Aerosol Science and Technology: History and Reviews

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About the Cover

The cover depicts an important episode in aerosol history—the Pasadena experiment and ACHEX. It includes a photograph of three of the key organizers and an illustration of a major concept of atmospheric aerosol particle size distribution. The photograph is from Chapter 8, Figure 1. The front row shows Kenneth Whitby, George Hidy, Sheldon Friedlander, and Peter Mueller; the back row shows Dale Lundgren and Josef Pich. The background figure is from Chapter 9, Figure 13, illustrating the trimodal atmospheric aerosol volume size distribution. This concept has been the basis of atmospheric aerosol research and regulation since the late 1970s.

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Aerosol Research at the University of Minnesota Particle Technology Laboratory

Benjamin Y. H. Liu, Virgil A. Marple, Peter H. McMurry, Thomas H. Kuehn, and David Y. H. Pui

History of the Particle Technology Laboratory

Research on airborne particles began in the Mechanical Engineering Department, University of Minnesota in the late 1920s, when Prof. R. C. Rowley, head of the department, established a collaborative research program on building ventilation and dust control with the American Society of Heating and Ventilating Engineers (ASHVE), which later became the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). He was joined in this research by Prof. R. C. Jordan, head of the department from 1949 to 1976, and later by others, including Kenneth T. Whitby, who was a graduate student in the department in the 1950s. Between 1929 and 1959, these scientists carried out airborne particle research related to building ventilation and dust control. They published papers with titles such as "Determination of the Quantity of Dust in Air by Impingement" (Rowley & Beal, 1929), "A Standard Air Filter Dust Test" (Rowley & Jordan, 1939), "A Comparison of the Weight, Particle Count, and Discoloration Methods of Testing Air Filters" (Rowley & Jordan, 1941), "Overloading of Viscous Air Filters During Accelerated Dust Tests" (Rowley & Jordan, 1942), and "The ASHRAE Airborne Dust Survey" (Whitby et al., 1957), among others. This research laid the foundation for the subsequent ASHRAE filter testing standards, some of which the building ventilation and worldwide filtration industries still use today.

Prof. Kenneth T. Whitby completed his doctoral studies in the department in 1954. His dissertation was entitled *Mechanics of Fine Sieving* (Whitby, 1954). He also developed a centrifuge particle size analyzer for sizing powder (Whitby, 1955), which the milling industry used to size flour particles. Flour milling was a major industry, and flour was a major agricultural product in Minnesota. Whitby established the Particle Technology Laboratory in 1956 to focus on particle research. His initial interest was in powder research. Topics of interest in the fields of powder and particle technologies included the creation of powder particles by grinding and their subsequent processing by sieving and centrifugal separation. Such particles are generally quite large, anywhere from a few to hundreds of micrometers in diameter. At the same time, Whitby also became interested in small airborne particles due to the building ventilation and dust control program in the Department. Over time, research on small airborne particles, i.e. aerosol research, has become the main research focus of the Laboratory. This aerosol focus has not changed substantially over the years.

After completing his doctoral research in solar energy, under Prof. R. C. Jordan, Prof. Benjamin Y. H. Liu joined the Mechanical Engineering Department as a faculty member in 1960. He began collaborating with Whitby in aerosol research in 1962. He was followed by Prof. Virgil A. Marple, who joined the faculty in 1970; Prof. Peter H. McMurry, who joined in 1977; Prof. Thomas H. Kuehn, who joined in 1983; and Prof. David Y. H. Pui, who joined in 1984. Prof. David B. Kittelson joined the faculty in 1970, with a research focus in internal combustion engines. His subsequent research, however, has been mainly in the area of particulate emission from diesel engines and, because of the importance of aerosol measurement in diesel emission and control, has become closely allied with the research of the Particle Technology Laboratory. Chapter 20 of this book ("Review of Particle Size Distribution Measurements of Engine Exhaust Before 1985," by Gilmore J. Sem, Oliver F. Bischof, and Kittelson) describes Kittelson's diesel particulate emission and control research.

As a group, the individual faculty members collaborated with each other extensively. Each has also established his own research specialty and focus. In subsequent sections, this chapter briefly summarizes the contributions of each individual faculty member.

Kenneth T. Whitby

Kenneth T. Whitby
Photo: Courtesy of the authors.

Whitby played an active, leadership role in the laboratory and helped to establish the research program and nurture younger faculty members as they joined the laboratory. He served as the laboratory director from 1956 to 1972, followed by Liu (1972–1995) and Pui (1995–present). He was active in the air pollution community and served on the Clean Air Scientific Advisory Committee of the U.S. Environmental Protection Agency (EPA). He was elected to the National Academy of Engineering in 1978 for his contribution to aerosol instrumentation and air-quality measurement. Whitby's untimely death in 1983 marked a great loss to the department and the laboratory.

Whitby's contribution to aerosol research included instrumentation and measurement techniques, as well as research on aerosol filtration and atmospheric aerosol characterization. He was interested in using sensor-based aerosol measuring techniques to study the changing concentration and size distribution of aerosols caused by mixing, transport, sedimentation, and/or coagulation. In 1966, he developed an electrical particle counter for measuring aerosol size distribution in the 0.01 to 1.0 μm range (Whitby & Clark, 1966). The instrument uses a sonic jet ionizer, which he had developed earlier (Whitby, 1961), as a unipolar ion source for charging particles by ion diffusion. The counter then measures aerosol size distributions by electrical mobility, using an electrometer as a charge detector. Figures 1 and 2 show, respectively, a schematic diagram and a photograph of the prototype instrument. Thermo-Systems Incorporated (TSI), later developed the instrument as a commercial product, principally through the effort of G. J. Sem and his colleagues. The instrument was marketed as a Whitby Aerosol Analyzer (WAA) and was used in both ambient and laboratory aerosol studies.

Whitby also experimented with commercially available optical particle counters (OPC) to determine their size response and the effect of particle refractive index and shape on instrument response. He developed techniques to generate chain aggregate aerosols and measured the response of the OPC to the chain aggregate particles (McFarland & Tomaides, 1969a, 1969b). He then combined the measurement capability of the WAA in the 0.01 to 1.0 μm range with the measurement capability of the OPC in the 0.3 to 10 μm range to measure aerosols in the 0.01 to 10 μm range. With funding from the EPA and other governmental agencies, he developed several such instrument systems to measure atmospheric aerosols in cities across the country. A typical system included a WAA, one or more OPCs, one or more condensation nucleus counters (CNCs), a computer, and additional manual sampling devices; the system could be used to conduct research on the size distribution of aerosols with a time resolution and size range that older, more traditional approaches could not achieve.

The first such system, the Minnesota Aerosol Analyzing System (Whitby et al., 1972b), was used in the Los Angeles Smog Study to characterize the smog aerosol size distribution from August 19 to September 19, 1969. Figure 3 shows the average size distribution of aerosols measured during the 4-week measurement period (Whitby et al., 1972a). The figure also includes similar measurements made in Minneapolis by William E. Clark (1965) and Carl M. Peterson (1967), as well as results reported by other researchers using different

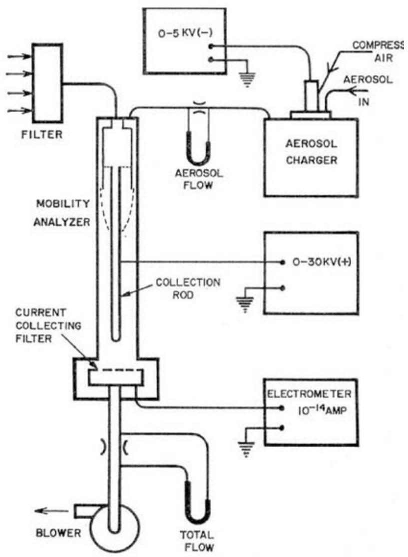


Figure 1. Schematic diagram of the electrical particle counter.
Source: Whitby & Clark (1966). Reprinted with permission from Wiley-Blackwell.

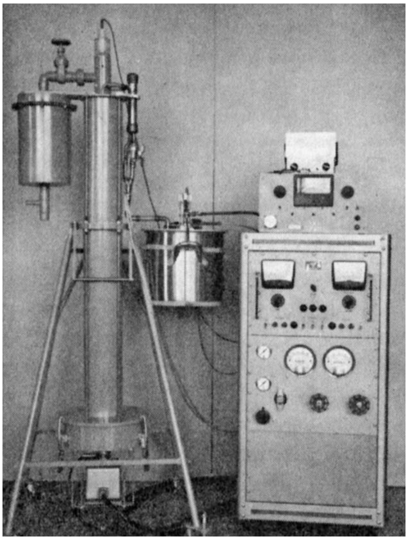


Figure 2. The electrical counter system showing the mobility analyzer, charger, and electric and flow instrumentation.
Source: Whitby & Clark (1966). Reprinted with permission from Wiley-Blackwell.

measurement techniques. Both Clark and Peterson were graduate students working in the Particle Technology Laboratory under Whitby's direction. He was generally credited for having developed the volume size distribution plot shown in Figure 3 that has helped to explain the nature and sources of atmospheric particles. Large particles with a mode in the 30 to 60 μm range—the "coarse-mode aerosol"—are thought to come from wind-blown dust, or generated by other mechanical processes, such as road dust suspended by vehicle traffic or plant debris. Fine particles with a peak diameter in the 0.1 to 1.0 μm range—the "accumulation-mode aerosol"—are thought to originate from combustion and atmospheric gas-to-particle conversion processes that have accumulated in this range through subsequent coagulation, sedimentation, removal, and other atmospheric transformation processes.

An interesting study in automotive aerosol emission occurred in 1975; the EPA and General Motors sponsored the study, using university and government laboratories as participants to take part in the measurement. This Sulfate Aerosol Dispersion Study was conducted at the General Motors proving ground in Milford, Michigan, in October 1975. In this study, 352 cars were driven around a 10 km test track, while observers made measurements at the roadside. The cars were equipped with catalytic mufflers for exhaust gas treatment, which also converted sulfur in the fuel to sulfate aerosols upon emission. The measured size distribution (Wilson et al., 1977) was found

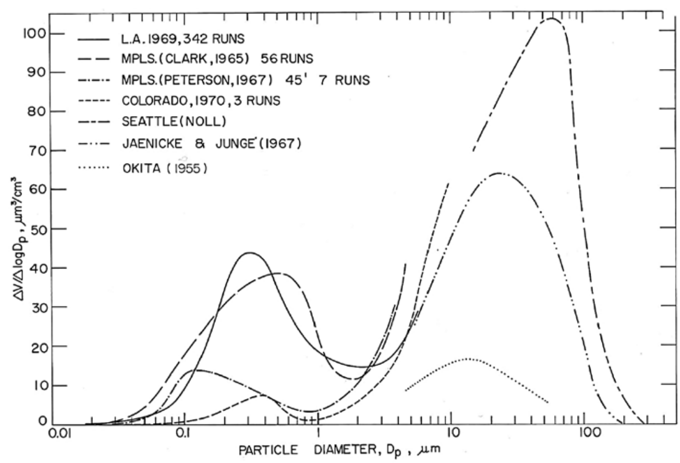


Figure 3. The bimodal size distribution of atmospheric aerosols.
Source: Whitby et al. (1972b). Reprinted with permission from Elsevier.

to be trimodal (as Figure 4 shows), having a pronounced "nuclei mode" at approximately 0.02 μm in diameter.

Whitby had a keen interest in aerosol instrumentation. Earl O. Knutson, a doctoral student working under Whitby's direction, developed a theory on the transfer function of the differential mobility analyzer (DMA). Knutson and Whitby showed that the DMA had a triangle-shaped transfer function (Knutson & Whitby, 1975a) and was capable of resolving the mobility of uniform polystyrene latex spheres carrying discrete units of electronic charges, as shown in Figure 5 (Knutson & Whitby, 1975b). The DMA subsequently became a key measuring instrument in the aerosol field. Several people contributed to the development of the device in the Particle Technology Laboratory. Liu and Pui (1974a) worked independently to develop the DMA as an electrostatic particle size classifier to generate monodisperse aerosols for instrument calibration and experimental purposes. More information about Whitby and his work can be found in Sem and colleagues (2005).

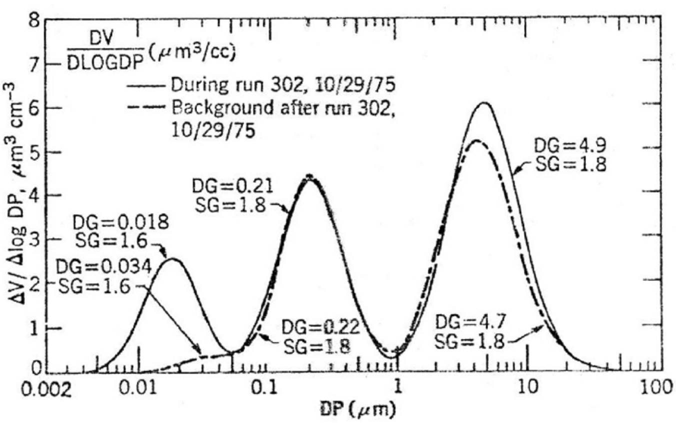


Figure 4. Trimodal aerosol size distribution measured at the General Motors Proving Ground on October 29, 1975.

Source: Wilson et al. (1977). Reproduced with permission of the Air and Waste Management Association from the *Journal of the Air Pollution Control Association* via Copyright Clearance Center, Inc.

Benjamin Y. H. Liu

Benjamin Y. H. Liu
Photo: Courtesy of the authors.

Liu joined the mechanical engineering faculty after completing his doctoral studies in solar energy. In 1962, Liu began his aerosol research in collaboration with Whitby in the Particle Technology Laboratory. He became a full professor in 1969 and the director of the laboratory in 1972. He was elected to the National Academy of Engineering in 1987 for his contribution to aerosol and solar energy research. In 1995, he was named a Regents' Professor, the highest academic honor given to a faculty member at the University of Minnesota. He retired from the University in 2002 and became the president and chief executive officer of MSP Corporation, a company he cofounded with Prof. Virgil A. Marple. At MSP, he continued his aerosol research, making new inventions and creating new products for commercial applications. The company has developed new aerosol research instruments; products for testing of metered-dose inhalers, dry-powder inhalers, and other inhaled drug delivery devices; and equipment for use in semiconductor applications, including wafer surface inspection and thin film deposition by atomic layer deposition through molecular self-assembly on the surface and by conventional chemical vapor deposition processes.

Liu's interest in aerosol research covers a wide range of topics. Over an academic career of 42 years, he and his students and colleagues have published many papers on aerosol instrumentation, experimental techniques, theoretical and experimental studies in aerosol filtration, inertial turbulent deposition, and charging and neutralization of aerosol particles, among other topics. Realizing that complex aerosol problems were generally not amenable to solution by classical analytical methods, they were among the first to apply computer-based numerical methods for basic aerosol research in filtration, inertial impaction, aerosol charging by ion drift, diffusive ion transport in an external electric field, and so forth.

As a founding director and past president of the American Association for Aerosol Research and an editor-in-chief (with David Shaw of the University of New York at Buffalo and David Ensor of Research Triangle Institute) of the journal *Aerosol Science and Technology*, Liu has also contributed to the field's general scientific and professional development. He and his University of Minnesota colleagues have contributed to the expanding awareness of aerosols in the larger scientific and technical community by providing it with training opportunities for professionals involved in aerosol work through the short-course offering at the University of Minnesota entitled “Aerosol and Particle Measurement”; this short course has been offered annually since 1978. They have also helped to promote international cooperation in aerosol science by organizing the First International Aerosol Conference in 1984 in Minneapolis and establishing the International Aerosol Research Assembly for organizing international aerosol conferences among the collaborative aerosol societies in different countries. In 1994, the aerosol societies of the United States, Europe, and Japan awarded Liu the Fuchs Memorial Award for his research and efforts in the aerosol field. Liu was elected to the National Academy of Engineering in 1987 for his contribution to solar energy and aerosol research, and the University of Minnesota named him a Regents’ Professor in 1993. He also received an honorary doctorate from the University of Kuopio in Finland.

Experimental Aerosol Science

Liu and his students and colleagues have contributed to experimental aerosol science by developing instruments and experimental techniques for calibrating optical particle counters (Whitby & Liu, 1967; Liu et al., 1974a; Willeke & Liu, 1976; Szymanski & Liu, 1986; Liu & Szymanski, 1987), diffusion batteries (Sinclair et al., 1976), and condensation nucleus counters (Liu et al., 1975; Liu & Kim, 1977). They have also developed various atomization, condensation, and fluidized-bed aerosol generators for aerosol research (Liu, 1974; Liu et al., 1966; Tomaides et al., 1971; Liu & Lee, 1975; Marple et al., 1978; Liu & Levi, 1980). Many of these techniques have since been used or adapted by others for laboratory research in air pollution, industrial hygiene, cleanrooms, and microcontamination control. In addition, Liu and colleagues have also contributed to the development of experimental methods for measuring electric mobility (Wahi & Liu, 1971) and charge on aerosol particles (Liu et al., 1967a, 1969a; Whitby & Liu, 1968; Liu & Pui, 1974b) and have studied the light scattering and ionization smoke detectors to determine their performance (Mulholland & Liu, 1980). Other experimental contributions include research on the electrostatic effects in aerosol sampling and filtration (Liu et al., 1985a), and size distribution measurement of atmospheric (Whitby et al., 1969, 1972a, 1972b, 1975; Husar et al., 1972) and laboratory generated aerosols (Liu et al., 1969b, 1982a; Sinclair et al., 1979; Mulholland et al., 1980), aerosols in the workplace environment (Liu et al., 1974b) and in the cleanroom (Liu et al., 1985b, 1986a). Additionally, they have contributed to the study of particle fragmentation during evaporation (Iribarne et al., 1977), methods for generating (Bartz et al., 1984) and measuring (Brockmann et al., 1982a, 1984) ultrafine aerosols, and particle dispersion by shock and expansion waves (Roth et al., 1984).

Monodisperse Aerosol Standards and Instrumentation

The development of particle size standards for aerosol research is a topic of considerable interest to Liu. He and his students have developed the vibrating orifice and mobility classification techniques for generating aerosols with a uniform and known particle size to use as size standards in instrument calibration and experimental studies. These techniques can generate a variety of aerosol materials with different physical and/or chemical properties to provide size standards from about 0.01 μm to more than 40 μm in diameter, covering nearly the entire size range of interest in aerosol studies.

The vibrating orifice technique uses a small vibrating orifice to produce a stream of uniform droplets with a piezoelectric ceramic, while maintaining a constant and steady liquid flow through the orifice, to form a jet. Figure 6 is a schematic diagram of the droplet generator that Liu, Berglund, and Agarwal (1974a) describe, and Figure 7 shows the uniform droplet stream generated by the device. Using the vibrating orifice droplet generator, Liu and colleagues developed a monodisperse aerosol generating system that includes additionally a turbulent air jet to disperse the uniform droplet stream from the droplet generator to prevent coalescence, a syringe pump to provide a

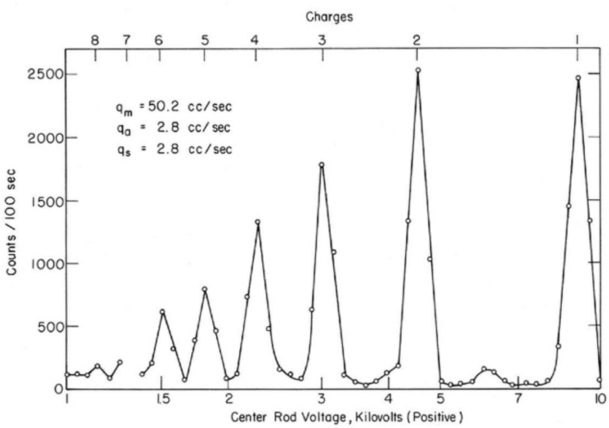


Figure 5. Mobility analyzer response to a neutralized polystyrene latex aerosol.

Source: Knutson & Whitby (1975a). Reprinted with permission from Elsevier.

controlled and known rate of liquid flow through the orifice, and a krypton-85 radioactive ionizer to neutralize the aerosol electrical charge. Uniform dioctyl phthalate (DOP) droplets of 9.5 μm diameter and solid 3.7 μm methylene blue particles generated by the system are shown in Figures 8 and 9.

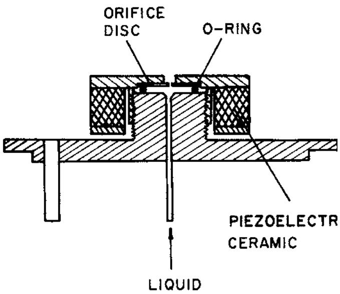


Figure 6. Monodisperse droplet generator of Berglund and Liu.

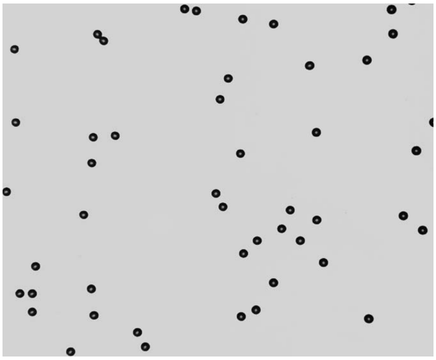


Figure 8. Monodisperse 9.5 μm dioctyl phthalate aerosols generated by the Berglund-Liu generator.

Source: Liu et al. (1974a). Reprinted with permission from Elsevier.

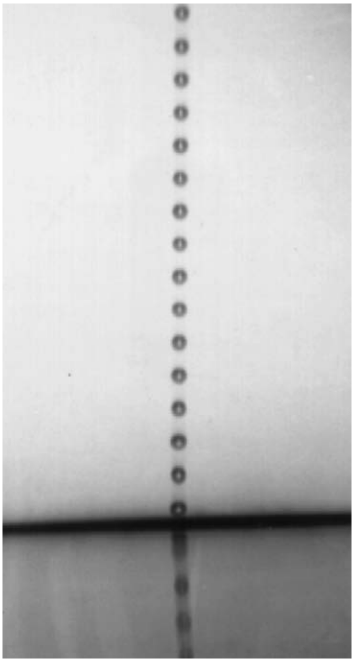


Figure 7. Uniform droplet stream produced by the Berglund-Liu droplet generator.

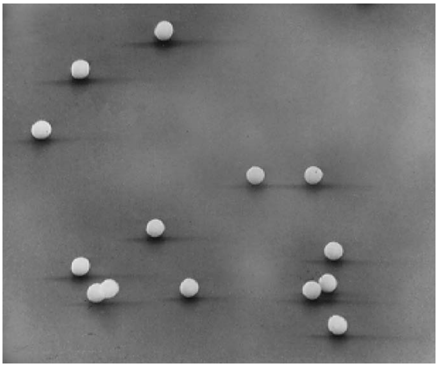


Figure 9. Monodisperse 3.7 μm methylene blue particles generated by the Berglund-Liu generator.

The vibrating orifice device operates by the controlled disintegration of a liquid jet by an orifice, with an attached piezoelectric ceramic vibrating the orifice at a known frequency. Within its useful operating range, the device produces one single droplet per cycle of oscillation. The rate of droplet generation is thus equal to the vibrating frequency of the orifice, which is the same as the frequency of the alternating current voltage applied to the piezoelectric ceramic. As a result, the droplet volume, V_d, and its diameter, D_d, are uniquely related to the liquid flow rate, Q_l, and the vibrating frequency, f, as follows:

$$Q_l = V_d f = \frac{1}{6} \pi D_d^3 f \qquad (1)$$

$$D_d = \left(\frac{6Q_l}{\pi f} \right)^{1/3} \qquad (2)$$

To generate a monodisperse aerosol, a liquid solution is generally prepared by dissolving a nonvolatile material with the desired physical and/or chemical property in a volatile solvent to form a solution having a known volumetric concentration, c, of the material in the solution. When this solution is sprayed through the vibrating orifice to form monodisperse solution droplets, the solvent can be evaporated from the droplets to form a nonvolatile residue aerosol having a known particle diameter, D_p; the particle diameter is relative to the diameter of the liquid solution droplets and the solution concentration according to the relation

$$D_p = c^{1/3} D_d = \left(\frac{6cQ_l}{\pi f} \right)^{1/3} \qquad (3)$$

With this approach, the diameter of the generated particles can be calculated accurately by using the liquid flow rate, the vibrating frequency, and the volumetric solution concentration of the aerosol material in the solution, all of which can be easily measured. The accuracy of the calculated particle diameter is generally within ±1 percent in routine use. With more careful measurement of the relevant operating parameters, an accuracy of ±0.25 percent in particle diameter can be achieved without too great a difficulty. The tedious, time-consuming, and often less-accurate method of sizing aerosol particles by collecting them on a substrate and measuring the diameter by an optical or electron microscope can often be avoided by using the standard aerosols generated by the vibrating orifice.

The vibrating orifice technique has a lower particle limit of about 1.0 μm. For particles less than 1.0 μm in diameter, Liu and Pui (1974a) developed a mobility classification technique for generating submicron aerosols in the 0.01 to 1.0 μm range. The technique uses a compressed-air atomizer to form a polydisperse aerosol by spray drying a solution to form a polydisperse residue aerosol. A krypton-85 neutralizer then brings this aerosol to a state of charge equilibrium, and a DMA classifies its size to produce a monodisperse aerosol that carries one single elementary unit of charge. Because the operating conditions of the DMA determine the particle mobility according to the equation

$$Z_\mathrm{p} = [q_c + \frac{1}{2}(q_a - q_s)]\,\frac{\ln(r_2 / r_1)}{2\pi VL} \tag{4}$$

and the mobility is related to the particle size according to Stokes's law with the slip correction

$$Z_\mathrm{p} = \frac{eC}{3\pi\mu D_p}, \tag{5}$$

these theoretical relations can be used to calculate the particle size using the pertinent operating parameters used for aerosol generation. In equations 4 and 5, Z_p represents particle mobility; q_c, q_a, and q_s represent the clean air, polydisperse input, and monodisperse output sampled aerosol flow rates; r_1 and r_2 are the inner and outer radii and L is the classification length of the DMA; and V is the applied voltage on the high-voltage electrode in the DMA; μ is the gas viscosity, C is the particle slip correction, and e is the elementary unit of charge on the particles. Figure 10 shows the monodisperse, 0.05 μm sodium chloride (NaCl) particles generated by the mobility classification technique. For nonspherical particles, the particle diameter generated by the electrostatic classification technique is a mobility equivalent diameter (i.e., the diameter of a sphere having the same electric mobility as the nonspherical particle carrying the same elementary unit of charge).

