

First M. W. *et al.* (1952) *Air Cleaning Studies Progress Report*, NYO-1586, Harvard University.

Golovin M. N. and Putman A. A. (1962) Inertial impaction on single elements. *Ind. Engng Chem. Fund.* **1,** 264–272.

Gussman R. A. and Gordon D. (1966) Notes on the modification and use of a cascade impactor for sampling in ducts. *Am. Ind. Hyg. Ass. J.* **27,** 252–255.

Langmuir I. and Blodgett K. B. (1945) Mathematical investigation of water droplet trajectories. *Gen. Elect.* report RL 225 and Ad 64354.

Laskin S. (1949) in *Pharmacology and Toxicology of Uranium Compounds* (edited by Voegtlin, C. and Hodge, H. C.). McGraw-Hill, New York.

Lewis W. and Brun R. J. (1956) Impingement of water droplets on a rectangular half body in a two-dimensional incompressible flow field. *NACA Rep.* 3658.

Lippmann, M. (1961). A compact cascade impactor for field survey sampling. *Am. Ind. Hyg. Ass. J.* **22,** 348–353.

May K. R. (1945) The cascade impactor: An instrument for sampling coarse aerosols. *J. scient. Instrum.* **22,** 187–195.

Mercer T. T. (1965) The interpretation of cascade impactor data. *Am. Ind. Hyg. Ass. J.* **26,** 236–241.

Mitchell R. J. and Pilcher J. M. (1957) *5th AEC Air Cleaning Conf.* Oak Ridge, Tenn., p. 67.

Noll K. E. and Pilat M. J. (1970) Inertial impaction of particles upon rectangular bodies. *J. Colloid. Interface Sci.* **33,** 197–207.

Parker G. W., Buchholz H. and Martin W. J. (1968) Radioactive aerosol size classification experience with a low pressure cascade impactor. *10th AEC Air Cleaning Conf.* pp. 265–31.

Ranz W. E. and Wong J. B. (1952) Jet impactors for determining the particle size distribution of aerosols, *Am. med. Ass. Archs Ind. Hyg. occup. Med.* **5,** 464–477.

Sell W. (1931) Dust precipitation on simple bodies and in air filters, *Forsch. Geb. Ingen.* **2,** 347; *Tech. Rep.* No. 3, Univ. of Illinois, Urbana, Ill. (1951)

White H. J. (1963) *Industrial Electrostatic Precipitation*, p. 335. Addison Wesley, Reading, Mass.

Wong J. B., Ranz R. E. and Johnstone H. F. (1955) Inertial impaction of aerosol particles on cylinders. *J. appl. Phys.* **26,** 244.