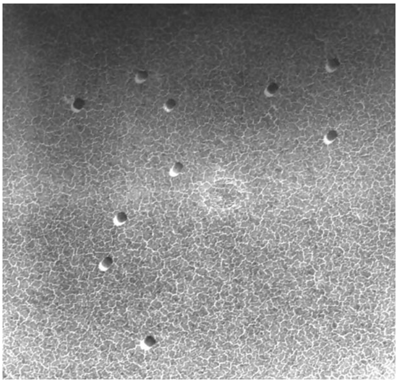


Figure 10. Monodisperse 0.05 μm sodium chloride particles generated by mobility classification.

Source: Liu & Pui (1974a). Reprinted with permission from Elsevier.

In addition, Liu and Pui have developed an electrometer-based concentration standard by collecting singly charged particles produced by the DMA into an electrometer sensor to produce a current flow. The measured current is related to the aerosol concentration, N, and the aerosol flow rate into the current detection. By measuring the electrometer current, I, and the aerosol flow, q, the aerosol concentration can be determined by the relationship

$$I = qeN\,, \tag{6}$$

where e is the elementary unit of charge. Figure 11 is the calibration result for a CNC (Liu & Pui, 1974a), using the electrometer current sensor as a concentration standard.

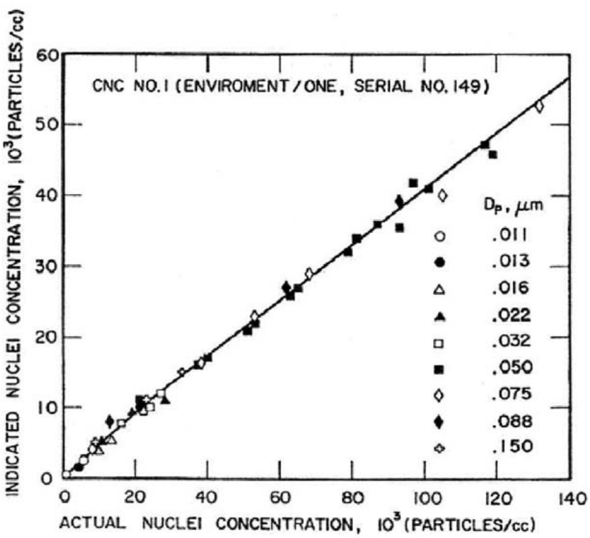


Figure 11. Calibration of the Environment/One Rich 100 condensation nucleus counter by the electrometer standard.
Source: Liu & Pui (1974a). Reprinted with permission from Elsevier.

The techniques described here have provided the basic standard for aerosol measurement for many years in many applications, including the calibration of the optical particle counters, electrical aerosol analyzers, condensation nucleus counters, and others. They have also been used extensively for aerosol research to determine the particle size–collecting characteristics of impactors and filter samplers as well as filtration devices for industrial air cleaning applications. The Berglund and Liu vibrating orifice technique has been accepted as the reference aerosol generation technique for calibrating size-selective $PM_{2.5}$ and PM_{10} samplers used in ambient air quality measurement to meet particulate air-quality standards in the United States.

Other significant instrument development effort includes the development of the pulse precipitating electrostatic aerosol sampler, a device for collecting quantitative samples of particles on a collecting substrate for electron and optical microscopy (Liu et al., 1967b; Liu & Verma, 1968) and the Electrical Aerosol Analyzer (Liu et al., 1974c, 1979; Liu & Pui, 1975; Pui & Liu, 1979), based on the unipolar charging and mobility analysis principle used in the WAA, but incorporating design improvement that resulted in the instrument being 5 times smaller and lighter than the WAA. Other contributions include the development of the aerosol mobility chromatograph, now referred to as the tandem-mobility analyzer (Liu et al., 1978), for measuring the changes in particle size caused by humidity or chemical reaction and the development of aerodynamic size measurement by the laser Doppler technique (Wilson & Liu, 1980; Liu et al., 1982b). Figure 12 shows the results of a predicted particle velocity downstream of a 1.0 mm diameter orifice with a gas flow of 12 m/s velocity showing the dependence of particle velocity on particle size and density and the underlying principle of the aerodynamic size measuring technique. Liu and colleagues also contributed to the theory of CNCs (Ahn & Liu, 1990a, 1990b; Zhang & Liu, 1991), which has helped to improve the understanding of how an important aerosol measuring technique operates.

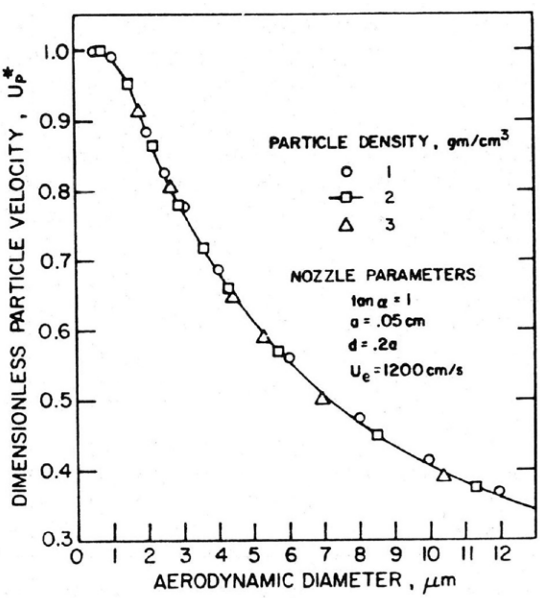


Figure 12. Calculated particle velocity as a function of aerodynamic diameter and particle density in a 1.0 mm diameter nozzle at a gas velocity of 12 m/s.

Source: Wilson & Liu (1980). Reprinted with permission from Elsevier.

Aerosol Charging and Neutralization

The charging of aerosol particles by unipolar ions and their neutralization by a bipolar ion mixture are important topics in aerosol studies. Charging by unipolar ions occurs in the electrostatic precipitator, which is used extensively for air pollution control and in laboratory apparatus for aerosol studies. Neutralizing aerosol particle charge with a mixture of positive and negative ions produced by bipolar ion–generating sources minimizes unwanted electrostatic effects and thus is important to laboratory studies.

Liu and his students contributed to the theory of unipolar diffusion charging in the continuum regime (Liu & Pui, 1977); combined field and diffusion charging theories (Liu & Yeh, 1968; Liu & Kapadia, 1978); the theory of aerosol neutralization using radioactive sources, including krypton-85 and polonium-210 ionizers (Liu & Pui, 1974c; Liu et al., 1986b); the measurement of charge on contaminant particles generated in computer disk drives (Pui et al., 1988); the development of the high-efficiency unipolar charger (Adachi et al., 1990); and the development of aerosol charge neutralization in microelectronic cleanrooms (Liu et al., 1987a). The charging and neutralization theories that they have developed have provided the fundamental knowledge base for the charging process in general and the application of particle electrostatics to aerosol measurement and charge control in particular. The use of the radioactive krypton-85 and polonium-210 ionizers for charge neutralization has become popular as a result of their study on the operating principle of the device leading to the correct use of such devices for aerosol charge neutralization in experimental aerosol physics and science.

The combined field and diffusion charging theory that Liu and Kapadia (1978) developed is based on the numerical solution of the steady state equation for ion diffusion

$$\nabla \bullet \left[D\nabla N - ZN\nabla V \right] = 0 \tag{7}$$

in an external electrical field around a spherical particle produced by an applied electric field

$$V = \frac{ne}{r} + \left[\frac{r}{a} \left(\frac{K-1}{K+3} \right) \frac{a^2}{r^2} \right] \; E_o a \cos\theta \, . \tag{8}$$

In equations 7 and 8, D is the diffusion coefficient of the unipolar ions, Z is the ion mobility, V is the electrical potential around the particles, n is the number of unit of charge on the particles, e is the elementary unit of charge,

K is the dielectric constant, E_0 is the applied electric field, and r and θ are the polar coordinates centered around the particle.

Figure 13 shows the theoretical prediction of the combined charging of aerosol particles by diffusive ion transport in an external applied electric field and its comparison with the experimental data. Figure 14 shows the measured ionization current in a krypton-85 aerosol charge neutralizer, which is useful for determining the ion concentration in the device to meet different aerosol charge neutralization needs.

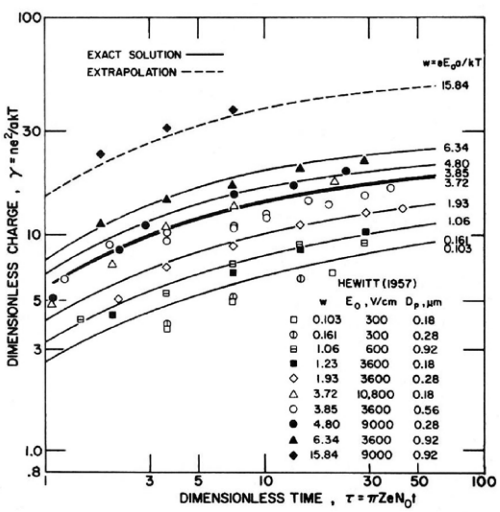


Figure 13. Comparison of the combined field and diffusion charging theory with experimental data.

Source: Liu & Kapadia (1978). Reprinted with permission from Elsevier.

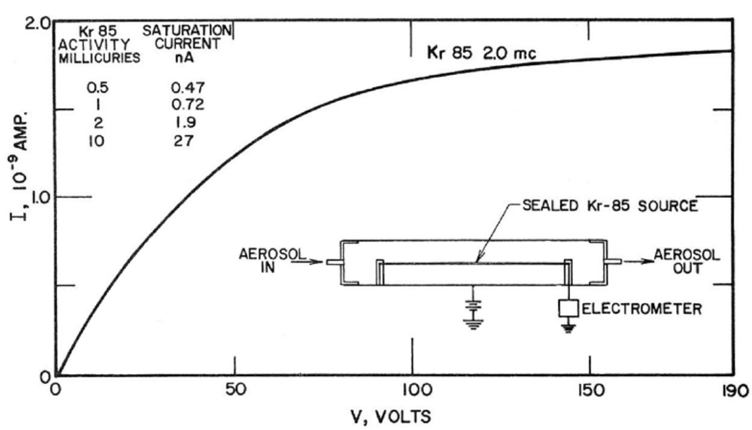


Figure 14. Measurement of ionization current and charge concentration in a krypton-85 neutralizer

Source: Liu & Kapadia (1978). Reprinted with permission from Elsevier.

Aerosol Filtration

Liu's major contributions to the aerosol field include the development of the theory of aerosol filtration using fibrous filters and taking into account the combined effect of particle collection by diffusion, interception, and inertial impaction (Yeh & Liu, 1973a, 1973b); the theory of fibrous filters based on the boundary layer approach and Kuwabara flow (Rubow & Liu, 1986; Lee & Liu, 1982a); theories of filtration in the most penetrating particle size range (Lee & Liu, 1980) and in the transition regime (Zhang & Liu, 1992); and characteristics of air filters with rectangular fibers (Fardi & Liu, 1992a, 1992b). Experimental contributions include the development of filter testing methods using monodisperse aerosols (Yeh & Liu, 1973b; Liu & Lee 1976; Lee & Liu, 1982b); experimental techniques applied to studying the performance of air-sampling filter media (Liu & Kuhlmey, 1977; Liu et al., 1983a), high-efficiency filters used in microelectronic cleanrooms (Liu et al., 1985c), and ultra–high-efficiency membrane filters for high-purity gas filtration in semiconductor device manufacturing (Accomazzo et al., 1983; Rubow & Liu, 1984, 1985; Rubow et al., 1988); techniques for testing industrial cartridge filters (Liu et al., 1986c; McDonald et al., 1986; Barris et al., 1986); ultra–high-sensitivity filter leak detection methods (Sadjadi & Liu, 1991); and the filtration of diesel particles (Kittelson et al., 1984). Other contributions include the application of fundamental filtration theory to industrial filter design (Schaefer et al., 1986) and respirator filtration studies (Liu & Fardi, 1985; Liu & Japuntich, 1987; Fardi & Liu, 1991). The careful experimental measurement of the size-dependent single fiber efficiencies has led to the development of a universal correlation for filter performance in the diffusion and interception regimes, as well as theoretical methods for calculating the most penetrating particle size and peak aerosol penetration through filters. This work has influenced the filtration industry in its acceptance of modern filtration theory for industrial filter design. The high-sensitivity filter efficiency measurement method that Liu and his students have developed is capable of measuring filter penetration to the part-per-billion level and thus has made it possible to experimentally evaluate membrane filters used by the microelectronics industry for high-purity gas filtration. This research background in filtration allowed Liu and his colleagues in the Particle Technology Laboratory to establish the Center for Filtration Research, which carries out filtration research with funding support from participating companies in the filtration industry. The center was established in 1991 and still operates; it is currently led and directed by David Pui.

Classical aerosol filtration theory is based on the Kuwabara flow field based on the solution of the Navier-Stokes equation in the creeping flow regime. Using a staggered array model for the filter, Yeh and Liu (1973) showed that the Kuwabara flow field and the fan model filter of Stechkina and Kirsh were in substantial agreement with the numerical results. They then went on to apply the staggered array model to calculate the single fiber efficiency, taking into account the combined effect caused by particle diffusion, interception, and inertial impaction at a Reynolds number of 30, the point at which the classical flow models are no longer expected to be valid. Figures 15 and 16 show the numerical result for the flow field calculation and its comparison with the Kuwabara flow field and the fan model of Fuchs and colleagues at a Reynolds number of 0.4, as well as a similar calculation at a Reynolds number of 30, the point at which the Kuwabara and the fan models are not valid.

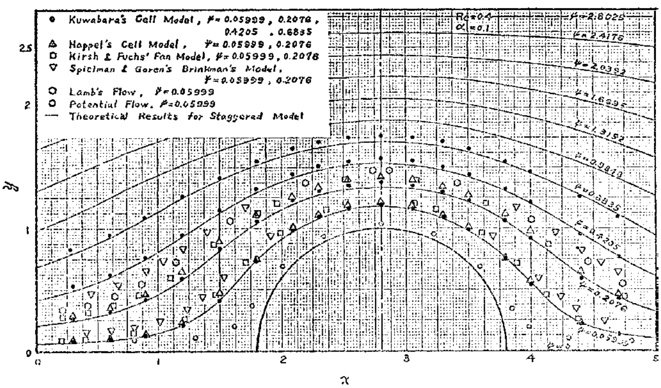


Figure 15. Numerical flow field calculation for a staggered array model at Re = 0.2.

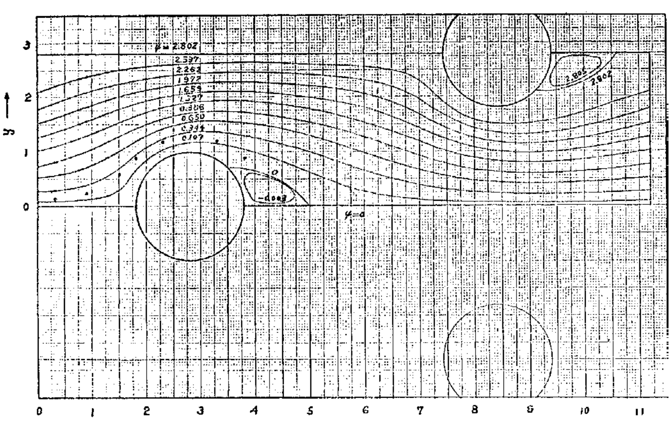


Figure 16. Numerical calculation flow field calculation for a staggered array model at Re = 30.

Subsequently, Lee and Liu (1982a, 1982b) used a boundary approach for filtration analysis and established the form of the dimensionless correlation between the single fiber efficiency, a dimensionless Péclet number, and the interception parameter for aerosol filtration in the interception and diffusion regimes. They then measured the single fiber efficiency using a model filter with a uniform fiber size and an aerosol filtration measuring system comprised of a monodisperse DOP aerosol generator and an electrical aerosol concentration detector. The results are then corrected in a dimensionless form as shown in Figure 17 and by the following equation:

$$\eta_s = 1.6 \left(\frac{1-c}{K}\right)^{\frac{1}{3}} \mathrm{Pe}^{-\frac{2}{3}} + 0.6 \left(\frac{1-c}{K}\right) \frac{R^2}{1+R}. \tag{9}$$

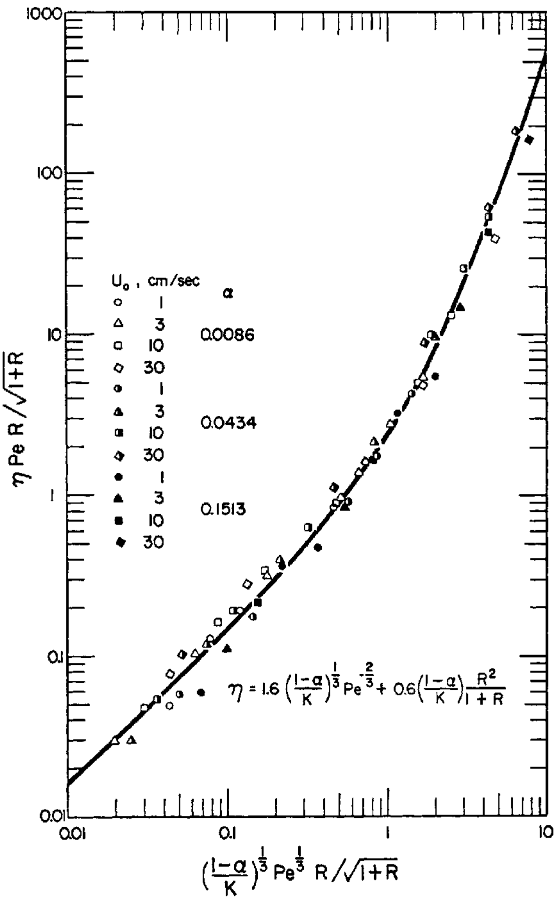


Figure 17. Correlation of single fiber efficiency with dimensionless parameters.
Source: Lee & Liu (1982a).

In Equation (9), η_s is the single fiber efficiency, *Pe* is the dimensionless Péclet number defined by

$$Pe = \frac{uD_f}{D} \quad . \tag{10}$$

K is the Kuwabara hydrodynamic factor,

$$K = -\frac{1}{2}\ \ln c + \frac{1}{2}\ \frac{c^2}{1+c^2} - \frac{1}{2}, \tag{11}$$

and c is the fiber volume fraction in the filter, where u is the gas velocity through the filter, D_f is the fiber diameter, and *D* is the diffusion coefficient of the aerosol particles.

Inertial Impaction

Research on inertial impaction began with Virgil Marple's doctoral dissertation. As with filtration, Marple used computational methods to study the flow field and particle collection by inertial impaction. The work has led to several publications on the theory of impactors and particle collection by impaction (Marple et al., 1973, 1974; Marple & Liu, 1974, 1975). Other impactor studies examined the influence of coating thickness on particle bounce (Pak et al., 1992) and fundamental adhesion and bounce studies (Tsai et al., 1991a) and developed the micro-orifice and micro-orifice uniform-deposit impactors (Kuhlmey et al., 1981; Marple et al., 1981) and the high-volume virtual and dichotomous samplers (Shanmugavely et al., 1987; Marple et al., 1990). The application of computational fluid and particle mechanics methods to impactor studies has significantly improved the understanding of impactor performance and has facilitated the development of precision impactors for high-accuracy aerosol sampling in atmospheric pollution, industrial hygiene, and other fields of study. The micro-orifice and micro-orifice uniform-deposit impactors that Marple and Liu developed have made it possible to sample particles less than 100 nm using the impactor principle with a high flow rate and moderate pressure drops. Because of subsequent development by Marple, inertial impaction can now collect particles as small as 10 nm in diameter.

Inertial-Turbulent Deposition

Liu and colleagues' major contributions to inertial-turbulent deposition include the theory of aerosol deposition in turbulent pipe flow (Liu & Ilori,

1974) and the accurate measurement of turbulent deposition velocity by taking into account particle inertia and fluid turbulence in the inertial turbulent deposition regimes (Liu & Agarwal, 1974). The turbulent deposition data that Liu and colleagues collected are among the most accurate results that have been reported. The data have helped to resolve the theoretical uncertainty in the predicted deposition velocity according to the different theories. Figure 18 is a plot that shows the dimensionless deposition velocity, V_+ as a function of the dimensionless relaxation time, τ_+ of the particle based on the defined dimensionless parameters

$$\tau_+ = \frac{\tau v_*^2}{v} \tag{12}$$

$$V_+ = \frac{V}{v_*} \tag{13}$$

$$\tau = \frac{2pa^2C}{9\mu} \tag{14}$$

$$f = \frac{0.316}{4\mathrm{Re}^{1/4}} \tag{15}$$

$$v_* = (f/2)^{1/2}\,\bar{u}\,. \tag{16}$$

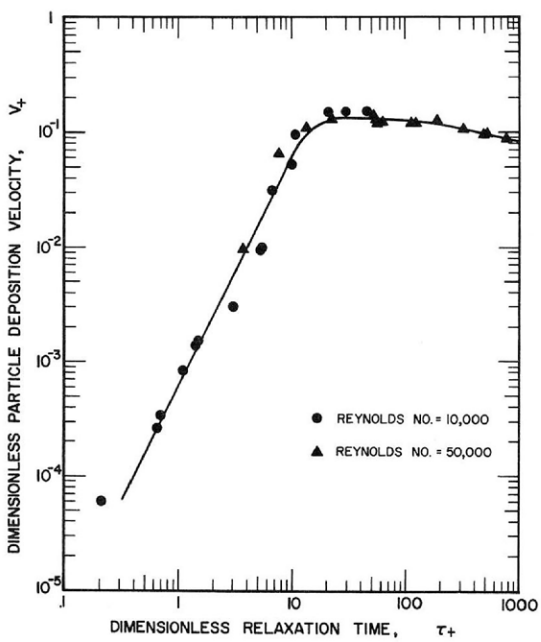


Figure 18. Dimensionless deposition velocity plotted against the dimensionless relaxation time of particles in turbulent pipe flow.

Source: Liu & Argarwal (1974). Reprinted with permission from Elsevier.

In these equations, τ is the dimensionless relaxation time, v* is the friction velocity, V is the deposition velocity, ρ is the gas density, a is the particle radius, C is the slip correction, μ is the gas viscosity, Re is the Reynolds number, *f* is the friction factor, and $\bar{u}$ is the mean gas velocity in turbulent pipe flow.

Theory of Aerosol Sampling

Contributions in aerosol sampling include the development of the theory of aerosol sampling in calm air (Agarwal & Liu, 1980), the theory of anisokinetic sampling (Liu & Zhang, 1989; Zhang & Liu, 1989), as well as practical atmospheric aerosol sampling inlets (Liu & Pui, 1981, 1986), sampling inlets for industrial hygiene and respirator studies (Liu et al., 1983b), and a sampling inlet for flowing gas streams (Liu & Pui, 1985). The criteria for aerosol sampling in calm air has significantly improved the understanding of aerosol sampling in calm air and the conditions that must be met in designing calm-air sampling inlets. The theory of anisokinetic sampling provides the most comprehensive numerical calculation of anisokinetic sampling errors, including errors caused by particle deposition inside the sampling inlet, an aspect that previous theoretical studies have not addressed rigorously.

Aerosol Studies in Contamination Control and Semiconductor Manufacturing

Liu established a Microcontamination Control Research Consortium in the Particle Technology Laboratory to support basic and applied research on particle-related problems in semiconductor, integrated circuit device manufacturing. The consortium received financial support from 15 member companies over a period of 12 years and conducted research on various topics of interest to the semiconductor industry. With the support of the consortium, Liu and his students and or colleagues carried out research and contributed to the development of the theory of aerosol deposition on semiconductor wafers that took into account deposition by diffusion, gravitation settling (Liu & Ahn, 1987; Liu et al., 1987b), and electrostatic (Liu, 1987) and thermophoretic effects (Ye et al., 1991a); the measurement of particle deposition on semiconductor wafers (Pui et al., 1990); the application of methods of computational fluid dynamic to cleanroom airflow studies (Shanmugavely et al., 1987; Kuehn et al., 1988); the measurement of charge and size of particles generated in thin-film computer disk drives (Pui et al., 1988; Tsai et al., 1991b, 1991c, 1991d, 1992); the development of particle generation and deposition in computer head-disk assemblies (Ananth &

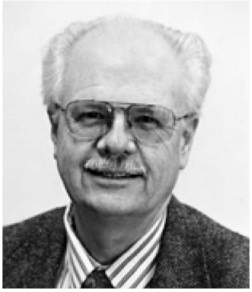
Liu, 1989; Campbell et al., 1990); the development of the absolute zero particle gas (Liu & Hsieh, 1989); the development of the noncontaminating fogger by quenching steam with liquid nitrogen to form a high-density, noncontaminating fog for air flow visualization in cleanrooms (Ramsey et al., 1988; Gallo et al., 1988); performance measurement of cleanrooms (Liu et al., 1986a; Brown et al., 1989) and cleanroom filter systems (Sadjadi & Liu, 1991); and the development of theoretical and experimental studies of wafer surface scanners (Lee et al., 1992; Kwok & Liu, 1992). The research has helped to establish aerosol science as a recognized area of study in semiconductor device manufacturing and has provided graduates of the program with satisfying career opportunities in the industry. The noncontaminating fogger that they developed has been used to visual air flow in the cleanroom near the production area where products are being made to help improve manufacturing and reduce contaminant deposition on the wafer.

With the support of the consortium, Liu and his colleagues and students also conducted studies of condensation-induced residue particle generation during vacuum pump-down and in vacuum semiconductor processing equipment (Zhao et al., 1991; Liu et al., 1991, 1992; Chae et al., 1992), as well as theoretical and experimental studies of high-purity liquid filtration and filtration mechanisms (Grant & Liu, 1991; Kuehn et al., 1992) and the droplet-flattening effects of surface collection (Tsai et al., 1991a).

Other Research Contributions

Liu and colleagues have also made other basic contributions, including data inversion by simplex minimization (Helsper et al., 1982); the theory of size distribution of atmospheric aerosols (Liu & Whitby, 1968); the theory of momentum, heat, mass, and charge transfer in the transition regime (Bademosi & Liu, 1971); coagulation and diffusion loss of aerosols in turbulent pipe flow (Brockmann et al., 1982b); and particle deposition in pipe bends (Liu et al., 1988). In addition, he and his students and colleagues have also conducted research in particle measurement and control in coal gasification and fundamental studies in spray painting (Liu, 1992).

Virgil A. Marple



Virgil A. Marple
Source: Photo courtesy of the authors.

Virgil Marple started his research at the Particle Technology Laboratory in 1967 as a PhD candidate. His doctoral dissertation, the basis for much of his future work, was entitled *A Fundamental Study of Inertial Impactors* (Marple, 1970). At that time, he acquired a preprint of a book on computational fluid dynamics (CFD) analysis from the Imperial College in London (Gousman et al., 1969), which solved the Navier-Stokes equations with no simplifying assumptions for laminar flow. Although the book was written for CFD analysis of heat and mass transfer in recirculating flows, Marple modified the program to model the flows in inertial impactors of both rectilinear and cylindrical coordinates to enable the modeling of rectangular jet and round jet impactors. Marple then wrote a program that would trace single particle trajectories through the flow field and determine whether the particles struck the impaction plate or exited with the flow from the impaction region. Marple constructed the impaction collection efficiency curve by starting particles of different sizes at different locations across the entrance to the impactor nozzle. This was likely the first time that CFD analysis had been applied to determine flow field and particle trajectories in aerosol sampling instruments.

To determine that the CFD-generated flow fields were correct, Marple constructed a water model using a 20-gallon aquarium tank and a Plexiglas model of a rectangular nozzle impactor. Marple pumped an electrolytic solution consisting of water, sodium hydroxide, hydrochloric acid, and methyl blue pH indicator through the impactor model. The solution was titrated to be slightly acidic, and the color of the fluid was then a light orange. Cathode wires were placed at strategic points in the impactor model, and the fluid would turn a dark blue in the immediate vicinity of the cathodes. This blue fluid became dark streamlines in the light orange fluid. Marple then compared photographs of these streamlines with CFD-generated streamlines in impactors of the same configuration. The comparison found very good agreement, and Marple then used the CFD analysis of the flow fields for the fundamental study of impactors.

Constructing a "variable point impactor" that could introduce particles at various points across the inlet checked the CFD determination of the particle trajectory. A mixture of polydisperse solid methylene blue particles and solid polystyrene latex (PSL) particles were generated in a spinning disk aerosol generator and were then introduced into the impactor at precise locations across the inlet. Marple then compared the impaction points on the impaction plate for the various sized particles with the CFD results, and again, the agreement was good.

With experimental verification that the flow fields and particle trajectories from the CFD analysis were accurate, Marple and colleagues performed a fundamental study of impactors, in which they constructed particle collection efficiency curves for various Reynolds number values, jet-to-plate distances, and throat lengths for both round and rectangular jet impactors. Results from various parts of the study were published in papers (Marple et al., 1973, 1974; Marple & Liu, 1974, 1975). Marple and Rader (1985) later refined the study using ultra-Stokesian drag and a smaller grid.

The results from the study have been widely cited and have become one of the important contributions from the Particle Technology Laboratory in the 1970s as evidenced in letters from Dr. N. Fuchs to Whitby (1975) and Liu (1980). Fuchs commented to Dr. Whitby, "Of the works done lately at your laboratory I have been most impressed by that of Marple.—Please tell him about my high opinion of his classical work" (N. Fuchs, personal communication, 1975). And Fuchs stated to Dr. Liu:

> Whereas there exist [sic] a substantial theory of jet impactors based chiefly on the brilliant theoretical and experimental work performed under your guidance by V. Marple, our knowledge of the "wide flow" [body] impaction on various objects is still insufficient although much work has been done on this subject. (N. Fuchs, personal communication, 1980)

Another facet of this work is that the logo for the American Association for Aerosol Research (AAAR) is a stylized version of an impactor flow field from Marple's doctoral dissertation (Marple, 1970). Figure 19 shows the AAAR logo and a computer-generated flow field from the dissertation.

With the understanding derived from the fundamental study of impactors, many impactors were designed, built, and evaluated. Figure 20 shows many of these impactors. The impactor stage shown in the center of this figure is the same in all of these impactors; other design criteria are the cause for the wide variety of designs. These impactors include (1) the micro-orifice uniform deposit impactor (MOUDI) that uses micro-orifice nozzles to collect particles as small as 0.056 μm and rotation of the impaction plates to obtain a uniform deposit on the impaction plate (Marple, 1978; Marple & McCormack, 1983; Marple et al., 1991); (2) the nano-MOUDI that adds three smaller cut stages to the MOUDI (Marple & Olson, 1999); (3) the Marple, Spengler, and Turner (MST) $PM_{2.5}$ and PM_{10} indoor air sampler (Marple et al., 1987); (4) the Marple personal cascade impactor (MPCI) (Rubow et al., 1987); (5) the micro-environmental monitor (MEM), an indoor impactor/filter sampler with cut sizes of 10 or 2.5 μm and operates at 10 l/min; (6) the respirable impactor (RI), a single-stage impactor that has either American Conference of Governmental Industrial Hygienists (ACGIH) or British Medical Research Council (BMRC) respirable cuts at flow rates of either 2 or 30 L/min (Marple, 1978; Marple & McCormack, 1983); (7) the personal dust aerosol sampler (PDAS), a 2 L/min personal sampler with a respirable cut cyclone first stage and 0.8 μm cut impactor second stage to separate coal dust particles from diesel exhaust particles in dieselized coal mines (Marple et al., 1995b); (8) the Marple-Miller impactor (MMI), built as either a 30 or 60 L/min cascade impactor for the pharmaceutical industry (Marple et al., 1995a); (9) the next-generation pharmaceutical impactor (NGI), a cascade impactor that operates at any flow rate from 15 to 100 L/min (Marple et al., 2003a, 2003b, 2004); and (10) the personal environmental monitor (PEM), a two-stage impactor/filter sampler that operates from 2 to 10 L/min and has cut sizes of 1.0, 2.5, or 10 μm.

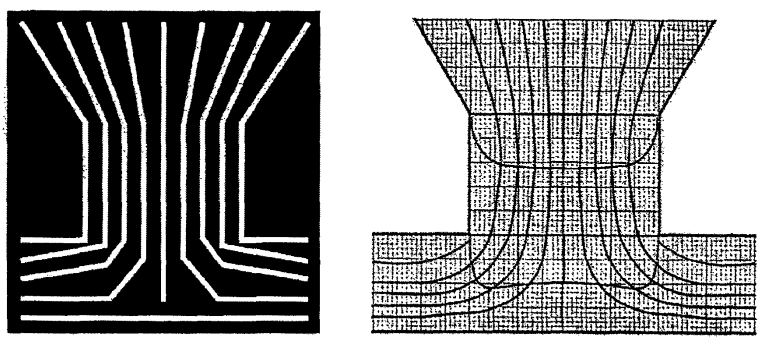


Figure 19. American Association for Aerosol Research logo (left) and flow field streamlines from Virgil Marple's (1970) dissertation A Fundamental Study of Inertial Impactors *(right).*

Source: Logo reproduced with permission from the American Association for Aerosol Research (AAAR).

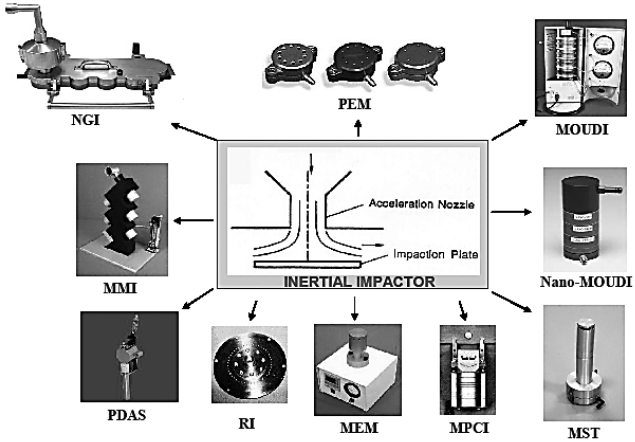


Figure 20. Various single stage impactors and cascade impactors designed from basic impactor concept.

Five of these impactors, the MOUDI, the nano-MOUDI, the MPCI, the PEM, and the NGI are widely used and deserve some explanation. The MOUDI was initially developed for EPA to conduct source apportionment studies (Marple et al., 1991). EPA requested that an impactor be developed that would spread the particles out uniformly on a 35 mm substrate so that the composition of the particles could be analyzed by X-ray fluorescence. This development was achieved by using multiple round nozzles on each stage and rotating the impaction plate relative to the nozzles. Each nozzle was located at a different distance from the center of rotation to obtain a uniform deposit. The micro-orifice feature was developed to achieve cut sizes as small as 0.056 μm at relatively high pressure drops across the nozzles. Each stage uses 2,000 nozzles that are approximately 50 μm in diameter each. Fang et al. (1991a) performed a study to determine how small the cluster diameter could be on a stage of multiple round nozzles before the cross-flow would lessen the sharpness of cut.

The nano-MOUDI was an extension of the MOUDI that allowed for three additional stages to obtain cut sizes as low as 0.010 μm. Relative humidity changes in the impaction region of the micro-orifice stages caused some concern, but Fang et al. (1991b) showed that the effect on this variable was small.

Our laboratory also provided instrument development work for the National Institute of Occupational Safety and Health (NIOSH), most notably the development of the Marple Personal Impactor (Rubow et al., 1987). The Particle Technology Laboratory originally developed the impactor to determine the size distribution and concentration of wood dust to which workers were exposed in machining hardwoods. The impactor used rectangular nozzles and integral nozzle and impaction plates, enabling a compact design. This impactor later found wide use in many types of personal sampling studies.

The PEMs were developed with cut sizes of 10, 2.5, and 1.0 μm for widespread personal sampling in EPA studies. They have a unique design with just three pieces that form the base, final filter, impaction plate, and nozzle plate. The standard PEM has 10 nozzles and operates at 10 L/min, or 1 L/min per nozzle. Other reduced flow rate impactors are created by simply reducing the number of nozzles. Using this technique, impactors of different flow rates can have identical flow fields and identical particle collection characteristics.

The NGI is an eight-stage impactor that Marple et al. (2003a) developed for the pharmaceutical industry to allow for easy automation. The NGI is unique because all of its impaction plates are on one plane. A quick-release locking handle enables a plate containing the nozzles of all stages to be lifted, exposing a tray with all of the impaction plates. Experimenters can remove this tray, insert another one, and close the impactor; the impactor is then ready for another run. This mechanism allows for much faster turnaround times than those for impactors in which the impaction plates are internal to a stack of nozzle plates. The impaction plates of the NGI are actually external to the impactor, allowing for easy access. The MMI also uses external impaction plates, in the form of external collection cups.

Some impactors that the Particle Technology Laboratory developed had respirable cut penetration curves. These impactors used multiple round or rectangular nozzles with different size nozzles on one stage. The number of nozzles and size of the nozzles were controlled such that the overall collection efficiency curve matched either the ACGIH or the BMRC respirable curves (Marple, 1978; Marple & McCormack, 1983).

Marple and Chien (1980) performed a study on virtual impactors that was similar to the fundamental study of inertial impactors. It was a parametric CFD study of virtual impactors similar to the one performed for plate impactors. The results from the CFD study of virtual impactors were used to design virtual impactors with sharper cuts, lower minor flow ratios, and lower particle losses than previous virtual impactors.

The most widely used virtual impactor that the Particle Technology Laboratory developed was a 2.5 μm cut high-volume virtual impactor (HVVI) developed for EPA to separate wood smoke particulate from other fugitive dust in areas in which there was substantial wood burning in home fireplaces (Marple et al., 1990). This virtual impactor operates at 40 ft^3/min and fits inside the Andersen high-volume 10 μm sampling head. The dimensions could be kept small by using a total of 12 virtual impactors, with 6 virtual impactors on each side of a cavity. The virtual impactors are located such that the axis of the 6 pairs are lined up to allow the exit flows from the receiving tubes (minor flows) to collide in the center of the cavity, slowing the speed of the large particles and therefore not allowing them to strike the opposite wall of the cavity where they would be lost to the wall. The laboratory designed a special version of the HVVI with a cut size of 1.0 L/min. This allowed a high-volume PM10/2.5/1.0 trichotomous sampler to be developed by using the 2.5 μm HVVI and the 1.0 μm HVVI in a cascade arrangement inside an Andersen 10 μm high-volume sampler (Marple & Olson, 1995; Lundgren et al., 1996).

Parallel with the ongoing research on impactors, from 1970 to 1983, the Particle Technology Laboratory also conducted research for the U.S. Bureau of Mines. In 1983, the laboratory became a charter member in the U.S. Bureau of Mines Mineral Technology Center for Respirable Dust, along with laboratories at Pennsylvania State University, West Virginia University, and the Massachusetts Institute of Technology. This work involved developing instruments and sampling techniques to measure the coal dust particle size distribution and concentration in order to reduce the occurrence of black lung disease (pneumoconiosis) in coal miners. Later, the work expanded to measuring the size distribution and concentration of diesel exhaust in dieselized coal mines. During this time, the laboratory developed instrument evaluation techniques and devices to evaluate these and commercially available instruments.

One of the devices to come out of this work was the fluidized bed dust generator, in which test dust was aerosolized from a fluidized bed of brass beads (Marple et al., 1978). The dust was fed into the fluidized bed from a dust supply chamber via a key-chain conveyer. The fluidizing action of the brass beads transferred the dust from the chain conveyer into the fluidized bed, breaking up any dust agglomerates into primary particles. The particles were then separated from the large brass beads in an elutriation chamber directly above the fluidized bed. This chamber also housed a radiation source to bring the electric charge on the particles to Boltzmann equilibrium.

Another aerosol generator was the small-scale powder disperser, which was developed to aerosolize coal dust particles collected on a filter. The intended purpose was to collect coal dust particles on a filter from parts of the mine where conventional samplers could not be used and then bring the filter to the surface where the dust particles could be resuspended and sampled. The dust generator later found a use in "rafter sampling" analysis, in which dust samples that had been settling for years could be resuspended in layers to provide some idea of how the dust changed as a function of time. The widest use of this dust generator has been to aerosolize bulk powder samples for analysis.

Much of this instrument evaluation work was done in a dust chamber in the Particle Technology Laboratory. The chamber was 4 ft in diameter and 8 ft high. Dust was introduced at the top of the chamber and flowed downward in a quiescent flow over the instruments being evaluated. Baffles in the chamber distributed the particles fairly uniformly throughout the chamber. However, to ensure that all instruments were exposed to the same concentration of the aerosol, the floor of the chamber where the instruments were sitting was continually rotated (Rubow & Marple, 1982).

Because dust particles are relatively large compared with atmospheric aerosols, the laboratory found that gravitational settling could be substantial in inertial impactors. This finding resulted in the shifting and distortion of the particle collection efficiency curves normally attributed to impactors. The laboratory performed this study using CFD analysis and collection efficiency curves generated with the Froude number as a parameter (Marple et al., 1992).

The work with the mining industry included many field studies to determine the dust concentration and particle size distribution in the mines. Many of the field studies were in underground coal mines, but some work was done in gold, talc, salt, and other types of mines. There were also a few studies in open-pit coal and taconite mines.

One of the more important results for the Bureau of Mines was the discovery of how to separate coal particles from diesel exhaust particles in mines that used diesel-powered equipment. The Particle Technology Laboratory did an extensive study of the diesel particulate size distribution in underground coal mines with the MOUDI sampler (Rubow & Marple, 1988). It was found that the coal dust particles were all larger than 0.8 µm and the diesel exhaust particles were all less than 0.8 µm (Rubow et al., 1990a). These discoveries led to the development of the PDAS and the virtual impactor personal aerosol sampler (VIPAS) that would separate particles at 0.8 µm, collecting the coal particles on one filter and the diesel particles on another (Marple et al., 1996). The exhaust particles from the diesel engines were small because the exhaust cooling water scrubbers removed the large exhaust particles.

In 1998 the Particle Calibration Laboratory was established for the expressed purpose of calibrating instruments. Although many instruments have been calibrated in the Particle Calibration Laboratory, the most notable was the calibration of the NGI for the pharmaceutical industry using Good Laboratory Practice procedures. This type of calibration is significant because as long as the NGI is built to this strict set of dimensions, no company in the pharmaceutical industry will have to recalibrate the instrument.

The work in the Particle Calibration Laboratory has led to the development of the multiplet reduction impactor (MRI). This impactor is attached to the exit of the vibrating orifice monodisperse aerosol generator (VOMAG) to remove all particles that have coalesced together to create particles larger than the primary particles. This allows the VOMAG-generated particles to be much more monodisperse than if the MRI were not used, providing for the high quality of particles needed to calibrate instruments accurately in the Particle Calibration Laboratory (Marple et al., 2005).

The Particle Calibration Laboratory also developed a new calibration technique for impactor evaluation and rapid check of cascade impactor cut sizes using a polydisperse challenge aerosol (Marple et al., 2005). In this technique, a polydisperse aerosol with a fluorescent dye tracer is generated and passed through the impactor. A histogram is constructed from the quantity of the aerosol deposited on each stage and the reported cut size of each stage. If the histogram does not show a smooth curve, one or more of the cut sizes of the impactor is incorrect. To find the correct cut sizes, the data are evaluated with DistFit (DisFit™, 2004) and the various cut sizes used in DistFit are adjusted to minimize the chi-square value. When the chi-square value is minimized, the cut sizes are correct.

Peter H. McMurry

Peter McMurry joined the Particle Technology Laboratory as an assistant professor in 1977, immediately after he completed his PhD in environmental engineering sciences with a physics minor at Caltech. At Caltech, McMurry worked under the guidance of Prof. Sheldon Friedlander. His doctoral dissertation addressed the dynamic behavior of aerosols undergoing gas-to-particle conversion, including nucleation in the presence of a preexisting aerosol. His research has continued to explore new particle formation, primarily atmospheric aerosols. In collaboration with colleagues, McMurry has also done research on characterizing properties of engine exhaust aerosols, contamination control in semiconductor processing equipment, and the synthesis of nanophase materials from nanoparticles produced in plasmas. His work has involved an integrated program of instrumentation development, theory and modeling, and experimental studies. He received the Fuchs Memorial Award in 2006, received a Guggenheim Fellowship in 2007, and became the editor-in-chief of *Aerosol Science and Technology* in 2008. He also served as the Head of the Mechanical Engineering Department from 1997 to 2007.

Peter H. McMurry
Source: Photo courtesy of the authors.

As with other Particle Technology Laboratory faculty, the development of new instrumentation has been a primary focus of McMurry. Significant contributions in this area include the ultrafine condensation particle counter (UCPC, commercialized as the "TSI 3025") (Stolzenburg & McMurry, 1991), the use of working fluids other than butanol that extend the lower detection limit of condensation particle counters (CPCs) to sizes approaching 1 nm (Iida et al., 2009), the development of tandem techniques for measuring aerosol physical and chemical properties (Park et al., 2008), aerodynamic lenses (Liu et al., 1995a, 1995b; Wang et al., 2005a, 2005b; Wang & McMurry, 2006a, 2006b), and multi-angle light scattering (Sachweh et al., 1995; Dick et al., 1996, 1998, 2000a). These tools improved our ability to accurately characterize the chemical and physical properties of aerosols.

McMurry's research on atmospheric aerosols has involved applications to visibility impairment, health effects, and global climatic effects of aerosols. Atmospheric observations have been the cornerstone of this work. McMurry's group has carried out measurements at the North Pole on a Swedish icebreaker, at the Mauna Loa observatory, above the Southern Ocean on a C130 aircraft, at the South Pole, as well as at many North American locations including Atlanta, Georgia, Los Angeles, California, St. Louis, Missouri, Mexico City, the Grand Canyon National Park, the Great Smoky Mountain National Park, and the Boulder, Colorado, area.

McMurry's early work on atmospheric aerosols focused largely on aerosol dynamics, especially for systems undergoing gas-to-particle conversion. He applied the concept of growth laws, originally introduced by Friedlander, to infer possible chemical mechanisms of particle growth by gas-to-particle conversion (McMurry et al., 1981; Wilson & McMurry, 1981; McMurry & Wilson, 1982, 1983). This work involved studying the dependence of particle growth rates on particle size. With colleagues, including Prof. J. Charles "Chuck" Wilson, McMurry showed that mass distributions of particles in dry climates tend to peak in the 0.2 to 0.3 μm range, whereas in more humid environments, average sizes range from 0.5 to 0.8 μm, as Figure 21 shows. McMurry and colleagues showed that this phenomenon occurs because the gas phase reactions, which lead to condensational growth primarily on small particles, dominate gas-to-particle conversion at low relative humidities, whereas liquid phase reactions are dominant at elevated relative humidities.

With Nagaraja Rao, McMurry carried out theoretical work on nucleation in the presence of an aerosol, results that continue to aid with interpreting atmospheric observations (McMurry, 1980, 1983; Rao & McMurry, 1989).

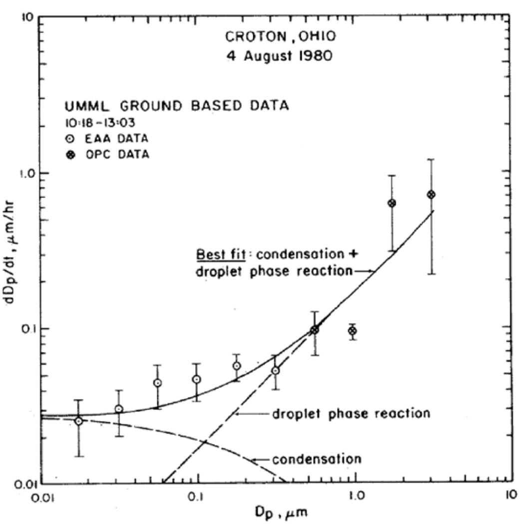


Figure 21. Contributions of condensation and droplet phase reactions to particle growth in the Columbus, Ohio, urban plume obtained using "growth law" analyses. Condensation of low vapor pressure species formed by gas phase reactions tends to dominate at low relative humidities and favors the growth of small particles. Liquid phase reactions occur at elevated relative humidities and favor the growth of larger particles.

Source: McMurry & Wilson (1982). Reprinted with permission from Elsevier.

Evan Whitby refined the modal aerosol dynamics (MAD) modeling method (Whitby & McMurry, 1997) that his father, Kenneth Whitby, had originally conceived. Several regional aerosol models incorporated this method.

Anand Gupta's doctoral research involved an experimental study of oxidation of sulfur dioxide by hydrogen peroxide in aqueous aerosol droplets (Gupta et al., 1995). His work set out to determine whether this process was responsible for the droplet reactions identified in the growth law analyses. This study was the first use of the tandem differential mobility analyzer (TDMA) method to study chemical transformations on aerosol particles.

Daniel Rader's doctoral research focused on the theoretical basis for using the TDMA as a quantitative tool for studying aerosol processes and properties (McMurry & Rader, 1986; Rader et al., 1987). Shortly after Rader graduated, McMurry and Mark Stolzenburg (1989) used the TDMA to carry out measurements of atmospheric aerosol water uptake in Los Angeles during the Southern California Air Quality Study (SCAQS). They showed that some particles of a given size grew significantly when humidified, whereas others did not, and concluded that Los Angeles aerosols are "externally mixed." Subsequent work showed that the nonhygroscopic particles consist of local primary soot emissions, whereas the hygroscopic particles are more aged, and contain significant amounts of secondary sulfates, organics, and nitrates (McMurry et al., 1996a). Modeling efforts provided some of the first direct evidence for the uptake of water by particulate organic compounds (Dick et al., 2000a). The hygroscopicity TDMA (HTDMA) is now used by many groups worldwide, as summarized in a recent review article (Swietlicki et al., 2008).

McMurry's atmospheric research in the late 1980s and early 1990s focused on visibility impairment. This work included measurements of water uptake and mixing characteristics with the TDMA, and size-resolved composition with the MOUDI impactor (Marple et al., 1991). Visibility studies were carried out in Los Angeles, at the Grand Canyon, and at the Great Smoky Mountain National Park. The work at the national parks was motivated by the "Prevention of Significant Deterioration" provision of the 1977 amendments to the Clean Air Act, which stipulated that pollution must not adversely affect visibility in so-called Class 1 areas. Xinqui Zhang carried out measurements that enabled him to create models for aerosol properties that reduced the number of assumptions needed to calculate species scattering efficiencies

(Zhang et al., 1993, 1994; McMurry et al., 1996b). Scattering efficiencies quantify the extent to which light scattering will decrease if the concentration of a species is decreased by a specified amount. Drs. Susanne Hering and Barbara Turpin were important collaborators in this work. Bill Dick's doctoral work on multi-angle light scattering (MALS) also sought to understand better the optical properties of aerosol particles. By measuring azimuthal variabilities in scattering, Dick was able to distinguish spherical from nonspherical particles (Sachweh et al., 1995; Dick et al., 1996, 1998). For the spherical particles, Dick was able to infer refractive index from measurements of the dependence of light-scattering intensities on polar angle. Dr. Bernd Sachweh was also an important contributor to the MALS work. Figure 22 is a photograph taken in the Grand Canyon during the winter of 1990, during an intensive study on the impact of the Navajo Generating Station on visibility impairment (Zhang et al., 1994).

New particle formation has been a topic of interest to McMurry ever since 1972, when Sheldon Friedlander suggested "nucleation in the presence of an aerosol" as a possible thesis topic. Although it was not known then that nucleation is an important atmospheric process, it was a conceptually interesting topic that had not been investigated. Work over the past 10 to 20 years has shown that atmospheric nucleation is indeed important (Kulmala et al., 2004). The development of instruments for detecting sub-10 nm

Figure 22. Light scattering from aerosols in the Grand Canyon, taken during the NGS Visibility Study in the winter of 1990.
Source: Photo courtesy of author.

particles enabled this discovery. A contour plot that shows a new particle formation event in Boulder, Colorado, is shown in Figure 23. Particle size is shown on the ordinate and time of day is on the abscissa. The magnitude of the particle size distribution function is shown in color. These measurements were obtained using scanning mobility particle spectrometers (SMPSs) including a nano-SMPS (3 to 40 nm), a conventional SMPS (20 to 300 nm), and an inclined grid mobility analyzer (IGMA), built by Prof. Hannes Tammet, for ion mobility distributions in the 0.5 to 6 nm mobility diameter range.

Early in the 1990s, with the encouragement of Prof. Robert Charlson, McMurry began to examine the effects of aerosols on global climate. His work in this area has focused on new particle formation, which can affect concentrations of cloud condensation nuclei and therefore the earth's albedo. The measurement of nanoparticle size distributions with the UCPC was a focus of his early work on this topic. McMurry and coworkers exploited John

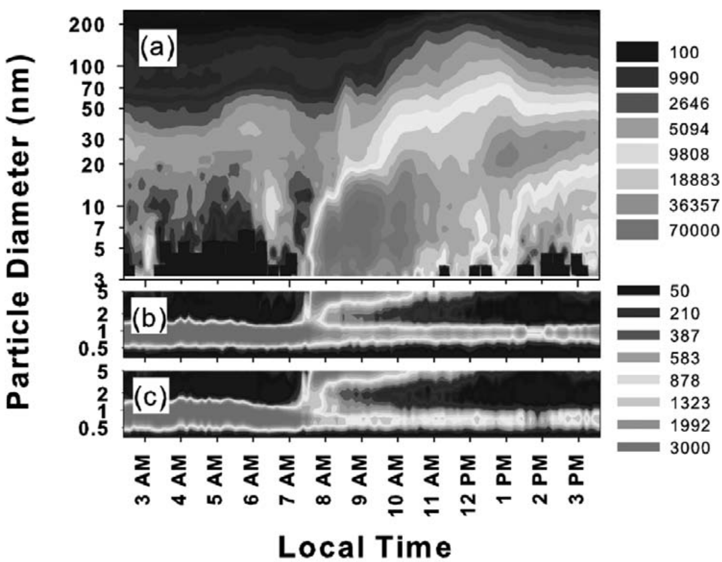


Figure 23. Contour plot of particle size distributions measured during a new particle formation event in Boulder, Colorado. Data in Figure 23a were obtained with a nano-SMPS (3–40 nm) and a conventional SMPS (20–300 nm). The distributions of positive and negative ions shown in Figure 23b and 23c were measured with Prof. Hannes Tammet's inclined grid mobility analyzer (IGMA). On this day, a new particle formation event occurred shortly after 7 a.m., and particles continued to grow until late in the afternoon.

Source: Courtesy of Kenjiro Iida.

Brockmann's observation that for particles smaller than ~10 nm, the final droplet size after condensation decreases with the initial particle size. This phenomenon occurs because, due to the Kelvin effect, small particles must travel further into the UCPC condenser to encounter a saturation ratio that is high enough to activate growth. Therefore, small particles have less time to grow, and they grow to a smaller final size. This observation was developed into the pulse height analysis (PHA) technique for measuring sub-10 nm size distributions (Saros et al., 1996; Weber et al., 1998a; Dick et al., 2000b). In work that is not yet published, Chongai Kuang developed the nanoparticle growth (NPG) instrument system that enables Kelvin effect sizing down to about 1.2 nm.

In 1992, McMurry joined forces with Dr. Fred Eisele of the National Center for Atmospheric Research (NCAR) to study the formation of atmospheric particles by homogeneous nucleation. Eisele and coworkers had developed a chemical ionization mass spectrometric technique for measuring sulfuric acid (H_2SO_4) vapor at mole fractions as small as 10-15 ppm and McMurry and coworkers had developed the UCPC. Theory suggested that H_2SO_4 was a likely participant in nucleation. They reasoned that parallel measurements of H_2SO_4 and freshly nucleated nanoparticles would provide new information about nucleation mechanisms. Rodney Weber's doctoral research focused on this topic. He carried out field studies with Eisele at Mauna Loa, Hawaii, Idaho Hill, Colorado, and over the Southern Ocean during ACE-I. Weber's work led to a number of important discoveries (Weber et al., 1995, 1999; Weber & McMurry, 1996; McMurry et al., 2000). Figure 24 illustrates one of these discoveries, which shows the dependence of 3 nm particle production rates on H_2SO_4 vapor concentrations for measurements carried out at Mauna Loa and in the Rocky Mountains at Idaho Hill (Weber et al., 1996). These results show that particle production rates vary as $[H_2SO_4]^p$ $(1 < p < 2)$ in contrast to the binary H_2SO_4-water nucleation theory, which predicted a much stronger dependence on H_2SO_4. Furthermore, the results showed that particle production rates at a given H_2SO_4 vapor concentration are orders of magnitude higher than theory predicts and that biogenic sources such as penguin colonies (!) greatly enhance rates of particle production (Weber et al., 1998b).

Recent work by Chongai Kuang has shown that for all studies carried out by the McMurry-Eisele team since 1992 in locations around the globe, nucleation rates (i.e., production rates of particles in the 1 nm range) vary

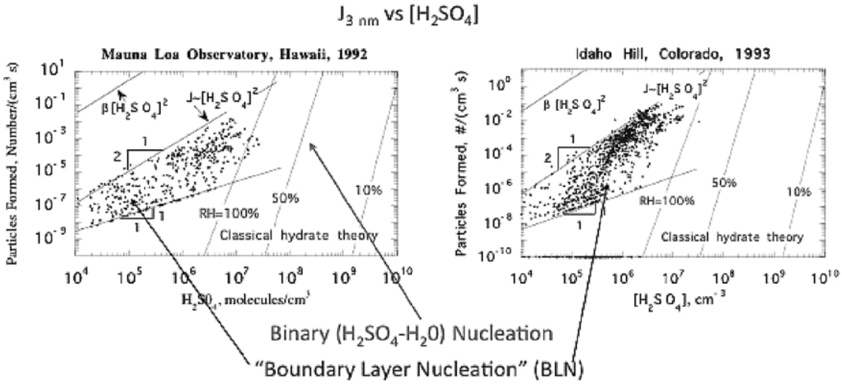


Figure 24. Dependence of particle production rates on sulfuric acid (H_2SO_4) vapor concentrations for measurements on Mauna Loa, Hawaii, and in the Rocky Mountains of Colorado. Observed rates greatly exceed nucleation rates predicted by the theory for binary nucleation of H_2SO_4 and water and have a much weaker dependence on H_2SO_4 vapor concentration.

Source: Weber et al. (1996). Reprinted with permission of the publisher (Taylor & Francis Group, www.informaworld.com).

as $[H_2SO_4]^2$ (Kuang et al., 2008). Rodney Weber also showed that growth rates of freshly nucleated particles are often 10 times faster than can be explained by H_2SO_4 vapor condensation (Weber et al., 1997), the only growth mechanism that was incorporated in atmospheric aerosol models at that time. As McMurry originally predicted in his doctoral research (McMurry & Friedlander, 1979), these high nucleation and growth rates cause new particle formation to be an important atmospheric process.

Much of McMurry's work over the past 15 years has attempted to understand the chemical processes responsible for the high rates of nucleation and particle growth observed in the atmosphere. With Hiromu Sakurai, McMurry collaborated with Fred Eisele and Jim Smith at NCAR to develop the thermal desorption chemical ionization mass spectrometer (TDCIMS) for measuring the composition of freshly nucleated particles as small as 7 nm (Voisin et al., 2003; Smith et al., 2005, 2008, 2010). Jim Smith's TDCIMS measurements in Boulder and Mexico City show that nucleated particles sometimes contain large quantities of organics and nitrates in addition to smaller amounts of sulfates. This observation helps to explain why observed growth rates are so high, but the chemical mechanisms responsible for the uptake of those species remain unresolved.

In 2005 McMurry and Fred Eisele began a major collaborative effort to bridge the gap in measurements between molecules, neutral molecular clusters and nanoparticles. This involved the efforts of Eisele and coworkers (especially Dr. Jun Zhao) to develop the cluster chemical ionization mass spectrometer (cluster CIMS) to masses up to 1,000 amu. At the same time, McMurry worked with Kenjiro Iida, Chongai Kuang, Jingkun Jiang, and Modi Chen to extend measurements of aerosol size distributions down to ~1 nm, which would overlap with cluster CIMS data. These measurements promise to elucidate the chemical mechanisms responsible for the fast rates of nucleation that have been observed in the atmosphere (Zhao et al., 2010; Jiang et al., in press).

Another focus of McMurry's work is particle characterization. Aerosol particles are often highly complex and may be irregularly shaped, contain multiple phases, and include many different compounds. McMurry has developed methods for accurately measuring certain properties of these complex particles. His first work in this area involved measurements with the TDMA (DMA-DMA). Subsequently, using the TMDA to separate particles according to size and hygroscopicity, he was able to use transmission electron microscopy (TDMA-TEM) to determine how the hygroscopic and nonhygroscopic particles differ morphologically and chemically (McMurry et al., 1996a). Dr. Kensei Ehara's development of the aerosol particle mass analyzer (APM) was also important (Ehara et al., 1996). The APM classifies particles by mass-to-charge ratio, independent of particle shape, density, and other characteristics. In his doctoral research, Kihong Park showed that by using the APM in series with other instruments (e.g., DMA-APM, TDMA-APM, DMA-APM-TEM), one can measure particle properties including "effective density," inherent material density, dynamic shape factor, and so forth. One can also determine transport properties such as diffusivity, sedimentation speed, and aerodynamic diameter. Dabrina Dutcher showed that by adding the aerosol time-of-flight mass spectrometer to this battery (TDMA-APM-ATOFMS), one can add information on vacuum aerodynamic diameter and composition. Dr. Hiromu Sakurai and Prof. David Kittelson were key collaborators in this research. These measurement methods can establish the relationships among different measures of size (geometric, aerodynamic, mobility) and provide information on differences in various properties (density, fractal dimension, volatility, dynamic shape factors, etc.) for particles of a given mobility size. In 2006 McMurry and Dr. Joachim Pagels joined forces with Prof. Renyi Zhang and Dr. Alexei Khalizov at Texas

A&M University to apply tandem DMA-DMA-APM-TEM measurements to study the effect of cloud processing on morphological and optical properties of chain agglomerate soot particles (Zhang et al., 2008). This study, which quantified the extent to which condensation and evaporation of liquids on soot agglomerates cause them to collapse into more compact forms, nicely illustrates the power of such tandem measurement methods. More recently, a collaborative effort with Prof. Sotiris Pratsinis applied the DMA-APM-TEM method to study properties of silica agglomerates produced in flames. Jacob Scheckman (2008) showed that this approach can be used to rapidly and accurately quantify properties of these agglomerates, including their fractal dimension and dynamic shape factor.

McMurry has also worked in other areas. In the late 1980s, while participating in meetings of the Semiconductor Contamination Control consortium led by Benjamin Liu, he became interested in the formation of contaminant particles in semiconductor processing chambers by gas-to-particle conversion. Although the chemistry was different, the process was analogous to the formation of secondary atmospheric aerosols. This work required the measurement of very small particles at low pressures, which led to the development of the particle beam mass spectrometer (PBMS). Dr. Paul Ziemann was instrumental in this work (Ziemann et al., 1995a, 1995b, 1996; Ziemann & McMurry, 1997, 1998; McMurry et al., 1996c). We used the PBMS to study nucleation and growth of contaminant particles in semiconductor processing equipment (Rao et al., 1998a, 1998b, 1998c; Nijhawan et al., 2000, 2003; Kim et al., 2002). Aerodynamic lenses were key to the development of the PBMS. Faculty collaborators on this work included Prof. Steve Campbell (EE), Prof. Steve Girshick, Prof. David Kittelson, and Prof. Uwe Kortshagen, and Sandeep Nijhawan and Taesung Kim wrote theses on this topic.

The development of aerodynamic lenses was an outcome of McMurry's work on semiconductor contamination control. The PBMS required that particles be focused into tightly collimated beams, and McMurry and coworkers developed aerodynamic lenses to accomplish this. These simple devices consist of a series of thin plate orifices mounted in a cylindrical tube, as illustrated in Figure 25. Aerodynamic lenses typically operate at pressures well below atmospheric to ensure that the flow is laminar, which is one reason they were suitable for sampling downstream of semiconductor processing equipment. The image at the top of Figure 25 shows gas streamlines, and the image at the bottom of Figure 25 shows particle trajectories, which are significantly affected by diffusion in this example, during flow through a sequence of aerodynamic lenses. Particles that have Stokes numbers close to 1.0 move toward the centerline as the gas flows through the lens. By using a series of lenses, particles can be concentrated along the centerline, thereby enabling the formation of a tightly collimated beam upon expansion through the downstream nozzle. Aerodynamic lenses, which enable efficient transport of particles from atmospheric pressure into low-pressure chambers, have been key to enabling real-time analyses of particle composition by mass spectrometry in instruments such as the TSI 3800 ATOFMS and the Aerodyne family of aerosol mass spectrometers (AMS). Peng Liu carried out the first work on this topic. Xiaoliang Wang later showed how to design

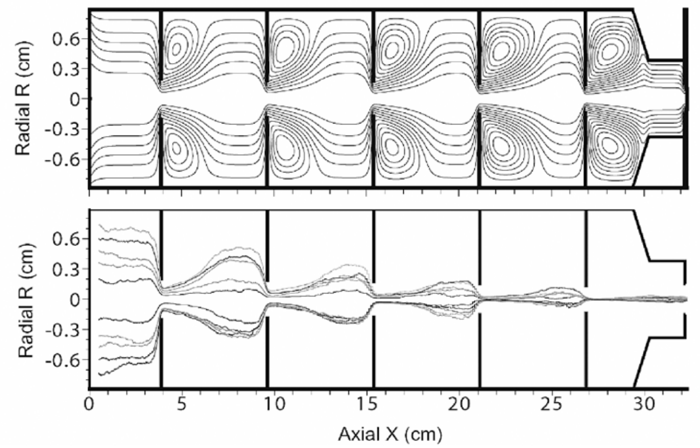


Figure 25. (Top) Gas flow streamlines and (bottom) particle trajectories in an aerodynamic lens. Note that particles with Stokes numbers close to 1.0 are inertially concentrated along the centerline. The fluctuations in the particle trajectories are due to the effects of diffusion.
Source: Courtesy of Xiaoliang Wang.

aerodynamic lenses that focus particles as small as 3 nm. Together with Peng Liu and McMurry, Prof. David Kittelson and Dr. Paul Ziemann were co-inventors of aerodynamic lenses.

McMurry has also collaborated with Prof. Girshick, Prof. Joachim Heberlein, and others on formation of nanoparticles in thermal plasmas. This work initially addressed nucleation and growth. More recently they have focused on the use of such nanoparticles to produce nanophase films with unique mechanical properties (Rao et al., 1995a, 1995b, 1998b; Girshick et al., 1990, 1993, 1996; Heberlein et al., 1997; Tymiak et al., 2001; DiFonzo et al., 2000). Key to this work is the hypersonic impaction of nanoparticles to form dense deposits (Fernandez de la Mora et al., 1990), and the use of aerodynamic lenses to produce tightly collimated beams for producing "high-definition" deposits.

David Y. H. Pui

David Pui became director of the Particle Technology Laboratory in 1995. He received the Distinguished McKnight University Professorship at the University of Minnesota in 1999 and the L. M. Fingerson/TSI Chair in Mechanical Engineering in 2002. As of 2010, he had published more than 200 journal papers and had received 17 patents. At the 2010 International Aerosol Conference (IAC2010) in Helsinki, he received the Fuchs Memorial Award in recognition of his research on industrial applications of aerosol technology.

David Y. H. Pui
Source: Photo courtesy of the authors.

Pui's research has focused on developing instrumentation and experimental techniques for environmental research and industrial applications. He collaborated with Liu (Liu & Pui, 1974a) on the development of the mobility classification technique for producing monodisperse aerosols of known size and concentration for instrument calibrations and fundamental research. His early particle standardization work was the basis of his collaboration with George Mulholland at National Institute of Standards and Technology (NIST) in developing 60 nm and 100 nm nanoparticle Standard Reference Materials (SRMs) (Mulholland et al., 2006).

Since the early 1990s, Pui has devoted significant effort to nanoparticle/nanotechnology research. Pui and Da-Ren Chen (Chen et al., 1995a; Chen & Pui, 1997) developed the electrospray technique for producing and dispersing monodisperse nanoparticles in the size range from 2 nm to 1 μm. In 1997, he and Chen wrote an editorial and edited a special issue of *Journal of Aerosol Science* on "Nanometer Particles: A New Frontier for Multidisciplinary Research." He organized a series of workshops and symposia on Nanoparticles, including the 1997 Department of Energy (DOE) Nano-Instrument Workshop, and the 1998–2002 National Science Foundation–European Science Foundation (NSF-ESF) Symposia (with Heinz Fissan), and the 2005 Nanoparticle and Occupational Health Symposium (with Andrew Maynard). Several books/proceedings resulting from the workshops/symposia (e.g., Friedlander & Pui, 2003; Maynard & Pui, 2007a, 2007b) have demonstrated to young researchers that aerosol is an enabling discipline and have pointed out the roles that young researchers can play in the ongoing nanoparticle/nanotechnology revolution.

Pui has also made seminal contributions to research on the following topics: particle charging and neutralization, sampling and transports, aerosol filtration, aerosol instrumentation, and micro- and nano-contamination control in semiconductor manufacture. He has also found novel applications for electrospray in nanobiotechnology (Chen et al., 2000), for which he has received six patents. These patents formed the basis of a new start-up company, Nanocopoeia, in St. Paul, Minnesota.

Mobility Classification for Producing Particle Standards

The paper, "A Submicron Aerosol Standard and the Primary, Absolute Calibration of the Condensation Nuclei Counter," by Liu and Pui (1974a) is perhaps one of the most cited aerosol instrumentation papers (cited nearly 250 times by 2006). It described the use of the DMA (Figure 26) to classify a monodisperse aerosol with known particle size, and the use of an electrometer to measure the aerosol concentration, with a high degree of precision and accuracy. It was the first available "particle standard" that gave both the airborne particle size and concentration, down to a particle diameter of approximately 10 nm.

The availability of the particle standard attracted several aerosol pioneers to calibrate and compare their particle counters and sizers with this standard. David Sinclair brought his collimated-holes diffusion battery to Minnesota to compare the particle sizes measured by his diffusion battery with those determined by the DMA (Sinclair et al., 1976). Excellent agreement was shown between the two techniques, which was a first verification of the Einstein relationship using the aerosol technique. Jean Bricard and Michel Pourprix brought their continuous flow condensation nuclei counter for particle concentration comparison, which became the CPC that TSI commercialized. Austin Hogan and Ted Rich brought the Pollak counter for particle concentration comparison and calibration (Liu et al., 1975). The standard was also used in several workshops for instrument calibrations. The first of these workshops, the "Workshop on Ultrafine Aerosol" (WUFA), was held in Vienna and was hosted by Othmar Preining, Paul Wagner, and Wladyslaw Szymanski (Liu et al., 1982a, 1984). These studies firmly established the mobility classification technique as the most important technique for submicron aerosol sizing and classification, down to particles as small as 10 nm and below. Sem and Sakurai have nearly completed an International Standardization Organization (ISO) standard (ISO TC24/SC4/WG12) on the differential mobility sizing of aerosol particles at the time of publication, and another ISO working group is being convened to work on

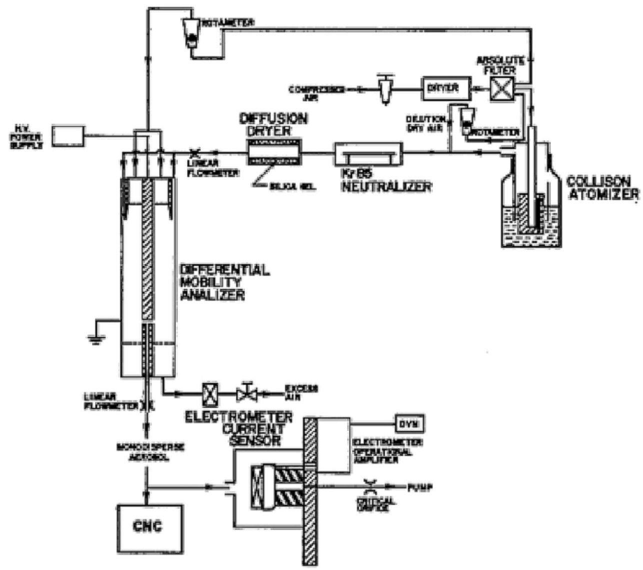


Figure 26. Schematic diagram of the monodisperse aerosol generator using the mobility classification technique.
Source: Liu & Pui (1974a). Reprinted with permission from Elsevier.

a new standard for the calibration of condensation particle counters using aerosol electrometry.

Using the mobility classification method, Pui and Mulholland collaborated in establishing the first NIST 100 nm SRM particles (Kinney et al., 1991) in 1991 (Figure 27). More recently, this technique was applied to establish the 60 nm and a second batch of the 100 nm SRM particles (Mulholland et al., 2006). As of 2008, the 60 nm SRM particle was the smallest size nanoparticle standard maintained at NIST.

Electrical Aerosol Analyzers

Liu and Pui (1975) developed the widely used electrical aerosol analyzer (TSI Model 3030 EAA). The technique used aerosol charging, mobility analysis, and electrometer detection. Whitby first established the principle in his early version of the analyzer. TSI 3030 EAA was compact and robust, and

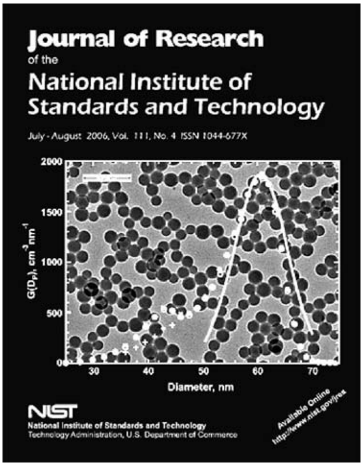


Figure 27. National Institute of Standards and Technology (NIST) 60 nm and 100 nm Standard Reference Material (SRM) particles published in the NIST journal.

became the workhorse for measuring submicron atmospheric aerosol size distributions during the 1970s and 1980s. Some of the EAA components are still in use today (e.g., the TSI Model 3068A Aerosol Electrometer for measuring aerosol concentration).

In collaboration with Heinz Fissan, Pui and Chen (Fissan et al., 1996) compared the performance of four DMAs for nanometer aerosol measurements. Subsequently, they collaborated with TSI to develop the nano-DMA (TSI 3085) for measuring aerosol size distributions in the 3 to 100 nm particle size range (Figure 28) (Chen et al., 1997).

Using the nano-DMA, a bipolar charger and an electrometer, a fast-scan nanometer aerosol size analyzer was developed to perform rapid (2-second cycle time) particle size distribution measurement in the 3 to 100 nm size range, which jet-engine emission measurements demonstrated successfully (Han et al., 2000).

Electrical Charging and Neutralization

Pui's MS thesis and doctoral dissertation at the University of Minnesota examined electrical charging by unipolar ions and by biopolar ions (neutralization) (Pui, 1973, 1976). Charging of aerosol particles by ions or free electrons is an important phenomenon in aerosol physics with many practical applications. For submicron aerosols and nanometer aerosols, the electrical force on the charged particles is the dominant force, which can be used to manipulate the aerosol particles for the purpose of measurement, classification, or control. Its application includes air pollution measurement and control, as well as process monitoring for materials production.

Pui performed definitive experiments on aerosol charging by unipolar ions (Liu & Pui, 1977), charge conditioning by bipolar ions (neutralization) (Liu & Pui, 1974b, 1974c), and charge conditioning by free electrons (Liu & Pui, 1977; Romay & Pui, 1992a). The studies have extended to charging under low pressure (Romay et al., 1991) and in high-purity gases (Adachi et al., 1987; Romay & Pui, 1992b). They have provided fundamental data for testing various theories on the combination coefficients of ions and particles in the

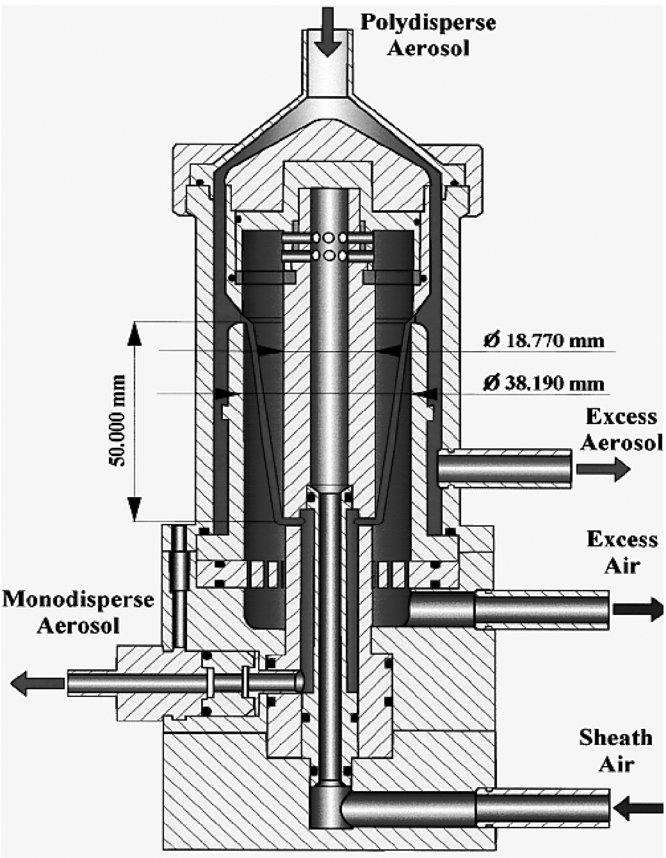


Figure 28. The nano-differential mobility analyzer (nano-DMA) designed for 3–100 nm particle size range.

transition and free molecular regimes. Several practical aerosol chargers and neutralizers have been developed, including the unipolar charger used in the electrical aerosol analyzer, the neutralizers that use the krypton-85 source (Liu & Pui, 1974c) and the polonium-210 source (Liu et al., 1986b; Adachi et al., 1990; Adachi et al., 1992a), and the unipolar and bipolar chargers using corona ionizers (Adachi et al., 1990, 1992b).

Pui's recent research on these topics includes developing a high-efficiency, high-throughput aerosol charger for the nanoparticle size range (Chen & Pui, 1998). Experiments have shown that the extrinsic charging efficiency of the charger is approximately 10 to 100 times higher than the best available charger for particles smaller than 10 nm. The charger is expected to have significant technological applications because it provides 10 to 100 times more throughput for nanoparticle classification and a 10- to 100-fold increase in detection sensitivity for size distribution measurement.

Aerosol Sampling, Transport, and Deposition

Pui and colleagues studied the basic topics of sampling, transport, and deposition in inlets and tubes, as well as deposition in bends and contractions. The fundamental results are subsequently used to study more complex topics of transport in cleanrooms and semiconductor process equipment, as well as deposition on semiconductor wafers, disk drives, and pressure reducers. A good example of the impact of his work in collaboration with Liu was the development of the PM_{10} inlet, which was accepted by EPA and the international community as a standard inlet (Liu & Pui, 1981; Liu et al., 1983c).

Pui and colleagues performed a series of numerical and experimental studies of particle deposition in bends (Pui et al., 1987; Tsai & Pui, 1990; Sato et al., 2001) and in contractions (Ye & Pui, 1990; Chen & Pui, 1994; Sato et al., 2002), leading to practical sampling systems for atmospheric measurement (Ye et al., 1991b; Poon et al., 1994a, 1994b) and for high-purity gas measurement (Lee et al., 1995; Rubow et al., 1990b). Studies of particle deposition on semiconductor wafers have led to methods for preventing particle deposition using thermal gradients during semiconductor manufacturing (Ye et al., 1991a; Opiolka et al., 1990). Studies of particle flows in the near wake of a disc (Gomes et al., 1993, 1999), under vacuum conditions (Sato et al., 2002), and particle rebound and adhesion (Tsai et al., 1990a), have provided insight in contamination control in computer disk drives (Tsai et al., 1991b, 1992), cleanrooms and semiconductor processing equipment (Kinney et al., 1996, 1997; Bae et al., 1997).

Aerosol Filtration and Dust Collectors

In 1991, Liu and Pui started the Center for Filtration Research (CFR) at the University of Minnesota. The center has been supported by a total of 14 filter companies as well as NIOSH. The current members of the center include 3M, Boeing, Cummins, Donaldson, DuPont, Entegris, W. L. Gore, Samsung Electronics, Shigematsu, TSI, and affiliated member NIOSH. Many fundamental and applied filtration research studies were performed under CFR. Pui and Chen studied the optimal design of pleated filters by developing a numerical model using a finite element method. A general correlation curve was obtained which reduces the filter and flow optimization parameters into a single curve for all six commercial filter media (Chen et al., 1995b, 1996). This work has subsequently been extended to ventilation filters at high flow, and to include effects of filter loading (Endo et al., 1997a, 1997b). These fundamental studies have brought filter pleating design from an empirical art to an exact science. Pui and colleagues have also performed laboratory and field measurements of industrial dust collectors (Liu et al., 1986c; Bergin et al., 1989; Fay et al., 1989), and have extended the work to include bioaerosol filtration (Kuehn et al., 1994; Kemp et al., 1995a, 1995b). Several papers from the doctoral dissertation of Liming Lo (Lo et al., 2008, 2010a, 2010b) provide the basic criteria for the design of reversed-pulsed dust collector for cleaning dust-loaded filters.

Electrospray and Its Applications

The electrospray research began with Da-Ren Chen's doctoral dissertation, which Pui advised. Two papers by Chen and Pui (Chen et al., 1995a; Chen & Pui, 1997) outlined the basic principles and scaling laws for operating the electrospray. The electrospray can be used to produce monodisperse airborne nanoparticles by spraying a solution with known concentration of solute, or by dispersing a colloidal suspension of standard spheres of PSL, quantum dots, and so forth.

Pui and Chen (U.S. Patent No. 6,399,362, 2002; U.S. Patent No. 6,764,720, 2004) introduced the dual-capillary electrospray concept that greatly enhanced the applications of the electrospray technique (Chen & Pui, 2009). For example, the start-up company Nanocopoeia was able to use the dual-capillary technique to spray drug-encapsulated polymers on medical stents with tunable drug release profiles. Chen and Pui collaborated with Chris Wendt in pulmonary medicine (Chen et al., 2000; Chen & Pui, 1997) to demonstrate the use of electrospray for gene transfection (Figure 29).

Ongoing Research Activities

Pui's recent research has focused on the environmental, health, and safety studies of nanoparticles. He gave several keynote and plenary talks at international conferences on this topic. The risk of inhaling nanoparticles is a function of both the hazard and exposure. Pui performed research addressing the hazard and exposure assessments of nanoparticles. He collaborated with Gunter Oberdörster at the University of Rochester, New York, and with Pratim Biswas and Da-Ren Chen at Washington University in St. Louis on nanoparticle toxicology; their research was funded by the Air Force Research Laboratory (AFRL). Chen and Pui developed an electrospray system to deliver single nanoparticles for in vitro and in vivo studies conducted at Oberdörster's laboratory. By providing unagglomerated airborne nanoparticles for

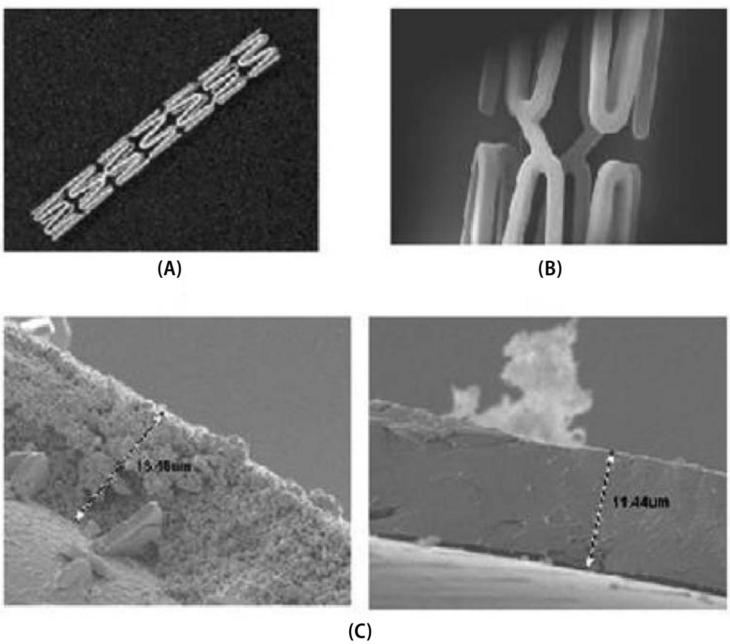


Figure 29. (A) A typical stent for the human use, (B) a coated stent prepared by electrospray technique, and (C) the morphology variation of the coated layer, prepared by electrospray technique, on the stents.

inhalation study, this research aims to assess the realistic inhalation exposure with the traditional instillation study.

To assess nanoparticle exposure, Pui collaborated with Fissan in setting up a new metric for exposure study. This research was initiated by the doctoral dissertation of Pui's student Hee-Siew Han. Using an electrical aerosol detector, they assessed using this integral aerosol monitor for measuring the surface area of atmospheric aerosol (Wilson et al., 2005). The validity of this approach was proven in a field test (Woo et al., 2001). Fissan and Pui (Fissan et al., 2007; Shin et al., 2007) found that by tuning the "ionizer voltage" of the Electrical Aerosol Detector (EAD), the signal can be related to the nanoparticle surface area deposited in different regions of the human lung. Subsequently, TSI has produced two commercial instruments—the Nanoparticle Surface Area Monitor (TSI Model 3550 NSAM) and the portable version Aerotrak (TSI Aerotrak 9000)—providing this new metric for exposure study. Ongoing research includes using the NSAM for "Experimental and Numerical Simulation of the Fate of Airborne Nanoparticles from a Leak in a Manufacturing Process to Assess Worker Exposure," a project funded by the National Science Foundation (NSF).

Pui's ongoing research activities involve using the nanoparticle tools he has developed and applying modeling methodology to perform systematic studies on nanoparticle research. Under Intel sponsorship, he collaborated with Fissan to develop protection schemes for extreme ultraviolet lithography (EUVL) systems, which are considered to be the next generation chip manufacturing technology. Photomasks, in a mask carrier or inside a vacuum scanner, need to be protected from nanoparticle contamination larger than 20 nm diameter, the minimum feature size expected from this technology. By using thermophoretic, particle drag, and gravity forces as well as the cover plate concept, Pui and colleagues developed several schemes to prevent nanoparticle deposition on EUVL systems down to 20 mTorr (Figure 30). The research has already resulted in a series of 15 journal papers (Asbach et al., 2006, 2007, 2008; Kim et al., 2006a, 2006b, 2006c; Yook et al., 2007a, 2007b, 2007c, 2008a, 2008b; Wang et al., 2008a). Some of the approaches have been implemented in mask carrier and scanner designs.

Most engineered nanoparticles are produced and dispersed in agglomerate form; however, most aerosol instruments measure equivalent diameters assuming a spherical particle. Pui and collaborators performed fundamental research on the mechanics of nanoparticle agglomerates (Shin et al., 2009a,

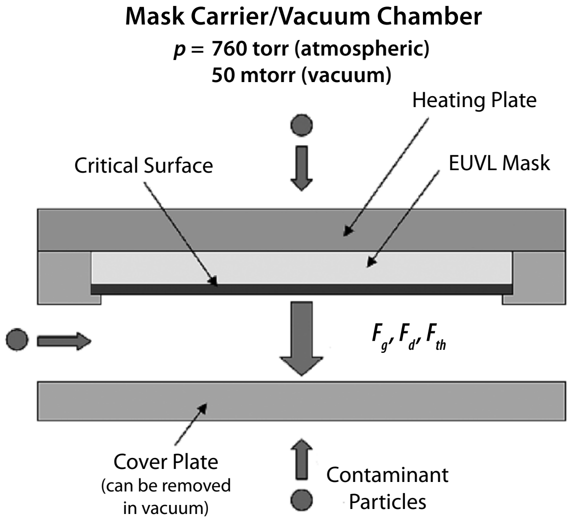


Figure 30. Use of thermophoretic, particle drag and gravity forces and the cover plate concept to prevent nanoparticle deposition on extreme ultraviolet lithography systems down to 20 mTorr.

2009b, 2009c) and the charging behavior of agglomerates (Shin et al., 2009c; Qi et al., 2009). Based on these fundamental studies, the Particle Technology Laboratory has developed and is currently field testing a real-time instrument for measuring nanoparticle agglomerates.

Nanoparticle research is also an important topic for CFR. Filters are used to collect nanoparticle products from reactors and are used in personal protection equipment to protect workers from nanoparticle exposure. Industry and government agencies are concerned with recent studies that have pointed to the potential penetration of nanoparticles through the filters due to thermal rebound. Pui and colleagues performed a systematic study of nanoparticle filtration using standard filters and filter media used in personal protection equipment (Kim et al., 2007a). Pui and colleagues compared the experimental results with models developed for nanoparticle filtration (Wang et al., 2007). The study found no thermal rebound of nanoparticles down to 3 nm diameter. Further, a cabin air filtration project found that filtration is an effective and low-cost way to protect commuters and nano-workers from nanoparticle exposures (Pui et al., 2008; Qi et al., 2008). Ongoing research projects compare the filtration efficiency between single nanoparticles and nanoparticle agglomerates (Kim et al., 2007b), load nanofiber filters with agglomerate and dust particles, and study the improved figure of merit of nanofiber filters (Wang et al., 2008b).

One of the ultimate objectives for CFR research is to develop a comprehensive filter performance model to help member companies design novel filters with improved performance. We would like to incorporate CFR research in this model, including nanoparticle and nanofiber filters, solid and liquid coated particle loading, filter pleating design, agglomerate filtration, and electrostatic filtration. The member companies have developed and are evaluating a Web-based software. The software allows filter manufacturers to design composite filters and compare different designs using a figure of merit approach. This will enable manufacturers to optimize filter performance under different conditions and to maintain and extend filter life (Figure 31).

Other new initiatives being conducted under CFR include (1) the use of aerosol techniques to evaluate liquid-borne particle filtration, (2) the removal of volatile organic compounds (VOCs) and airborne molecular contaminants (AMCs) using modified TiO_2 nanoparticles, and (3) the filtration of bioaerosols including bacteria and viruses. Several papers are being prepared on these topics.

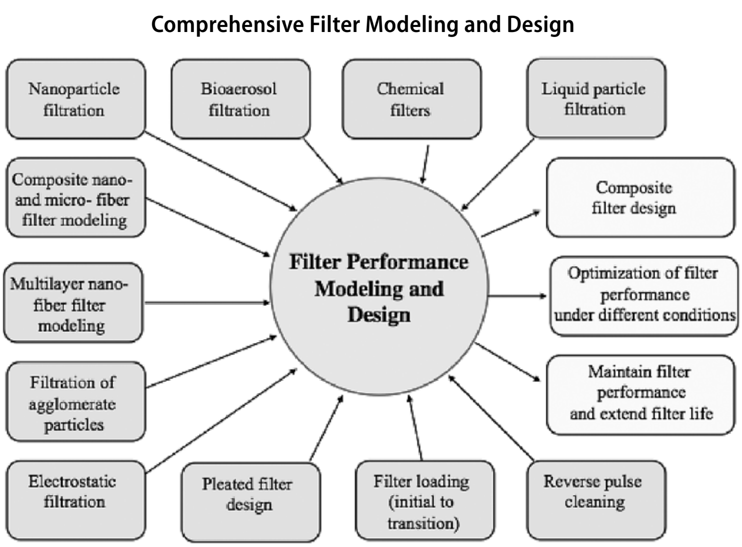


Figure 31. Filter performance modeling to design and optimize filters and to extend filter life.

Thomas H. Kuehn

Thomas Kuehn
Source: Photo courtesy of the authors.

Prof. Kuehn joined the Department of Mechanical Engineering in March 1983 and was assigned to the Environmental Division, at that time headed by Whitby. The position was a continuation of the teaching and research activity developed by Prof. James Threlkeld in the area of thermal environmental engineering. Both Threlkeld and Kuehn were faculty members at Iowa State University prior to joining the faculty at Minnesota. Threlkeld used his lecture notes developed while teaching at Iowa State as the basis for his pioneering textbook, *Thermal Environmental Engineering*, first published in 1962. The publisher, Prentice Hall, contracted with professors Kuehn and Ramsey to revise and update the text that was then published as the third edition in 1998 (Kuehn et al., 1998).

Prof. Kuehn's background was primarily in the thermal sciences (e.g., fluid mechanics, thermodynamics, and heat and mass transfer). He had developed expertise in both experimental and numerical approaches. Research topics included natural convection heat transfer in enclosures (Kuehn & Goldstein, 1976, 1980a), providing benchmark solutions to the classical problem of natural convection from a horizontal circular cylinder (Kuehn & Goldstein, 1980b); the performance of finned tube heat exchangers, including the discovery of a similarity solution for conjugate conduction-natural convection heat transfer in fins (Kuehn et al., 1983; Kwon & Kuehn, 1983; Tolpadi & Kuehn, 1984); and analysis of heat transfer in above-grade and below-grade building structures (Szydlowski & Kuehn, 1981; Kuehn, 1982).

Upon joining the faculty at the University of Minnesota, Kuehn began collaborative research activities with others in the Particle Technology Laboratory. He brought his expertise with numerical solution techniques to the Navier-Stokes equations for fluid flow simulations and his experimental measurement skills to investigating indoor and outdoor environmental parameters. Kuehn mainly collaborated with Pui, who was promoted to the faculty shortly after Kuehn arrived. These collaborative efforts primarily focused on applications of technology because others in the Particle Technology Laboratory had experience developing instrumentation and test protocols. In addition to laboratory and field measurements, investigation of applications involved many levels of numerical simulations. A brief review of selected projects and primary outcomes follows.

Cleanrooms

One of the earliest studies was co-sponsored by the Institute of Environmental Sciences (IES) and the Particulate Contamination Control Research Consortium at the University of Minnesota. In the 1980s, there was considerable discussion about and research activity to improve the performance of cleanrooms used for the manufacture of semiconductors. One design, pioneered by Ed Gallo at IBM, was a tunnel-type configuration in which clean aisles with solid floors were separated by return chases that also served as maintenance corridors. Rather than trying to maintain a clean environment in the entire space, the design focused on the areas above process tools and benches where contamination was most likely to occur. The Microelectronics Research Laboratory at the University of Minnesota had adopted and recently constructed such a design. Thus we had a unique opportunity to assess the performance of this design. Kuehn and Pui approached the IES subcommittee charged with cleanroom performance and suggested a cleanroom flow modeling exercise in which a carefully detailed two-dimensional cross section through an at-rest cleanroom would be published in the IES Journal with well-described flow and particle source boundary conditions. IES would request submissions of numerical solutions to this problem, and we would obtain the corresponding experimental data from our cleanroom, compare the numerical submissions to each other and to the data, and publish the results in the IES literature. Figure 32 illustrates the configuration and boundary conditions that were specified. Four particle source locations were specified to represent two leaks through the high-efficiency particulate air (HEPA) filters, particles generated from a robot arm above the clean bench process area, and one simulating particles shed from a human operator in the aisle.

Six submissions were received from Intel, the University of Akron, Interatom GmbH, the University of Minnesota, Ryowa Air Conditioning and Refrigeration Company Limited, and Hitachi. The results showed good agreement between all the submissions and the experimental data for the flow pattern and velocity magnitudes within the space (Pui et al., 1991; Kuehn et al., 1991). However, the particle concentrations at the specified sample locations did not agree nearly as well. The conclusion was that flow modeling was much better developed than aerosol transport modeling, at least in the fairly large turbulent environment considered here. Much more sophisticated models were required to handle more realistic scenarios in which three-dimensional flows occurred and transients caused by moving robotic arms and human operators were found. However, this at-rest cleanroom scenario did challenge the limits of contemporary aerosol modeling and identified several challenges ahead.

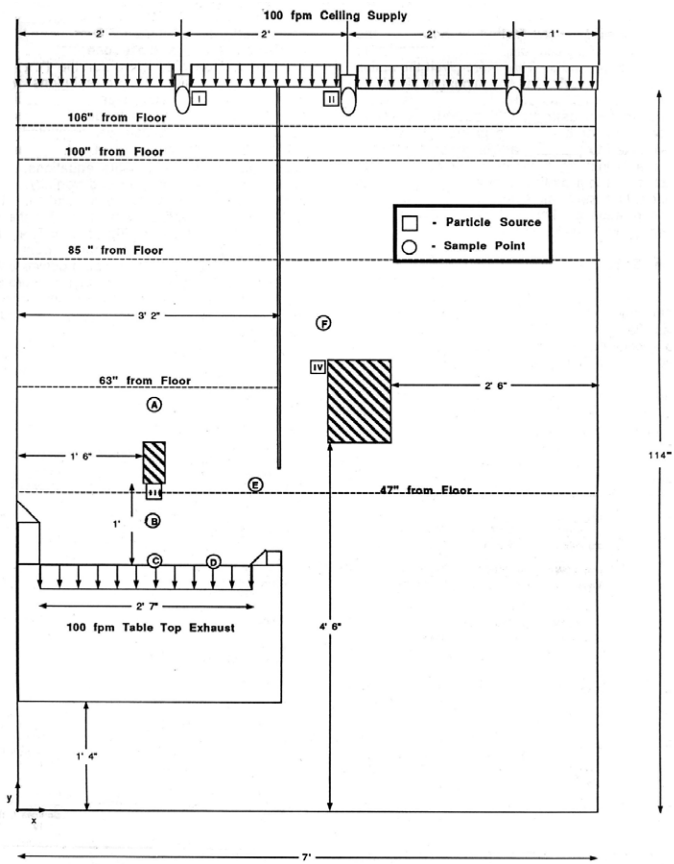


Figure 32. Specifications for the Institute of Environmental Sciences cleanroom flow modeling exercise, 1988.

Bioaerosols

One of the emerging areas in the particle and aerosol field is the interdisciplinary study of bioaerosols. No one else in the Particle Technology Laboratory had focused on this aspect of aerosol science, which has played an increasingly important role in the study of human health and disease transmission in buildings, so Kuehn expanded the traditional scope of Particle Technology Laboratory activity and began research activity in this area. Much of the early interest came from the building engineering community through ASHRAE. ASHRAE is unique in that it is a professional society that not only supports technical conferences but publishes handbooks, establishes standards that are often incorporated into building codes, and supports its own research program primarily with industry contributions. Kuehn and colleagues at the University of Minnesota have conducted much of the pioneering work on the study of bioaerosols in buildings. Because this requires an interdisciplinary approach, faculty, staff, and students outside the traditional Particle Technology Laboratory umbrella were required to collaborate. Personnel have included researchers from the School of Public Health, the Minnesota Building Research Center, the Veterinary Diagnostics Laboratory, the Department of Biosystems Engineering, the Department of Civil Engineering, and the Department of Environmental Health and Safety. Kuehn has served as the principal investigator for most of these studies. Outlines of some of the more interesting projects follow.

An early study with ASHRAE was to determine the capture efficiency of fungi and bacteria aerosols by typical heating, ventilation, and air-conditioning (HVAC) filters and whether these filters could support microbial growth. Field measurements were also obtained in one commercial building and in one residence to determine the effect of the filtration systems on the indoor levels on fungi and bacteria (Kemp et al., 1995a, 1995b).

In one portion of the study, three filters, two bag filters (glass media and polymer media), and a two-stage electronic air cleaner were challenged with outdoor air for a period of 1 year. Two-stage Andersen impactors sampled the upstream and downstream air for cultural bacteria and fungi, and an optical particle counter provided real-time total particle counts. Figure 33 shows representative results in which the filtration capture efficiency is plotted versus time for the three test filters using standard methods with agar (SMA) as the culture media. The electronic air cleaner was overloaded and did not perform well because we intentionally did not clean it as recommended by the manufacturer. However, the two media filters performed better than expected based on the assumed size of the bioaerosol particles and the fractional efficiency curves for the filters. This was an unexpected result and indicated that perhaps the ambient particles are usually found in larger sizes than predicted by assuming single spores. No growth was measured on any of these filters although the temperature and relative humidity (RH) were often in the range to support growth (RH > 70 percent). This finding suggested that the continuous air flow may have desiccated the dust cake and served to inhibit growth and/or the variation in ambient environmental conditions was sufficient to inhibit growth. More work to better understand these issues is currently in progress.

Field tests in the commercial building showed that the cleanest air in the building was immediately downstream from the filter bank of fiberglass bag filters. Figure 34 provides the results from a Monday, Wednesday, Friday sampling sequence conducted in May. The total concentration of culturable fungi was always highest in the outdoor air but varied significantly from day to day, as Figure 34 shows. The conclusion was that in a fairly new building with a well-maintained forced-air ventilation system with good filtration, the filters make a significant difference in the building's internal bioaerosol concentrations.

A similar study was conducted in a residence that had an installed electronic air cleaner that was identical to the one used in the 100 percent outdoor air challenge tests. Figure 35 shows representative results. The outdoor day-to-day concentration of fungal aerosol varied by orders of magnitude because of local weather variations. Because the home had no provision for outdoor ventilation air, all the air sent to the filtration system was return air from within the building. Thus the concentration entering the filter was a mix of indoor levels and had no direct bearing on the outdoor concentration. Open windows defeated the performance of the air cleaner as did cleaning activities and pets. Conclusions from this portion of the study were that commercial building systems are better designed to control indoor levels of bioaerosols and aerosols in general than residences and that personal behavior in a residence can overwhelm the performance of a good filtration system.

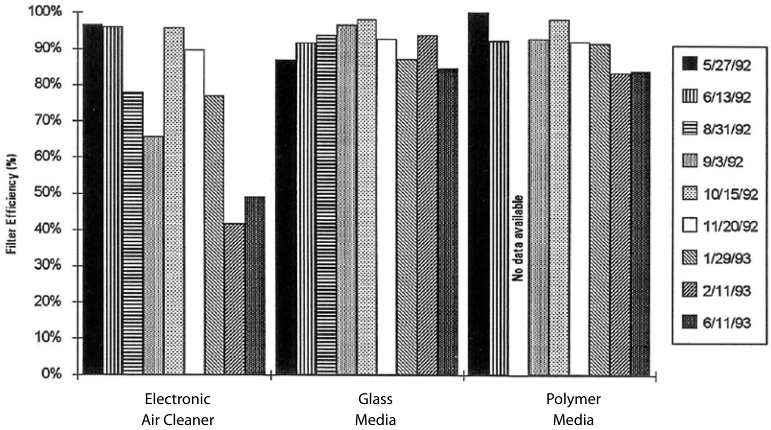


Figure 33. Filter efficiency versus time of year for ambient fungi and bacteria using standard methods agar culture media, 1993.

Source: Kemp et al. (1995a). Reprinted with permission; © American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., www.ashrae.org.

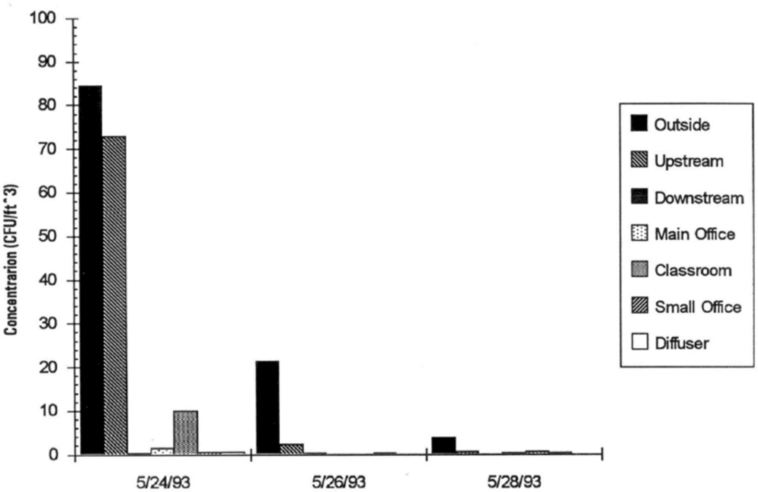


Figure 34. Culturable fungal aerosol concentrations at various locations in a classroom building for 1 week in May 1993.

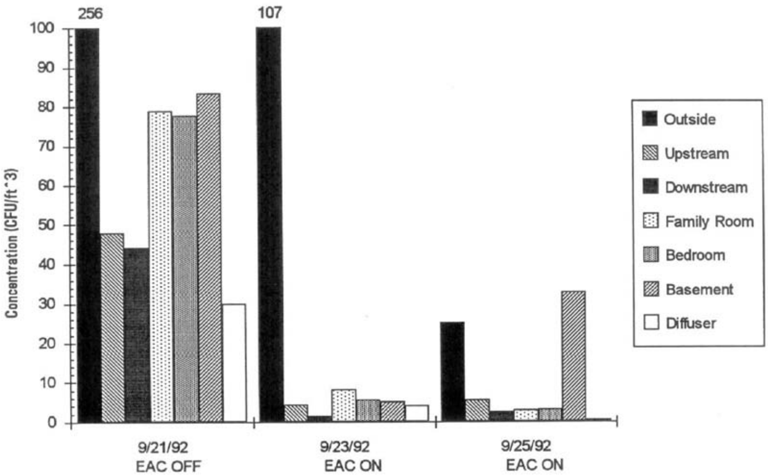


Figure 35. Culturable fungal aerosol concentrations at various locations in a residence for 1 week in September 1992.

Another study supported by ASHRAE researched the effects of construction and renovation activities on indoor air quality. Some of the results were quite surprising (Kuehn et al., 1996; Kuehn 2003). For more than 25 years, there had been a good correlation between renovation activities and hospital patient deaths documented in several countries. Further investigation revealed that the cause was the increased exposure to fungal aerosols by immune compromised patients, primarily bone marrow transplant patients. The pioneering studies conducted at the University of Minnesota Hospital and Clinic on bone marrow transplant procedures verified the assessment. The results led to the establishment of a short course (Health Care Facility Construction Management: Indoor Air Quality) that the University of Minnesota offered to train those involved with hospital construction and renovation projects to reduce the likelihood of patient infection and premature death (Figure 36). The course was offered for 10 years and resulted in hundreds of contractors, construction managers, hospital infection control practitioners, and project supervisors being trained in necessary precautions that should be taken in a health care setting. As a result of the success of this training process, the American Society of Hospital Engineers now requires certification in this area for all those who bid on health care construction projects and also conducts the certification training program on a national level.

Figure 36. Brochure from health care facility short course, 2005.

In the post–9/11 world, there is an increased concern about a bioterrorist event similar to the anthrax release in the Senate Office Building and the Brentwood Post Office facility. As bioaerosol sensors are developed to sound alarms from such a release, there is the realization that very little is known about the existing background bioaerosol population, particularly in and near buildings with a high risk for such events. We received a contract from the Department of Homeland Security to develop and demonstrate methods that can be used to document the background concentration of targeted potential threat bacteria and virus agents and their near neighbors that might cause false positive alarms. The natural background concentration of these threat agents and near neighbors is thought to be exceedingly low and thus very difficult to quantify. The approach we took was to use the existing HVAC ventilation filters in buildings as high-volume bioaerosol samplers. This would cause minimum disruption to the operation of the facility, would not be noticed by those not aware of the study, and could capture extremely small concentrations of selected bioaerosol particles over the life of the filter. We constructed a modified ASHRAE Standard 52.2 filter test facility in our laboratory, and developed methods to aerosolize, sample, and elute from a large filter several test bacteria and virus aerosols that are surrogates for various threat agents (Figure 37).

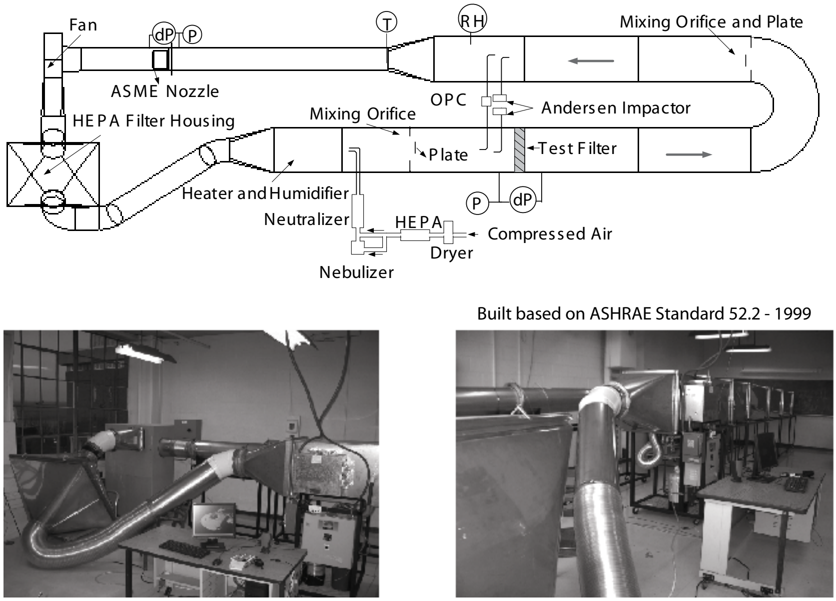


Figure 37. Bioaerosol test facility based on American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 52.2, 2004.

Notes: ASME = American Society of Mechanical Engineers; HEPA = high-efficiency particulate air; OPC = optical particle counter.

Upon satisfactorily demonstrating that the protocols would work, we conducted two field trials in large high-risk buildings located in Minneapolis and Seattle (Farnsworth et al., 2006). Results of the field trials were successful and showed that some of the threat agents and their near neighbors are indeed present in the natural background aerosol at these locations. However, their presence is also dependent on the local environmental conditions. Some of the bacteria were recovered by culture methods using an automated identification system. Targeted bacteria and viruses were also identified using polymerase chain reaction (PCR) and RT-PCR molecular identification methods.

Much more effort is necessary to better quantify the biological nature of the background aerosol in various locations around the world. Our approach is a very simple, noninvasive method that holds promise for providing these data including those at extremely low concentrations that might not be observed using other methods.

Commercial Kitchens

One of the more interesting series of studies has been the work associated with commercial kitchens and restaurants. We have conducted a series of studies funded either by ASHRAE or directly by companies to better understand cooking effluents and their control from commercial kitchens. When we began our work in the mid-1990s, very little was known about emissions or the performance of grease filters. In fact, the common understanding was that grease emissions were entirely in the particle phase because EPA had classified them as condensable particulate matter. Our initial study showed that this was a misconception and that approximately one-half of the effluent entering a hood is in the vapor phase and some of it is nearly 100 percent vapor. Another misconception was that grease filters installed into kitchen hoods captured 95 percent of the effluent. There was no publicly available method to verify these claims made by the filter manufacturers. We have shown that typical grease filters have about a 20 percent capture efficiency. Over the past 15 years, we have established our laboratory as the world's preeminent laboratory for classifying cooking effluents and testing the performance of novel grease capture systems. Some of the individual studies are summarized subsequently.

The purpose of our initial study was to characterize the emissions from 10 different commercial cooking appliances and high grease-producing food products. This included 5 electric and 5 gas-fired appliances to test the hypothesis that there would be a difference based on the type of energy used. William Gerstler was the PhD student who conducted most of the tests. This study provided lunch for many of the department's graduate students as a side benefit. Unfortunately the menu was a month of hamburgers followed by a month of french fries, then pizza, and so forth. Not a particularly healthy diet. The particle results included the mass of grease effluent per unit mass of food cooked by particle size using a modified MPCI and a MOUDI (Figure 38) (Gerstler et al., 1999; Kuehn et al., 1999). The final report from this project has become the bible of the commercial food industry (Gerstler et al., 1998) and has been reprinted by the PG&E Food Service Technology Center, San Ramon, California, for widespread distribution.

Another project was to consider the effect of exhaust velocity on the rate of grease deposition in kitchen exhaust ducts. The prevailing code, NFPA 96, required that a minimum velocity of 1,500 ft/min was required. No one knew the origin of this requirement. We built a 10 in × 10 in horizontal duct in

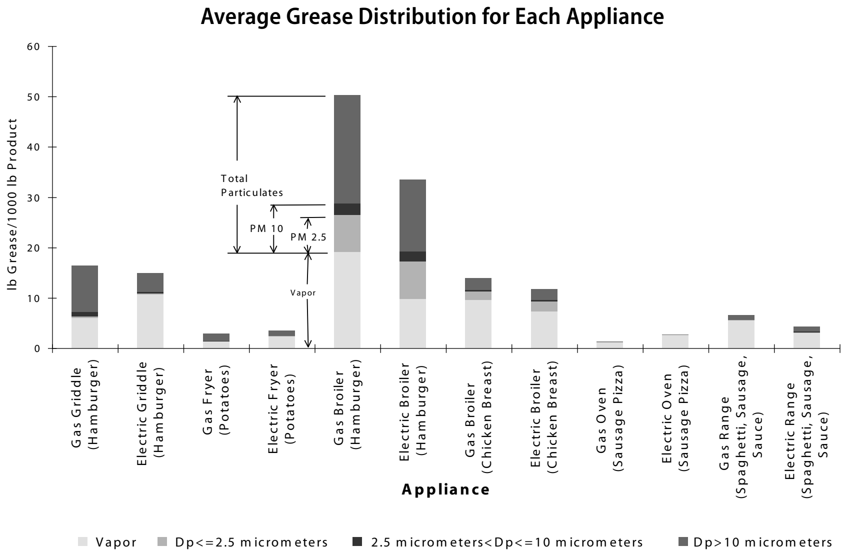


Figure 38. Grease emissions data from 10 different commercial cooking appliances and food products, 1999.

the laboratory and challenged it with uranine dye–tagged aerosol of various mean size. By swabbing the deposited material from substrates placed on the top, bottom, and sides of the duct, we were able to determine the effect of exhaust velocity on the deposition velocity versus surface orientation in a highly turbulent flow (Kuehn et al., 2001). The results were more complex than anticipated but could be explained as follows. The deposition rate was relatively high at low velocities near 500 ft/min, dropped to a minimum near 750 ft/min, and then increased as the velocity rose. With the assumption of a constant source, the high rates of deposition at the lower velocities could be explained by the increased concentration of particles within the duct. The increase at higher velocities was caused by increased turbulence in the flow. Thus a minimum in deposition velocity occurred near 750 ft/min. Thermophoretic deposition in real exhaust ducts also plays a role, as the results indicate. Based on these findings, the NFPA 96 code was changed in 2002 to allow restaurants in the United States to operate their exhaust ducts at velocities higher than 500 ft/min. This change has tremendous ramifications for the industry. Now restaurants can use variable speed fans that were previously not allowed. Between heavy cooking operations, the fans can be slowed down to capture the small amount of effluent being generated. This reduces the fan power, the amount and energy required to heat or cool makeup air, and the rate of grease buildup in the duct so that cleaning is not required as frequently. The fire hazard from grease buildup in the duct is also reduced that may result in lower insurance rates. Vendors have been retrofitting kitchen exhaust systems with the new variable speed control technology in many restaurants and kitchens around the country.

The third major effort in the commercial kitchen arena was to establish a standard method of test for the particle capture performance of commercial kitchen grease filters. We were contracted by a consortium of companies to perform the work based on our good performance on previous projects and good reputation in the field. This included end users such as McDonalds and Burger King and several equipment suppliers such as Halton, Greenheck, and Captiveaire. Our method was based on ASHRAE Standard 52.2, a standard method of test for determining the fractional efficiency for ventilation filters. We began by using hamburger cooked on a griddle with an OPC sampling the aerosol in the exhaust duct with and without the filters present. Then we developed an artificial effluent generator by modifying a vibrating orifice generator using an Altec nozzle and replacing the syringe pump with a container of liquid maintained at constant pressure with a compressed air regulator. The medium we used was based on oleic acid with an alcohol/water mix to control the resulting mean particle size. The artificial effluent matched the hamburger effluent particle size distribution quite well although the total mass flow was about one-half that of the hamburger (Figure 39) (Kuehn et al., 2004; Schrock et al., 2006). Our test method was adopted by ASTM as a standard method of test (ASTM Standard F2519-05, 2005) that can be applied to replacement filters as well as entirely new systems such as water wash systems.

As a result of our work to better characterize cooking effluent and improve codes and standards, several equipment vendors have been developing second-generation grease capture systems that remove a majority of the grease emissions from restaurants. Federal and state agencies are using our work to better regulate particulate and vapor emissions from food service operations, most notably in California where catalytic converters are required for use over some appliances in the LA basin and similar regulations are being considered in the San Francisco Bay area.

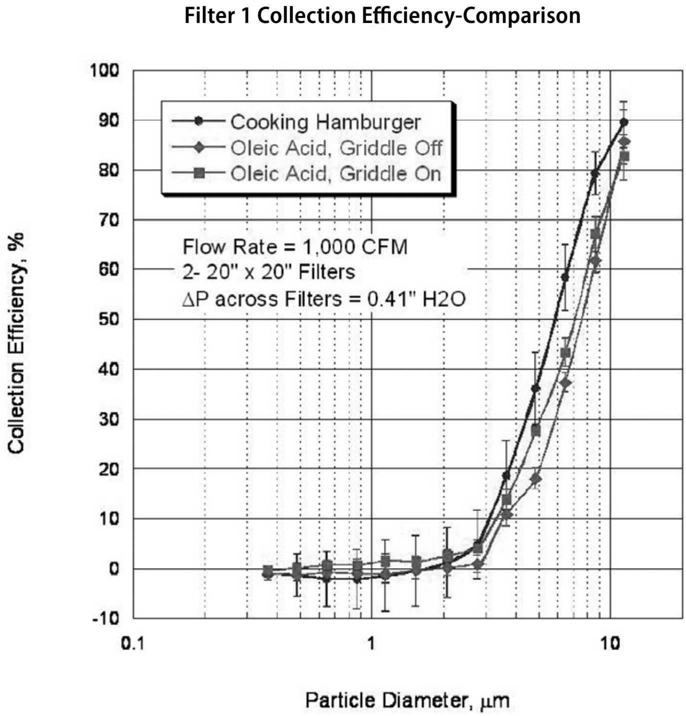


Figure 39. Fractional efficiency curves for representative commercial kitchen grease filters according to ASTM F2519-05, 2004.

References

Accomazzo, M., Rubow, K., & Liu, B. Y. H. (1983). Ultrahigh efficiency membrane filters for semiconductor gases. *Solid State Technology*, 27, 141–146.

Adachi, M., Okuyama, K., Kousaka, Y., Kozuru, H., & Pui, D. Y. H. (1987). Diffusion charging of ultrafine aerosol particles by positive helium, argon, and nitrogen ions. *Journal of Applied Physics, 62,* 3050–3052.

Adachi, M., Pui, D. Y. H., & Liu, B. Y. H. (1992b). Aerosol charge by a corona ionizer. *Aerosol Science and Technology, 18,* 48–58.

Adachi, M., Pui, D. Y. H., Romay, F. J., & Liu, B. Y. H. (Eds.). (1990). *High efficiency unipolar charger using alpha-ray radioactive source*. New York, NY: Pergamon Press.

Adachi, M., Romay, F. J., & Pui, D. Y. H. (1992a). High efficiency unipolar aerosol charger using a radioactive alpha source. *Journal of Aerosol Science, 23,* 123–137.

Agarwal, J. K., & Liu, B. Y. H. (1980). A criterion for accurate aerosol sampling in calm air. *American Industrial Hygiene Association Journal, 41,* 191–197.

Ahn, K. H., & Liu, B. Y. H. (1990a). Particle activation and droplet growth processes in condensation nucleus counter, I. Theoretical background. *Journal of Aerosol Science, 21,* 249–261.

Ahn, K. H., & Liu, B. Y. H. (1990b). Particle activation and droplet growth processes in condensation nucleus counter, II. Experimental study. *Journal of Aerosol Science, 21,* 263–275.

Ananth, G. P., & Liu, B. Y. H. (1989). *Particle transport and deposition in computer disk drives.* 35th Annual Technical Meeting of the Institute of Environmental Sciences, Anaheim, CA.

Asbach, C., Fissan, H., Kim, J. H., Yook, S. J., & Pui, D. Y. H. (2006). Technical note: Concepts for protection of EUVL masks from particle contamination. *Journal of Nanoparticle Research, 8,* 705–708.

Asbach, C., Fissan, H., Kim, J. H., Yook, S.-Y., & Pui, D. Y. H. (2007). Simple theoretic approach to estimate the effect of gravity and thermophoresis on the diffusional nanoparticle contamination under low pressure conditions. *Journal of Vacuum Science and Technology, B25,* 47–53.

Asbach, C., Stahlmecke, B., Fissan, H., Kuhlbusch, T. A., Wang, J., & Pui, D. Y. H. (2008). Analytical-statistical model to accurately estimate diffusional nanoparticle deposition on inverted surfaces at low pressure. *Applied Physics Letters, 92,* 064107.

ASTM Standard F2519-05. (2005). Standard test method for grease particle capture efficiency of commercial kitchen filter and extractors, ASTM. doi: 10.1520/F2519-05. Retrieved from http://www.astm.org/Standards/F2519.htm

Bademosi, F., & Liu, B. Y. H. (1971). *A universal law for transfer processes in Knudsen aerosols* (Unpublished doctoral dissertation). Particle Technology Laboratory, Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN.

Bae, G.-N., Kinney, P. D., Liu, B. Y. H., & Pui, D. Y. H. (1997). Investigation of aerosol spatial distribution downstream of a critical orifice at low pressure. *Aerosol Science and Technology, 28,* 474–488.

Barris, M. A., Weik, T. M., & Liu, B. Y. H. (1986). A measurement system for high purity air filter media performance. In *32nd annual technical meeting of the Institute of Environmental Sciences* (pp. 551–555). Dallas-Ft. Worth, TX.

Bartz, H., Fissan, H., & Liu, B. Y. H. (1984). A new aerosol generator for studies of ultrafine particles in the size range below 0.01 μm. In B. Y. H. Liu, D. Y. H. Pui, & H. Fissan (Eds.), *Aerosols: Science, technology, and industrial applications of airborne particles* (pp. 725–728). New York, NY: Elsevier Science.

Bergin, M. H., Pui, D. Y. H., Kuehn, T. H., & Fay, W. T. (1989). Laboratory and field measurements of fractional efficiency of industrial dust collectors. *ASHRAE Transactions, 95*(2), 102–112.

Brockmann, J. E., Liu, B. Y. H., & McMurry, P. H. (1984). A sample extraction diluter for ultrafine aerosol sampling. *Aerosol Science and Technology, 3*(4), 441–451.

Brockmann, J. E., McMurry, P. H., & Liu, B. Y. H. (1982a). Experimental study of simultaneous coagulation and diffusional loss of free molecule aerosols in turbulent pipe flow. *Journal of Colloid and Interface Science, 88,* 522–529.

Brockmann, J. E., McMurry, P. H., & Liu, B. Y. H. (1982b). On simultaneous coagulation and diffusional loss of free molecule aerosols in turbulent pipe flow. *Aerosol Science and Technology, 1,*163–178.

Brown, N. E., Liu, B. Y. H., & O'Hanlon, J. F. (1989). Performance of clean areas at Sandia National Labs exceeds goals. *Microcontamination,* 22–26.

Campbell, S. A., Ahn, K. H., Knutson, K. L., Liu, B. Y. H., & Leighton, J. D. (1990). Steady state thermal uniformity and gas flow patterns in a rapid thermal processing chamber. *IEEE Transactions on Semiconductor Manufacturing, 4*(1), 14–20.

Chae, S. K., Lee, H. S., & Liu, B. Y. H. (1992). Size response characteristics of a wafer surface scanner for non-ideal, real-world particles. *Journal of the IES, 35,* 45–52.

Chen, D. R., & Pui, D. Y. H. (1994). Numerical and experimental studies of particle deposition in a tube with a conical contraction-laminar flow regime, *Journal of Aerosol Science, 26,* 563–574.

Chen, D. R., & Pui, D. Y. H. (1997). Experimental investigation of scaling laws for electrospraying: Dielectric constant effect. *Aerosol Science and Technology, 27,* 367–380.

Chen, D.-R., & Pui, D. Y. H. (1998). A high efficiency, high throughput unipolar charger for nanoparticles. *Journal of Nanoparticle Research, 1,* 115–116.

Chen, D. R., & Pui, D. Y. H. (2009). Electrospray and its medical applications. In L. Gradon & J. Marijinissen (Eds.), *Nanoparticles in medicine and environment: Inhalation and health effects* (pp. 59–76). New York, NY: Springer Verlag.

Chen, D. R., Pui, D. Y. H., & Kaufman, S. L. (1995a). Electrospraying of conducting liquids for monodisperse aerosol generation in the 4 nm to 1.8um diameter range. *Journal of Aerosol Science*, *26*, 963–977.

Chen, D. R., Pui, D. Y. H., & Liu, B. Y. H. (1995b). Optimization of pleated filter designs using a finite-element numerical model. *Aerosol Science and Technology, 23,* 579–590.

Chen, D. R., Pui, D. Y. H., & Tang, Y. M. (1996). *Filter pleating for cabin air filtration.* SAE International Congress and Exposition, Detroit, MI.

Chen, D.-R., Pui, D. Y. H., Hummes, D., Fissan, H., Quant, F., & Sem, G. (1997). Design and evaluation of a nanometer aerosol differential mobility analyzer (Nano-DMA). *Journal of Aerosol Science, 29,* 497–509.

Chen, D.-R., Wendt, C. H., & Pui, D. Y. H. (2000). A novel approach for introducing bio-materials into cells. *Journal of Nanoparticle Research, 2,* 133–139.

Dick, W. D., McMurry, P. H., Weber, R. J., & Quant, F. R. (2000b). White-light detection for nanoparticle sizing with the TSI ultrafine condensation particle counter. *Journal of Nanoparticle Research, 2,* 85–90.

Dick, W. D., Sachweh, B. A., & McMurry, P. H. (1996). Distinction of coal dust particles from liquid droplets using the DAWN-A detector. *Applied Occupational & Environmental Hygiene, 11,* 637–645.

Dick, W. D., Saxena, P., & McMurry, P. H. (2000a). Estimation of water uptake by organic compounds in submicron aerosols measured during the Southeastern Aerosol and Visibility Study. *Journal of Geophysical Research, 105,*1471–1479.

Dick, W. D., Ziemann, P. J., Huang, P.-F., & McMurry, P. H. (1998). Optical shape fraction measurements of submicrometre laboratory and atmospheric aerosols. *Measurement Science & Technology, 9,* 183–196.

DiFonzo, F., Gidwani, A., Fan, M., Neumann, D., Iordanoglou, D., Heberlein, J., McMurry, P. H., Girshick, S. L., Tymiak, N., Gerberich, W., & Rao, N. P. (2000). Focused nanoparticle beam deposition of patterned microstructures. *Applied Physics Letters, 77,* 910–912.

DisFit^{TM} (2004). *Users Guide V. 2.0.* Forest Lake, MN: Chimera Technologies Inc.

Ehara, K., Hagwood, C., & Coakley, K. J. (1996). Novel method to classify aerosol particles according to their mass-to-charge ratio: Aerosol particle mass analyser. *Journal of Aerosol Science, 27,* 217–234.

Endo, Y., Chen, D.-R., & Pui, D. Y. H. (1997a). Effects of particle polydispersity and shape factor during dust cake loading on air filters. *Powder Technology, 98,* 241–249.

Endo, Y., Chen, D.-R., & Pui, D. Y. H. (1997b). Bimodal aerosol loading and dust cake formation on air filters. *Filtration and Separation, 35,* 191–195.

Fang, C. P., Marple, V. A., & Rubow, K. L. (1991a). Influence of cross-flow on particle collection characteristics of multi-nozzle impactors. *Journal of Aerosol Science, 22,* 403–415.

Fang, C. P., McMurry, P. H., Marple, V. A., & Rubow, K. H. (1991b). Effect of flow-induced relative humidity changes on size cuts for sulfuric acid droplets in the microorifice uniform deposit impactor (MOUDI). *Aerosol Science and Technology, 14,* 266–277.

Fardi, B., & Liu, B. Y. H. (1991). Performance of disposable respirators. *Particle & Particle Systems Characterization, 8,* 308–314.

Fardi, B., & Liu, B. Y. H. (1992a). Flow field and pressure drop of filters with rectangular fibers. *Aerosol Science and Technology, 17,* 36–44.

Fardi, B., & Liu, B. Y. H. (1992b). Efficiency of fibrous filters with rectangular fibers. *Aerosol Science and Technology, 17,* 45–58.

Farnsworth, J. E., Goyal, S. M., Kim, S. W., Kuehn, T. H., Raynor, P. C., Ramakrishnan, M. A., ... & Tang, W. (2006). Development of a method for bacteria and virus recovery from heating, ventilation, and air conditioning (HVAC) filters. *Journal of Environmental Monitoring*, *8*, 1006–1013.

Fay, W. T., Kuehn, T. H., Pui, D. Y. H., & Bergin, M. H. (1989). Dust collector modeling for industrial operations. *ASHRAE Transactions, 95,* 92–101.

Fernandez de la Mora, J., Rao, N. P., & McMurry, P. H. (1990). Hypersonic impaction of ultrafine particles. *Journal of Aerosol Science, 21,*169–187.

Fissan, H., Hummes, D., Stratmann, F., Buscher, P., Neumann, S., Pui, D. Y H., & Chen, D. R. (1996). Experimental comparison of four differential mobility analyzers for nanometer aerosol measurements. *Aerosol Science and Technology, 24,* 1–13.

Fissan, H., Neumann, S., Trampe, A., Pui, D. Y. H., & Shin, W. G. (2007). Rationale and principle of an instrument measuring lung deposited nanoparticle surface area. *Journal of Nanoparticle Research, 9,* 53–59.

Friedlander, S. K., & Pui, D. Y. H. (2003). NSF workshop report on *"Emerging Issues in Nanoparticle Science and Technology."* Retrieved from http://www.nano.gov/html/res/NSFAerosolParteport.pdf

Gallo, E. J., Ramsey, J. W., & Liu, B. Y. H. (1988). Flow visualization studies in clean rooms. In *9th international symposium on contamination control* (pp. 637–645).

Gerstler, W., Kuehn, T., Pui, D. Y. H., & Ramsey, J. W. (1999). Measurements of the effluent from hamburger cooked on a gas underfired broiler. *ASHRAE Transactions, 105,* 303–315.

Gerstler, W., Kuehn, T., Pui, D., Ramsey, J., Rosen, M., Carlson, R., & Petersen, S. (1998). Identification and characterization of effluents from various cooking appliances and processes as related to optimum design of kitchen ventilation systems (ASHRAE 745-RP, Phase II Final Report). Minneapolis, MN: University of Minnesota, Department of Mechanical Engineering.

Girshick, S. L., Chiu, C. P., & McMurry, P. H. (1990). Time-dependent aerosol models and homogeneous nucleation rates. *Aerosol Science and Technology, 13,* 465–477.

Girshick, S. L., Chiu, C.-P., Muno, R., Wu, C. Y., Yang, L., Singh, S. K., & McMurry, P. H. (1993). Thermal plasma synthesis of ultrafine iron particles. *Journal of Aerosol Science, 24,* 367–382.

Girshick, S. L., McMurry, P. H., Heberlein, J., Rao, N. P., & Lee, H. J. (1996). Nanostructured materials synthesis using hypersonic plasma particle deposition. *Bulletin of the American Physical Society, 41,*1287–1288.

Gomes, M. S. P., Pui, D. Y. H., Vincent, J. H., & Liu, B. Y. H. (1993). The effect of Taylor diffusion on time dependent particle concentration measurements. *Journal of Aerosol Science, 24,* 643–654.

Gomes, M. S. P., Vincent, J. H., & Pui, D. Y. H. (1999). The effect of freestream turbulence of the transport of particles in the vicinity of a blunt flow obstacle. *Atmospheric Environment, 33,* 4459–4468.

Gousman, A. D., Pun, W. M., Runchal, A. K., Spalding, D. S., & Wolfshtein, M. (1969). *Heat and mass transfer in recirculating flows.* New York, NY: Academic Press.

Grant, D. C., & Liu, B. Y. H. (1991). Sieving capture of liquidborne particles by microporous membrane filtration media. *Particle & Particle Systems Characterization, 8,* 142–150.

Gupta, A., Tang, D., & McMurry, P. H. (1995). Growth of monodisperse, submicron aerosol particles exposed to SO_2, H_2O_2, and NH_3. *Journal of Atmospheric Chemistry, 20,* 117–139.

Han, H.-S., Chen, D.-R., Pui, D. Y. H., & Anderson, B. E. (2000). A nanometer aerosol size analyzer (nASA) for rapid measurement of high-concentration size distributions. *Journal of Nanoparticle Research, 2,* 43–52.

Heberlein, J., Rao, N. P., Neuman, A., Blum, J., Tymiak, N., McMurry, P., & Girshick, S. (1997). Thermal spraying of nanostructured coatings by hypersonic plasma particle deposition. *Thermal spray: A united forum for scientific and technological advances.* Materials Park, OH: ASM International.

Helsper, C., Fissan, H., Kapadia, A., & Liu, B. Y. H. (1982). Data inversion by simplex minimization for the electrical aerosol analyzer. *Aerosol Science and Technology, 1,* 135–146.

Husar, R. B., Whitby, K. T., & Liu, B. Y. H. (1972). Physical mechanisms governing the dynamics of Los Angeles smog aerosol. *Journal of Colloid and Interface Science, 39,* 211–224.

Iida, K., Stolzenburg, M., & McMurry, P. H. (2009). Effect of working fluid on sub-2nm particle detection with a laminar flow ultrafine condensation particle counter. *Aerosol Science and Technology, 43,* 81–96.

Iribarne, J. V., Corr, D., Liu, B. Y. H., & Pui, D. Y. H. (1977). On the hypothesis of particle fragmentation during evaporation. *Atmospheric Environment, 11,* 639–642.

Jiang, J., Zhao, J., Chen, M., Scheckman, J., Williams, B.J., Eisele, F.L., et al. (in press). Aerosol Research Letter: First measurements of atmospheric cluster and 1-2nm particle number distributions during nucleation events. *Aerosol Science and Technology.*

Kemp, S. J., Kuehn, T. H., Pui, D. Y. H., Vesley, D., & Streifel, A. J. (1995a). Filter collection efficiency and growth of microorganisms on filters loaded with outdoor air. *ASHRAE Transactions, 101,* 228–238.

Kemp, S. J., Kuehn, T. H., Pui, D. Y. H., Vesley, D., & Streifel, A. J. (1995b). Growth of microorganisms on HVAC filters under controlled temperature and humidity conditions. *ASHRAE Transactions, 101,* 305–316.

Kim, J. H., Fissan, H., Asbach, C., Yook, S. J., & Pui, D. Y. H. (2006b). Speed-controlled particle injection into a low-pressure system. *Journal of Vacuum Science and Technology, A: Vacuum, Surfaces, and Films, 24,* 229–234.

Kim, J. H., Fissan, H., Asbach, C., Yook, S. J., Pui, D. Y. H., & Orvek, K. (2006c). Investigation of thermophoretic protection with speed-controlled particles at 100, 50, and 25 mTorr. *Journal of Vacuum Science and Technology, B: Microelectronics and Nanometer Structures—Processing, Measurement, and Phenomena, 24,* 1178–1184.

Kim, J. H., Fissan, H., Asbach, C., Yook, S. J., Wang, J., & Pui, D. Y. H. (2006a). Effect of reverse flow by differential pressure on the protection of critical surfaces against particle contamination. *Journal of Vacuum Science and Technology, B: Microelectronics and Nanometer Structures—Processing, Measurement, and Phenomena, 24,* 1844–1849.

Kim, S. C., Harrington, M., & Pui, D. Y. H. (2007a). Experiemental study of nanoparticle penetration through commercial filter media. *Journal of Nanoparticle Research, 9,* 117–125.

Kim, S. C., Wang, J., Emery, M., & Pui, D. Y. H. (2007b). Filtration of silver nanoparticle agglomerates. *10th World Filtration Congress*, Leipzig, Germany.

Kim, T., Suh, S.-M., Girshick, S. L., Zachariah, M. R., McMurry, P. H., Rassel, R. M., Shen, Z., & Campbell, S. A. (2002). Particle formation during low-pressure chemical vapor deposition from silane and oxygen; Measurement, modeling and film properties. *Journal of Vacuum Science & Technology, A: Vacuum, Surfaces, and Films, 20,* 412–423.

Kinney, P. D., Bae, G. N., Pui, D. Y. H., & Liu, B. Y. H. (1996). Particle behavior in vacuum systems: Implications for in situ particle monitoring in semiconductor process equipment. *Journal of the IEST*, 39, 40–48.

Kinney, P., Pui, D. Y. H., & Liu, B. Y. H. (1997). Particle transmission through a turbo pump. *Journal of the IEST, 43,* 31–34.

Kinney, P., Pui, D. Y. H., Mulholland, G., & Bryner, N. P. (1991). Use of the electrostatic classification method to size 0.1 μm SRM particles—A feasibility study. *Journal of Research of the National Institute of Standards and Technology, 96,*147–176.

Kittelson, D. B., Moon, K. C., & Liu, B. Y. H. (1984). Filtration of diesel particles. In *Second International Conference on Carbonaceous Particles in the Atmosphere*, Linz, Austria.

Knutson, E. O., & Whitby, K. T. (1975a). Aerosol classification by electric mobility: Apparatus, theory, and applications. *Journal of Aerosol Science, 6,* 443–451.

Knutson, E. O., & Whitby, K. T. (1975b). Accurate measurement of aerosol electric mobility moments. *Journal of Aerosol Science, 6,* 453–460.

Kuang, C., McMurry, P. H., McCormick, A., & Eisele, F. L. (2008). Dependence of nucleation rates on sulfuric acid concentration in diverse atmospheric locations. *Journal of Geophysical Research, 113,* D10209.

Kuehn, T. (1982). Field heat-transfer measurements and life-cycle cost analysis of four wood-frame wall construction. *ASHRAE Transactions, 88*(Pt. 1), 651–665.

Kuehn, T., Gacek, B., Yang, C. H., Gimsrud, D. T., Janni, K. A., Streifel, A. J., & Pearce, M. (1996). Identification of contaminants, exposures, effects and control options for construction/renovation activities. *ASHRAE Transactions, 102,* 89–101.

Kuehn, T., Gerstler, W., Ortiz, H., Sandberg, A., Tjandra, H., Vidhani, J., . . . Pui, D. (2001). *Effects of air velocity on grease deposition in exhaust ductwork.* ASHRAE Final Report (1033-RP). Retrieved from http://rp.ashrae.biz/page/rp-1033.pdf

Kuehn, T., Gerstler, W., Pui, D. Y. H., & Ramsey, J. W. (1999). Comparison of emissions from selected commercial kitchen appliances and food products. *ASHRAE Transactions, 105,* 128–141.

Kuehn, T., & Goldstein, R. J. (1976). An experimental and theoretical study of natural convection in the annulus between horizontal concentric cylinders. *Journal of Fluid Mechanics, 74,* 695–719.

Kuehn, T., & Goldstein, R. J. (1980a). A parametric study of Prandtl number and diameter ratio effects on natural convection heat transfer in horizontal cylindrical annuli. *Journal of Heat Transfer ASME, 102,* 768–770.

Kuehn, T., & Goldstein, R. J. (1980b). Numerical solution to the Navier-Stokes equations for laminar natural convection about a horizontal circular cylinder. *International Journal of Heat Mass Transfer, 23,* 971–979.

Kuehn, T., Kwon, S., & Tolpadi, A. (1983). Similarity solution for conjugate natural convection heat transfer from a long vertical plate fin. *International Journal of Heat and Mass Transfer, 26,* 1718–1721.

Kuehn, T., Olson, B., Ramsey, J., Friell, J., & Rocklage, J. (2004). *Development of a standard method of test for commerical kitchen effluent grease removal systems* (Report). San Ramon, CA: Fisher-Nickel, Inc.

Kuehn, T. H. (2003). Airborne infection control in health care facilities. *Journal of Solar Energy Engineering, 125,* 366–371.

Kuehn, T. H., Marple, V. A., Han, H., Liu, B. Y. H., Shanmugavelu, I., & Youssef, S. W. (1988). Comparison of measured and predicted airflow patterns in a clean room. In *34th annual technical meeting of the Institute of Environmental Sciences* (pp. 98–107). Valley Forge, PA.

Kuehn, T. H., Pui, D. Y. H., & Gratzek, J. P. (1991). Numerical results of cleanroom flow modeling exercise. In *37th annual technical meeting of the Institute of Environmental Sciences* (pp. 98–107). San Diego, CA.

Kuehn, T. H., Pui, D. Y. H., Vesley, D., Kemp, S. J., Streifel, A., Marx, J., & Alfred, A. (1994). *Matching filtration to health requirements.* Minneapolis, MN: Particle Technology Laboratory, Department of Mechanical Engineering, University of Minnesota.

Kuehn, T. H., Ramsey, J. W., & Threlkeld, J. L. (1998). *Thermal environmental engineering* (3rd ed.). Upper Saddle River, NJ: Prentice Hall.

Kuehn, T. H., Wu, Y., & Liu, B. Y. H. (1992). Particle contamination below a robot arm in a clean room. In *38th annual technical meeting of the Institute of Environmental Sciences,* (pp. 45–53). Baltimore, MD.

Kuhlmey, G. A., Liu, B. Y. H., & Marple, V. A. (1981). A micro-orifice impactor for sub-micron aerosol size classification. In *89th national meeting of the American Institute of Chemical Engineers*, Portland, OR.

Kulmala, M., Vehkamaki, H., Petaja, T., Dal Maso, M., Lauri, A., Kerminen, V.-M., Birmili, W., & McMurry, P. H. (2004). Formation and growth rates of ultrafine atmospheric particles: a review of observations. *Journal of Aerosol Science, 35,* 143–176.

Kwok, K.-C., & Liu, B. Y. H. (1992). How atomization affects transfer efficiency. *Industrial Finishings, 28,* 28–32.

Kwon, S., & Kuehn, T. (1983). Conjugate natural convection heat transfer from a horizontal cylinder with a long vertical longitudinal fin. *Numerical Heat Transfer, 6,* 85–102.

Lee, J.-K., Rubow, K. L., Liu, B. Y. H., & Zahka, J. G. (1992). Particulate retention by microporous membrane filters in liquid filtration: A predictive model and experimental study. In *38th annual technical meeting of the Institute of Environmental Sciences* (pp. 297–308). Nashville, TN.

Lee, J. K., Rubow, K. L., Pui, D. Y. H., & Liu, B. Y. H. (1995). Comparative study of pressure reducers for aerosol sampling from high purity gases. *Aerosol Science and Technololgy, 23,* 481–490.

Lee, K. W., & Liu, B. Y. H. (1980). On the minimum efficiency and the most penetrating particle size for fibrous filters. *Journal of the Air Pollution Control Association, 30,* 377–381.

Lee, K. W., & Liu, B. Y. H. (1982a). Theoretical study of aerosol filtration by fibrous filters. *Aerosol Science and Technology, 1,* 147–161.

Lee, K. W., & Liu, B. Y. H. (1982b). Experimental study of aerosol filtration by fibrous filters. *Aerosol Science and Technology, 1,* 35–46.

Liu, B. Y. H. (1974). Laboratory generation of particulates with emphasis on submicron aerosols. *Journal of the Air Pollution Control Association, 24,* 1170–1172.

Liu, B. Y. H. (1984). Application of modern aerosol instrumentation for industrial particle measurement. *In European symposium on particle characterization* (pp. 501–513), Nuremberg, West Germany.

Liu, B. Y. H. (1987). Particle filtration by fibrous and membrane filters. In *Pharm Tech Conference '87*, East Rutherford, NJ.

Liu, B. Y. H. (1992). Aerosol science and contamination control in microelectronics. In *4th Chinese Aerosol Conference*, Heifei and Huangshan, China.

Liu, B. Y. H. & Agarwal, J. K. (1974). Experimental observation of aerosol deposition in turbulent flow. *Journal of Aerosol Science, 5,* 145–155.

Liu, B. Y. H. & Ahn, K. H. (1987). Particle deposition on semiconductor wafers. *Aerosol Science and Technology, 6,* 215–224.

Liu, B. Y. H., Berglund, R. N., & Agarwal, J. K. (1974a). Experimental studies of optical particle counters. *Atmospheric Environment, 8,* 717–732.

Liu, B. Y. H., Chae, S.-K., & Bae, G.-N. (1992). Sizing accuracy, counting efficiency, lower detection limit and repeatability of a wafer surface scanner to ideal and real-world particles. *Journal of the Electrochemical Society, 140,* 1403–1409.

Liu, B. Y. H. & Fardi, B. (1985). *A fundamental study of respirator air filtration.* Minneapolis, MN: Particle Technology Laboratory, Department of Mechanical Engineering, U of Minnesota.

Liu, B. Y. H., Fardi, B., & Ahn, K. H. (1987b). Deposition of charged and uncharged aerosol particles on semiconductor wafers. In *33rd annual technical meeting of the Institute of Environmental Sciences* (pp. 461–465). San Jose, CA.

Liu, B. Y. H., & Hsieh, K. C. (1989). Progress towards an absolute zero particle gas. In *35th Annual Technical Meeting of the Institute of Environmental Sciences*, Anaheim, CA.

Liu, B. Y. H., & Ilori, T. A. (1974). Aerosol deposition in turbulent pipe flow. *Environmental Science & Technology, 89,* 351–356.

Liu, B. Y. H., & Japuntich, D. A. (1987). Respirator. In *McGraw-Hill encyclopedia of science and technology, 6th ed.* (pp. 394–397). New York, NY: McGraw-Hill.

Liu, B. Y. H., & Kapadia, A. (1978). Combined field and diffusion charging of aerosol particles in the continuum regime. *Journal of Aerosol Science, 9,* 227–242.

Liu, B. Y. H. & Kim, C. S. (1977). On the counting efficiency of condensation nuclei counters. *Atmospheric Environment, 11,* 1097–1100.

Liu, B. Y. H., Kuehn, T. H., & Zhao, J. (1991). Particle generation during vacuum pump down. In *37th annual technical meeting of the Institute of Environmental Sciences* (pp. 737–740). San Diego, CA.

Liu, B. Y. H., & Kuhlmey, G. A. (1977). Efficiency of air sampling filter media. In *Symposium and workshop on X-ray fluorescence analysis of environmental samples* (pp. 107–119). Ann Arbor, MI: Ann Arbor Science Publishers.

Liu, B. Y. H., & Lee, K. W. (1975). An aerosol generator of high stability. *American Industrial Hygiene Association Journal, 36,* 861–865.

Liu, B. Y. H., & Lee, K. W. (1976). Efficiency of membrane and nuclepore filters for submicrometer aerosols. *Environmental Science & Technology, 10,* 345–350.

Liu, B. Y. H., Lee, J. W., Pui, D. Y. H., Ahn, K. H., & Gilbert, S. L. (1986a). Performance of a model clean room. In *8th international symposium on contamination control* (pp. 22–25). Milan, Italy.

Liu, B. Y. H., & Levi, J. (1980). Generation of submicron sulfuric acid aerosol by vaporization and condensation. In K. Willeke, (Ed.), *Generation of aerosols* (317–336). Ann Arbor, MI: Ann Arbor Science Publishers.

Liu, B. Y. H., Marple, V. A., Whitby, K. T., & Barsic, N. J. (1974b). Size distribution measurement of airborne coal dust by optical particle counters. *American Industrial Hygiene Association Journal, 35,* 443–445.

Liu, B. Y. H., Marple, V. A., & Yazdani, H. (1969b). Comparative size measurements of monodisperse liquid aerosols by electrical and optical methods. *Environmental Science & Technology, 3,* 381–386.

Liu, B. Y. H., & Pui, D. Y. H. (1974a). A submicron aerosol standard and the primary, absolute calibration of the condensation nuclei counter. *Journal of Colloid and Interface Science. 47,* 155–171.

Liu, B. Y. H., & Pui, D. Y. H. (1974b). Equilibrium bipolar charge distribution of aerosols. *Journal of Colloid and Interface Science, 49,* 305–312.

Liu, B. Y. H., & Pui, D. Y. H. (1974c). Electrical neutralization of aerosols. *Journal of Aerosol Science, 5,* 465–472.

Liu, B. Y. H., & Pui, D. Y. H. (1975). On the performance of the electrical aerosol analyzer. *Journal of Aerosol Science, 6,* 249–264.

Liu, B. Y. H., & Pui, D. Y. H. (1977). On unipolar diffusion charging of aerosols in the continuum regime. *Journal of Colloid and Interface Science, 58,* 142–149.

Liu, B. Y. H., & Pui, D. Y. H. (1981). Aerosol sampling inlets and inhalable particles. *Atmospheric Environment, 15,* 589–600.

Liu, B. Y. H., & Pui, D. Y. H. (1985). A universal aerosol sampling probe for high efficiency particle sampling from flowing gas streams. *Particle & Particle Systems Characterization, 2,* 125–132.

Liu, B. Y. H., & Pui, D. Y. H. (1986). Aerosol sampling and sampling inlets. In *Aerosols: 2nd U.S.-Dutch International Symposium*. Chelsea, MI: Lewis Publishers.

Liu, B. Y. H., Pui, D. Y. H., Hogan, A. W., & Rich, T. A. (1975). Calibration of the Pollak counter with monodisperse aerosols. *Journal of Applied Meteorology, 14,* 46–51.

Liu, B. Y. H., Pui, D. Y. H., & Kapadia, A. (1979). Electrical aerosol analyzer: History, principle, and data reduction. In *Aerosol Measurement Workshop* (pp. 341–383). Gainesville, FL: University Presses of Florida.

Liu, B. Y. H., Pui, D. Y. H., Kinstley, W. O., & Fisher, W. G. (1987a). Aerosol charging and neutralization and electrostatic discharge in clean rooms. *Journal of Environmental Sciences, 30,* 42–46.

Liu, B. Y. H., Pui, D. Y. H., & Lin, B. Y. (1986b). Aerosol charge neutralization by a radioactive alpha source. *Particle & Particle Systems Characterization, 3,* 111–116.

Liu, B. Y. H., Pui, D. Y. H., & Rubow, K. L. (1983a). Characteristics of air sampling filter media. In *International symposium on aerosols in the mining and industrial work environment* (pp. 989–1038). Ann Arbor, MI: Ann Arbor Science Publishers.

Liu, B. Y. H., Pui, D. Y. H., McKenzie, R. L., Agarwal, J. K., Jaenicke, R., Pohl, F. G., Preining, O., . . . Wagner, P. E. (1982a). Intercomparison of different "absolute" instruments for measurement of aerosol number concentration. *Journal of Aerosol Science, 13,* 429–450.

Liu, B. Y. H., Pui, D. Y. H., McKenzie, R. L., Agarwal, J. K., Pohn, F. G., Preining, O., . . .Wagner, P. E. (1984). Measurements of Kelvin-equivalent size distributions of well-defined aerosols with particle diameters >13 nm. *Aerosol Science and Technology, 3,* 107–115.

Liu, B. Y. H., Pui, D. Y. H., Rubow, K. L., & Szymanski, W. W. (1985a). Electrostatic effects in aerosol sampling and filtration. *Annals of Occupational Hygiene, 29,* 251–269.

Liu, B. Y. H., Pui, D. Y. H., Schaller, R. E., McDonald, B. N., & Johnson, T. W. (1986c). An optical particle counting system for testing industrial pulse-cleaned cartridge dust collectors. *Particle & Particle Systems Characterization, 3,* 68–73.

Liu, B. Y. H., Pui, D. Y. H., & Wang, X. Q. (1982b). Drop size measurement of liquid aerosols. *Atmospheric Environment, 16,* 563–567.

Liu, B. Y. H., Pui, D. Y. H., Wang, X. Q., & Lewis, C. W. (1983c). Sampling of carbon fiber aerosols. *Aerosol Science and Technology, 2,* 499–511.

Liu, B. Y. H., Pui, D. Y. H., Whitby, K.T., Kittelson, D. B., Kousaka, Y. & McKenzie, R. L. (1978). The aerosol mobility chromatograph: A new detector for sulfuric acid aerosols. In *International Symposium of Sulfur in the Atmosphere* (pp. 99–104). Dubrovnik, Yugoslavia.

Liu, B. Y. H., Rubow, K. L., & Pui, B. Y. H. (1985c). On the performance of HEPA and ULPA filters. In *31st annual technical meeting of the Institute of Environmental Sciences* (pp. 25–28). Las Vegas, NV.

Liu, B. Y. H., Rubow, K. L., & Pui, D. Y. H. (1988). New concepts in aerosol filtration: Data analysis and performance evaluation. In *1987 U.S. Army Chemical Research, Development and Engineering Center Scientific Conference on Chemical Defense Research* (pp. 457–465). Aberdeen Proving Ground, MD.

Liu, B. Y. H., Sega, K., Rubow, K. L., Lenhart, S. W., & Myers, W. R. (1983b). In-mask aerosol sampling for powered air purifying respirators. *American Industrial Hygiene Association Journal, 44,* 361–367.

Liu, B. Y. H., & Szymanski, W. W. (1987). Counting efficiency, lower detection limit and noise level of optical particle counter. In *33rd annual technical meeting of the Institute of Environmental Sciences* (pp. 417–421). San Jose, CA.

Liu, B. Y. H., Szymanski, W., & Ahn, K. H. (1985b). On aerosol size distribution measurement by laser and white light optical particle counters. *Journal of Environmental Science, 28,* 19–24.

Liu, B. Y. H., & Verma, A. C. (1968). A pulse-charging, pulse-precipitating electrostatic aerosol sampler. *Analytical Chemistry, 40,* 843–847.

Liu, B. Y. H., Wajsfelner, R., Billard, F., & Bricard, J. (1969a). Etude de la charge electrique porte par des particules spheriques de latex polystyrene mises en suspension dans l'air. *Les Comptes Rendus de l'Académie des sciences, 268,* 1682–1685.

Liu, B. Y. H., & Whitby, K. T. (1968). Dynamic equilibrium in self-preserving aerosols. *Journal of Colloid and Interface Science, 26,* 161–165.

Liu, B. Y. H., Whitby, K. T., & Pui, D. Y. H. (1974c). A portable electrical analyzer for size distribution measurement of submicron aerosols. In *66th annual meeting of the Air Pollution Control Association: Journal of the Air Pollution Control Association* (pp. 1067–1072). Chicago, IL.

Liu, B. Y. H., Whitby, K. T., & Yu, H. H. (1966). A condensation aerosol generator for producing monodispersed aerosols in the size range 0.036 μm to 1.3 μm. *Journal de Recherches Atmospheriques, 3,* 397–406.

Liu, B. Y. H., Whitby, K. T., & Yu, H. H. S. (1967a). Diffusion charging of aerosol particles at low pressures. *Journal of Applied Physics, 38,* 1592–1597.

Liu, B. Y. H., Whitby, K. T., & Yu, H. H. S. (1967b). Electrostatic aerosol sampler for light and electron microscopy. *Review of Scientific Instruments, 38,* 100–102.

Liu, B. Y. H., & Yeh, H. C. (1968). On the theory of charging of aerosol particles in an electric field. *Journal of Applied Physics, 39,* 1396–1402.

Liu, B. Y. H., & Zhang, Z. Q. (1989). A numerical study of inertial errors in anisokinetic sampling. *Journal of Aerosol Science, 20,* 367–380.

Liu, P., Ziemann, P. J., Kittelson, D. B., & McMurry, P. H. (1995a). Generating particle beams of controlled dimensions and divergence: I. Theory of particle motion in aerodynamic lenses and nozzle expansions. *Aerosol Science and Technology, 22,* 293–313.

Liu, P., Ziemann, P. J., Kittelson, D. B., & McMurry, P. H. (1995b). Generating particle beams of controlled dimensions and divergence: II. Experimental evaluation of particle motion in aerodynamic lenses and nozzle expansions. *Aerosol Science and Technology, 22,* 314–324.

Lo, L. M., Chen, D. R., & Pui, D. Y. H. (2010a). Experimental study of pleated fabric cartridges in a pulse-jet cleaned dust collector. *Powder Technology, 197,* 141–149.

Lo, L. M., Hu, S. C., Chen, D. R., & Pui, D. Y. H. (2010b). Numerical study of pleated fabric cartridge during pulse-jet cleaning. *Powder Technology, 198,* 75–81.

Lo, L. M., Hu, S. C., Chen, D. R., & Pui, D. Y. H. (2008). *Effect of pleat ratio on pulsejet cleaning of pleated filter cartridge.* Manuscript submitted for publication.

Lundgren, D. A., Hlaing, D. N., Rich, T. A., & Marple, V. A. (1996). PM_{10}/$PM_{2.5}$/$PM_{1.0}$ Data from a trichotomous sampler (Technical Note). *Aerosol Science and Technology, 25,* 353–357.

Marple, V. A. (1970). *A fundamental study of inertial impactors* (Unpublished doctoral dissertation). Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN.

Marple, V. A. (1978). Simulation of respirable penetration characteristics by inertial impaction. *Journal of Aerosol Science, 9,* 125–134.

Marple, V. A., & Chien, C. M. (1980). Virtual impactors: A theoretical study. *Environmental Science & Technology, 14,* 976–985.

Marple, V. A., & Liu, B. Y. H. (1974). Characteristics of laminar jet impactors. *Environmental Science & Technology, 8,* 648–654.

Marple, V. A., & Liu, B. Y. H. (1975). On fluid flow and aerosol impaction in inertial impactors. *Journal of Colloid and Interface Science, 53,* 31–34.

Marple, V. A., Liu, B. Y. H., & Burton, R. M. (1990). High-volume impactor for sampling fine and coarse particles. *Journal of the Air and Waste Management Association, 40,* 762–767.

Marple, V. A., Liu, B. Y. H., & Kuhlmey, G. A. (1981). A uniform deposit impactor. *Journal of Aerosol Science, 12,* 333–337.

Marple, V. A., Liu, B. Y. H., & Rubow, K. L. (1978). A dust generator for laboratory use. *American Industrial Hygiene Association Journal, 39,* 26–32.

Marple, V. A., Liu, B. Y. H., & Whitby, K. T. (1973). Fluid mechanics of the laminar flow aerosol impactor. *Journal of Aerosol Science, 5,* 1–16

Marple, V. A., Liu, B. Y. H., & Whitby, K. T. (1974). On the flow fields of inertial impactors. *Journal of Fluids Engineering, 96,* 394–400.

Marple, V. A., & McCormack, J. E. (1983). Personal sampling impactor with respirable aerosol penetration characteristics. *American Industrial Hygiene Association Journal, 44,* 916–922.

Marple, V. A., & Olson, B. (1995). High volume PM10/2.5/1.0 trichotomous sampler. In *Particulate Matter: Health and Regulatory Issues, VIP-49.* Pittsburgh, PA: Air & Waste Management Association.

Marple, V. A., & Olson, B. (1999). A microorifice impactor with cut sizes down to 10 nanometers (Final Report for Grant Number G1135242, G1145242, G1155242/2782). Morgantown, WV: West Virginia University, National Research Center for Coal and Energy, Generic Mineral Technology Center for Respirable Dust.

Marple, V. A., Olson, B. A., & Miller, N. C. (1995a). A low loss cascade impactor with stage collection cups: Calibration and pharmaceutical inhaler applications. *Aerosol Science and Technology, 22,* 124–134.

Marple, V. A., Olson, B., & Rader, D. (1992). The effect of gravity on particle collection efficiency of inertial impactors. In R. L. Frantz & R. V. Ramani (Eds.), *Generic Mineral Technology Center for Respirable Dust Publications 1990, 11,* 26–29.

Marple, V., Olson, B., & Santhanakrishnan, K. (2005). Rapid check of cascade impactor cut-sizes using polydisperse challenge aerosol calibration method. *Aerosol Science and Technology, 40,* 1064–1070.

Marple, V., Olson, B., Santhanakrishnan, K., & Mitchell, J. P. (2004). Next generation pharmaceutical impactor (a new impactor for pharmeceutical inhaler testing)— Part III: Extension of archival calibration to 15 L/min. *Journal of Aerosol Medicine, 17,* 335–343.

Marple, V., Olson, B., Santhanakrishnan, K., Mitchell, J. P., Murray, S. C., & Hudson-Curtis, B. L. (2003b). Next generation pharmaceutical impactor (a new impactor for pharmaceutical inhaler testing)—Part II: Archival calibration. *Journal of Aerosol Medicine, 16,* 301–324.

Marple, V. A., & Rader, D. J. (1985). Effect of ultrastokesian drag and particle interception on impaction characteristics. *Aerosol Science and Technology, 4,* 141–156.

Marple, V., Roberts, D. L., Romay, F. J., Miller, N. C., Truman, K. G., Van Oort, M., . . . Hochrainer, D. (2003a). Next generation pharmaceutical impactor (a new impactor for pharmaceutical inhaler testing)—Part I: Design. *Journal of Aerosol Medicine, 16,* 283–299.

Marple, V. A., Rubow, K. L., & Behm, S. M. (1991). A microorifice uniform deposit impactor (MOUDI): Description, calibration, and use. *Aerosol Science and Technology, 14,* 434–446.

Marple, V. A., Rubow, K. L., & Olson, B. (1995b). Diesel exhaust/mine dust personal aerosol: Sampler design, calibration and field evaluation. *Aerosol Science and Technology, 22,* 140–150.

Marple, V. A., Rubow, K. L., & Olson, B. (1996). Diesel exhaust/mine dust personal aerosol sampler utilizing virtual impactor technology. *Applied Occupational & Environmental Hygiene, 11,* 721–727.

Marple, V. A., Rubow, K. L., Turner, W., & Spengler, J. D. (1987). Low flow rate sharp cut impactors for indoor air sampling: Design and calibration. *Journal of the Air Pollution Control Association, 37,* 1303–1307.

Maynard, A. D., & Pui, D. Y. H. (Eds.). (2007a). *Nanoparticles and occupational heath.* Dordrecht, The Netherlands: Springer.

Maynard, A. D., & Pui, D. Y. H. (Eds.). (2007b). Special issue on nanoparticles and occupational health [Special issue]. *Journal of Nanoparticle Research, 9*(1).

McDonald, B. N., Schaller, R. E., Engel, M. R., Liu, B. Y. H., Pui, D. Y. H., & Johnson, T. (1986). Time resolved measurements of industrial pulse-cleaned cartridge dust collectors. In R. R. Raber (Ed.), *Fluid Filtration: Gas.* Philadelphia, PA: ASTM.

McFarland, A. R., & Tomaides, M. (1969a). Characterization of chain agglomerate aerosols—A low pressure impactor for aerosol sampling on electron microscope grids; An improved exploding wire aerosol generator; response of an optical counter to a chain agglomerate aerosol. Particle Technology Laboratory, Department of Mechanical Engineering, University of Minnesota: Minneapolis, MN.

McFarland, A. R., & Tomaides, M. (1969b). Response of an optical counter to chain agglomerate aerosols. *Environmental Science & Technology.*

McMurry, P. H. (1980). Photochemical aerosol formation from SO_2: A theoretical analysis of smog chamber data. *Journal of Colloid and Interface Science, 78,* 513–527.

McMurry, P. H. (1983). New particle formation in the presence of an aerosol: Rates, time scales, and sub-0.01 μm size distributions. *Journal of Colloid and Interface Science, 95,* 72–80.

McMurry, P. H., & Friedlander, S. K. (1979). New particle formation in the presence of an aerosol. *Atmospheric Environment, 13,* 1635–1651.

McMurry, P. H., Litchy, M., Huang, P.-F., Cai, X., Turpin, B. J., Dick, W. D., & Hanson, A. (1996a). Elemental composition and morphology of individual particles separated by size and hygroscopicity with the TDMA. *Atmospheric Environment, 30,* 101–108.

McMurry, P. H., Nijhawan, S., Rao, N., Ziemann, P., Kittelson, D. B., & Campbell, S. (1996c). Particle beam mass spectrometer measurements of particle formation during low pressure chemical vapor deposition of polysilicon and silicon dioxide films. *Journal of Vacuum Science and Technology, A*(14), 582–587.

McMurry, P. H., & Rader, D. J. (1986). Application of the tandem differential mobility analyzer to studies of droplet growth or evaporation. *Journal of Aerosol Science, 17,* 771–787.

McMurry, P. H., Rader, D. J., & Stith, J. (1981). Studies of aerosol formation in power plant plumes—I. Growth laws for secondary aerosols in power plant plumes: Implications for chemical conversion mechanisms. *Atmospheric Environment, 15,* 2315–2327.

McMurry, P. H., & Wilson, J. C. (1982). Growth laws for the formation of secondary ambient aerosols: Implications for chemical conversion mechanisms. *Atmospheric Environment, 16,* 121–134.

McMurry, P. H., & Wilson, J. C. (1983). Droplet phase (heterogeneous) and gas phase (homogenous) contributions to secondary ambient aerosol formation as functions of relative humidity. *Journal of Geophysical Research, 88,* 5101–5108.

McMurry, P. H., Woo, K.-S., Weber, R. J., Chen, D.-R., & Pui, D. Y. H. (2000). Size distributions of 3-10 nm atmospheric particles: Implications for nucleation mechanisms. *Philosophical Transactions of the Royal Society of London, Series A: Physical Sciences and Engineering, 358,* 2625–2642.

McMurry, P. H., Zhang, X., & Lee, C.-T. (1996b). Issues in aerosol measurement for optic assessments. *Journal of Geophysical Research, 101,* 19189–19197.

Mulholland, G. W., Donnelly, M., Hagwood, C., Kukuck, S., & Hackley, V. (2006). Measurement of 100nm and 60nm particle standards by differential mobility analysis. *Journal of Research of the National Institute of Standards and Technology , 111,* 257–312.

Mulholland, G. W., & Liu, B. Y. H. (1980). Response of smoke detectors to monodisperse aerosols. *Journal of Research of the National Bureau of Standards, 85,* 223–238.

Mulholland, G. W., Pui, D. Y. H., Kapadia, A., & Liu, B. Y. H. (1980). Aerosol number and mass concentration measurements: A comparison of the electrical aerosol analyzer with other measurement techniques. *Journal of Colloid and Interface Science, 77,* 57–67.

Nijhawan, S., McMurry, P. H., & Campbell, S. A. (2000). Particle transport in parallel-place semiconductor reactor: Chamber modification and design criterion for enhanced process cleanliness. *Journal of Vacuum Science and Technology, A: Vacuum, Surfaces, and Films, 18,* 2198–2206.

Nijhawan, S., McMurry, P. H., Swihart, M. T., Suh, S.-M., Girshick, S. L., Campbell, S. A., & Brockmann, J. E. (2003). An experimental and numerical study of particle nucleation and growth during low-pressure thermal decomposition of silane. *Journal of Aerosol Science, 34,* 691–711.

Opiolka, S., Fissan, H., Ye, Y., & Pui, D. Y. H. (1990). Reduction of particle deposition on a free-standing semiconductor wafer by thermophoretic effect. In *10th international symposium on contamination control* (pp. 85–88). Zurich, Switzerland.

Pak, S. S., Liu, B. Y. H., & Rubow, K. L. (1992). The effect of coating thickness on particle bounce in inertial impactors. *Aerosol Science and Technology, 16,*141–150.

Park, K., Dutcher, D., Emery, M., Pagels, J., Sakurai, H., Scheckman, J., . . . & McMurry, P. H. (2008). Tandem measurements of aerosol properties—A review of mobility techniques with extensions. *Aerosol Science and Technology, 42,* 801–816.

Poon, W. S., Pui, D. Y. H., Lee, C.-T., & Liu, B. Y. H. (1994a). A compact porous denuder for atmospheric sampling of inorganic aerosols. *Journal of Aerosol Science, 25,* 923–934.

Poon, W. S., Pui, D. Y. H., Liu, B. Y. H., & Sun, J.-J. (1994b). A compact porous-metal denuder sampler for atmospheric and indoor air sampling of inorganic acidic pollutants: Field comparison with an annular denuder system. *Journal of Aerosol Science, 25,* 923–934.

Pui, D. Y. H. (1973). *Electrical neutralization and stationary charge distribution of aerosol particles* (Unpublished master's thesis). Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN.

Pui, D. Y. H. (1976). *Experimental study of diffusion charging of aerosols* (Unpublished doctoral dissertation). Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN.

Pui, D. Y. H., & Chen, D. R. (2002). *U.S. Patent No. 6,399,362*. Washington, DC: U.S. Patent and Trademark Office.

Pui, D. Y. H., & Chen, D. R. (2004). *U.S. Patent No. 6,764,720.* Washington, DC: U.S. Patent and Trademark Office.

Pui, D. Y. H., & Liu, B. Y. H. (1979). Electrical aerosol analyzer: Calibration and performance. In *Aerosol measurement workshop* (pp. 384–399). Gainesville, FL: University Presses of Florida.

Pui, D. Y. H., Gratzek, J. P., & Kuehn, T. H. (1991). Experimental measurements of cleanroom airflow and particle transport for flow modelling exercise. In *37th annual technical meeting of the Institute of Environmental Sciences,* San Diego, CA.

Pui, D. Y. H., Qi, C., Stanley, N., Oberdorster, G., & Maynard, A. (2008). Recirculating air filtration significantly reduces exposure to airborne nanoparticles. *Environmental Health Perspectives, 116,* 863–866.

Pui, D. Y. H., Romay-Novas, F., & Liu, B. Y. H. (1987). Experimental study of particle deposition in bends of circular cross section. *Aerosol Science and Technology, 7,* 301–315.

Pui, D. Y. H., Tsai, C. J., & Liu, B. Y. H. (1988). Charge level on aerosol particles: Measurement of particle charge and size distribution in disk drive. In *34th annual technical meeting of the Institute of Environmental Sciences,* King of Prussia, PA.

Pui, D. Y. H., Ye, Y., & Liu, B. Y. H. (1990). Experimental study of particle deposition on semiconductor wafers. *Aerosol Science and Technology, 12,* 795–804.

Qi, C., Asbach, C., Shin, W. G., Fissan, H., & Pui, D. Y. H. (2009). The effect of particle pre-existing charge on unipolar charging and its implication on electrical aerosol measurements. *Aerosol Science and Technology, 43,* 232–240.

Qi, C., Stanley, N., Pui, D. Y. H., & Kuehn, T. H. (2008). Laboratory and on-road evaluations of cabin air filters using number and surface area concentration monitors. *Environmental Science and Technology, 42,* 4128–4132.

Rader, D. J., McMurry, P. H., & Smith, S. (1987). Evaporation rates of monodisperse organic aerosols in the 0.02- to 0.2-μm-diameter range. *Aerosol Science and Technology, 6,* 247–260.

Ramsey, J. W., Liu, B. Y. H., & Gallo, E. J. (1988). A non-contaminating fog generator for flow visualization in clean rooms. In *9th international symposium on contamination control* (pp. 637–645). Los Angeles, CA.

Rao, N., Girshick, S., Heberlein, J., McMurry, P. H., Jones, S., Hansen, D., & Micheel, B. (1995b). Nanoparticle formation using a plasma expansion process. *Plasma Chemistry and Plasma Processing, 15,* 581–606.

Rao, N., Micheel, B., Hansen, D., Fandrey, C., Bench, M., Girshiek, S., . . . & McMurry, P. H. (1995a). Synthesis of nanophase silicon, carbon, and silicon carbide powders using a plasma expansion process. *Journal of Material Research, 10,* 2073–2084.

Rao, N. P., & McMurry, P. H. (1989). Nucleation and growth of aerosol in chemically reacting systems: A theoretical study of the near-collision-controlled regime. *Aerosol Science and Technology, 11,* 120–132.

Rao, N. P., Nijhawan, S., Kim, T., Wu, Z., Campbell, S., Kittelson, D. B., . . . Mastromatteo, E. (1998c). Investigation of particle generation during the low pressure chemical vapor deposition of borophosphosilicate glass. *Journal of the Electrochemical Society, 145,* 2051–2057.

Rao, N. P., Tymiak, N., Blum, J., Neuman, A., Lee, H. J., Girshick, S. L., . . . & Heberlein, J. (1998b). Hypersonic plasma particle deposition of nanostructered silicon and silicon carbide. *Journal of Aerosol Science, 29,* 707–720.

Rao, N. P., Wu, Z., Nijhawan, S., Ziemann, P., Campbell, S., Kittelson, D. B., & McMurry, P. (1998a). Investigation of particle formation during the plasma enhanced chemical vapor deposition of amorphous silicon, oxide, and nitride films. *Journal of Vacuum Science and Technology, B: Microelectronics Processing and Phenomena, 16,* 483–489.

Romay, F. J., & Pui, D. Y. H. (1992a). Free electron charging of ultrafine aerosol particles. *Journal of Aerosol Science, 23,* 679–692.

Romay, F. J., & Pui, D. Y. H. (1992b). On the combination coefficient of positive ions with ultrafine neutral particles in the transition and free-molecule regimes. *Aerosol Science and Technology, 17,* 134–147.

Romay, F., Pui, D. Y. H., & Adachi, M. (1991). Unipolar diffusion charging of aerosol particles at low pressure. *Aerosol Science and Technology, 15,* 60–68.

Roth, P., Zell, U., & Liu, B. Y. H. (1984). Particle dispersion by shock and expansion waves: Preliminary observations and experiments. *Journal of Aerosol Science, 15,* 293–296.

Rowley, F. B., & Beal, J. (1929). Determining the quantity of dust in air by impingement. *ASHVE Transactions, 35,* 483–498.

Rowley, F. B., & Jordan, R. C. (1939). A standard air filter dust test. *ASHVE Journal Section, Heating, Piping, and Air Conditioning, 11,* 633–638.

Rowley, F. B., & Jordan, R. C. (1941). A comparison of the weight, particle count and discoloration methods of testing air filters. *ASHVE Journal Section, Heating, Piping, and Air Conditioning, 13,* 246–255.

Rowley, F. B., & Jordan, R. C. (1942). Overloading of viscous air filters during accelerated tests. *ASHVE Journal Section, Heating, Piping, and Air Conditioning, 14,* 438–477.

Rubow, K. L., Cantrell, B. K., & Marple, V. A. (1990a). Measurement of coal dust and diesel exhaust aerosols in underground mines. In *VII international pneumoconioses conference* (pp. 645–650). Pittsburgh, PA.

Rubow, K. L., Lee, J. K., Pui, D. Y. H., & Liu, B. Y. H. (1990b). Performance evaluation and comparative study of pressure reducers for aerosol sampling from high purity gases. In *10th international symposium on contamination control.* Zurich, Switzerland.

Rubow, K. L., & Liu, B. Y. H. (1984). Evaluation of ultra-high efficiency membrane filters. In *30th Annual Technical Meeting of the Institute of Environmental Sciences* (pp. 64–68).

Rubow, K. L., & Liu, B. Y. H. (1985). Evaluation of ultra high-efficiency membrane filters. *Microcontamination,* 39–43.

Rubow, K. L., & Liu, B. Y. H. (1986). Characteristics of membrane filters for particle collection. In R. R. Raber, (Ed.), *Filtration: Gas volume 1* (pp. 74–94). Philadelphia, PA: American Society for Testing and Materials.

Rubow, K. L., Liu, B. Y. H., & Grant, D. C. (1988). Characteristics of ultra-high efficiency membrane filters in gas applications. In *33rd annual technical meeting of the Institute of Environmental Sciences* (pp. 383–387). San Jose, CA.

Rubow, K. L., & Marple, V. (1988). Determining the size distribution of coal/diesel aerosol mixtures with the microorifice uniform deposit impactor. In *International symposium on respirable dust in the mineral industries,* University Park, PA.

Rubow, K. L., & Marple, V. A. (1982). Instrument evaluation chamber: Calibration of commercial photometers. In *International symposium on aerosols in the mining and industrial work environment,* Minneapolis, MN.

Rubow, K. L., Marple, V. A., Olin, J., & McCawley, M. A. (1987). A personal cascade impactor: Design, evaluation and calibration. *American Industrial Hygiene Association Journal, 48,* 532–538.

Sachweh, B. A., Dick, W. D., & McMurry, P. H. (1995). Distinguishing between spherical and nonspherical particles by measuring the variability in azimuthal light scattering. *Aerosol Science and Technology, 23,* 373–391.

Sadjadi, R. S. M., & Liu, B. Y. H. (1991). Characteristics of pin-hole leaks in HEPA and ULPA filters. In *36th annual technical meeting of the Institute of Environmental Sciences.* New Orleans, LA.

Saros, M. T., Weber, R. J., Marti, J. J., & McMurry, P. H. (1996). Ultrafine aerosol measurement using a condensation nucleus counter with pulse height analysis. *Aerosol Science and Technology, 25,* 200–213.

Sato, S., Chen, D.-R., & Pui, D. Y. H. (2001). Particle transport at low pressure: Particle deposition in bends of circular cross section. *Aerosol Science and Technology, 37,* 770–779.

Sato, S., Chen, D.-R., & Pui, D. Y. H. (2002). Particle transport at low pressure: Particle deposition in a tube with an abrupt contraction. *Journal of Aerosol Science, 33,* 659–671.

Schaefer, J. W., Barris, M. A., & Liu, B. Y. H. (1986). Filter media design for high purity air applications, *Journal of Environmental Science, 29,* 27–31.

Scheckman, J. (2008). Mass mobility relationship for silica agglomerates: *Implications for transport and morphological properties* (Unpublished master's thesis). Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN.

Schrock, D. W., Olson, B., Urness, R. I., Kuehn, T., & Breitenfeld, A. L. (2006). A new standard method of test for determining the grease particulate removal efficiency of filter systems for kitchen ventilation. *ASHRAE Transactions, 112,* 583–590.

Sem, G. J., Boulaud, D., Brimblecombe, P., Ensor, D. S., Gentry, J. W., Marijnissen, J. C. M., & Preining, O. (Eds.). (2005). *History and reviews of aerosol science. (Proceedings of the second symposium on the history of aerosol science, October 13–14, 2001, Portland, Oregon, USA).* Mount Laurel, NJ: American Association for Aerosol Research.

Shanmugavely, I., Kuehn, T. H., & Liu, B. Y. H. (1987). Numerical simulation of flow fields in clean rooms. In *33rd annual technical meeting of the Institute of Environmental Sciences,* San Jose, CA.

Shin, W. G., Mulholland, G. W., Kim, S. C., Wang, J., Emery, M., & Pui, D. Y. H. (2009a) Friction coefficient and mass of silver agglomerates in the transition regime. *Journal of Aerosol Science, 40,* 575–587.

Shin, W. G., Pui, D. Y. H., Fissan, H., Neumann, S., & Trampe, A. (2007). Calibration and numerical simulation of the nanoparticle surface area monitor (TSI Model 3550 NSAM). *Journal of Nanoparticle Research, 9,* 61–69.

Shin, W. G., Qi, C., Wang, J., Fissan, H., & Pui, D. Y. H. (2009b) The effect of dielectric constant of materials on unipolar charging. *Journal of Aerosol Science, 40,* 463–468.

Shin, W. G., Wang, J., Mertler, M., Sachweh, B., Fissan, H., & Pui, D. Y. H. (2009c). Structural properties of silver nanoparticle agglomerates based on transmission electron microscopy: Relationship to particle mobility analysis. *Journal of Nanoparticle Research, 11,* 163–173.

Sinclair, D., Countess, R. J., Liu, B. Y. H., & Pui, D. Y. H. (1976). Experimental verification of diffusion battery theory. In *68th annual meeting of the Air Pollution Control Association* (pp. 661–663). Boston, MA.

Sinclair, D., Countess, R. J., Liu, B. Y. H., & Pui, D. Y. H. (1979). Automatic analysis of submicron aerosol. In *Aerosol measurement workshop* (pp. 544–563). Gainesville, FL: University of Florida Presses.

Smith, J. N., Dunn, M. J., VanReken, T. M., Iida, K., Stolzenburg, M. R., . . . & Huey, G. (2008). The chemical composition of atmospheric nanoparticles formed from nucleation in Tecamac, Mexico: Evidence for an important role for organic species in nanoparticle growth. *Geophysical Research Letters, 35,* L04808.

Smith, J. N., Moore, K. F., Eisele, F. L., Voisin, D., Ghimire, A. K., Sakurai, H., & McMurry, P. H. (2005). Chemical composition of atmospheric nanoparticles during nucleation events in Atlanta, Georgia. *Journal of Geophysical Research, 110,* D22S03.

Smith, J. N., Barsanti, K. C., Friedli, H. R., Ehn, M., Kulmala, M., Collins, D. R., Scheckman, J. H., Williams, B. J., & McMurry, P. H. (2010). Observations of aminium salts in atmospheric nanoparticles and possible climatic implications. *Proceedings of the National Academy of Sciences, 107,* 6634–6639.

Stolzenburg, M. R., & McMurry, P. H. (1991). An ultrafine aerosol condensation nucleus counter. *Aerosol Science and Technology, 14,* 48–65.

Swietlicki, E., Hansson, H.-C., Hämeri, K., Svenningsson, B., Massling, A., McFiggans, G., . . . Kulmala, M. (2008). Hygroscopic properties of submicrometer atmospheric aerosol particles measured with H-TDMA instruments in various environments—A review. *Tellus. Series B: Chemical and Physical Meteorology, 60B,* 432–469.

Szydlowski, R., & Kuehn, T. (1981). Analysis of transient heat loss in earth sheltered stuctures. *American Underground Space Journal, 5,* 237–246.

Szymanski, W. W., & Liu, B. Y. H. (1986). On the sizing accuracy of laser optical particle counters. *Particle & Particle Systems Characterization, 3,* 1–7.

Tolpadi, A., & Kuehn, T. (1984). Conjugate three-dimensional natural convection heat transfer from a horizontal cylinder with long transverse plate fins. *Numerical Heat Transfer, 7,* 319–341.

Tomaides, M., Liu, B. Y. H., & Whitby, K. T. (1971). Evaluation of the condensation aerosol generator for producing monodispersed aerosols. *Journal of Aerosol Science, 2,* 39–46.

Tsai, C. J., & Pui, D. Y. H. (1990). Numerical study of particle deposition in bends of a circular cross section — laminar flow regime. *Aerosol Science and Technology, 12,* 813–831.

Tsai, C. J., Pui, D. Y. H., & Liu, B. Y. H. (1990a). Capture and rebound of small particles upon impact with solid surfaces. *Aerosol Science and Technology, 12,* 497–507.

Tsai, C. J., Pui, D. Y. H., & Liu, B. Y. H. (1991a). Elastic flattening and particle adhesion. *Aerosol Science and Technology, 15,* 239–255.

Tsai, C.-J., Pui, D. Y. H., & Liu, B. Y. H. (1991d). Numerical study of transport and deposition of wear particles in computer disk drives. In *37th annual technical meeting of the Institute of Environmental Sciences*, San Diego, CA.

Tsai, C. J., Pui, D. Y. H., & Liu, B. Y. H. (1991c). Particle detachment from disk surfaces of computer disk drives. *Journal of Aerosol Science, 22,* 737–746.

Tsai, C. J., Pui, D. Y. H., & Liu, B. Y. H. (1991b). Wear particle generation in thin film computer disk drives: Experimental study. *Aerosol Science and Technology, 15,* 36–48.

Tsai, C.-J., Pui, D. Y. H., & Liu, B. Y. H. (1992). Transport and deposition of wear particles in computer disk drives. *Particle & Particle Systems Characterization, 9,* 31–39.

Tymiak, N., Blum, J., Neuman, N., Rao, N., Gerberich, W., McMurry, P. H., Heberlein, J.V.R., & Girshick, S. (2001). Hypersonic plasma particle deposition of nanostructured silicon carbide films for friction and wear resistance. *Journal of Thermal Spray Technology, 10,* 173–174.

Voisin, D., Smith, J. N., Sakurai, H., McMurry, P. H., & Eisele, F. L. (2003). Thermal desorption chemical ionization mass spectrometer for ultrafine partilce chemical composition. *Aerosol Science and Technology, 37,* 471–475.

Wahi, B. N., & Liu, B. Y. H. (1971). The mobility of polystyrene latex particles in the transition and the free molecular regimes. *Journal of Colloid and Interface Science, 37,* 374–381.

Wang, J., Chen, D.-R., & Pui, D. Y. H. (2007). Modeling of filtration efficiency of nanoparticles in standard filter media. *Journal of Nanoparticle Research, 9,*109–115.

Wang, J., Kim, S. C., & Pui, D. Y. H. (2008b). Figure of merit of composite filters with micrometer and nanometer fibers. *Aerosol Science and Technology, 42,* 722–728.

Wang, J., Pui, D. Y. H., Qi, C., Yook, S.-J., Fissan, H., Ultanir, E., & Liang, T. (2008a). Controlled deposition of NIST-traceable nanoparticles as additional size standards for photomask applications. In *SPIE symposium on advanced lithography* (pp. 1–10). San Jose, CA.

Wang, X., Gidwani, A., Girshick, S. L., & McMurry, P. H. (2005a). Aerodynamic focusing of nanoparticles: II. Numerical simulation of particle motion through aerodynamic lenses. *Aerosol Science and Technology, 39,* 624–636.

Wang, X., Kruis, F. E., & McMurry, P. H. (2005b). Aerodynamic focusing of nanoparticles: II. Numerical simulation of particle trajectories through aerodynamic lenses. *Aerosol Science and Technology, 39,* 611–623.

Wang, X., & McMurry, P. H. (2006b). A design tool for aerodynamic lens systems. *Aerosol Science and Technology, 40,* 320–334.

Wang, X., & McMurry, P. H. (2006a). An experimental study of nanoparticle focusing with aerodynamic lenses. *International Journal of Mass Spectroscopy, 258,* 30–36.

Weber, R. J., Marti, J. J., McMurry, P. H., Eisele, F. L., Tanner, D. J., & Jefferson, A. (1996). Measured atmospheric new particle formation rates: Implications for nucleation mechanisms. *Chemical Engineering Communications, 151,* 53–64.

Weber, R. J., Marti, J. J., McMurry, P. H., Eisele, F. L., Tanner, D. J., & Jefferson, A. (1997). Measurements of new particle formation and ultrafine particle growth rates at a clean continental site. *Journal Geophysical Research, 102,* 4375–4385.

Weber, R. J., & McMurry, P. H. (1996). Fine particle size distributions at the Mauna Loa observatory, Hawaii. *Journal of Geophysical Research, 101,* 14767–14775.

Weber, R. J., McMurry, P. H., Eisele, F. L., & Tanner, D. J. (1995). Measurement of expected nucleation procurer species and ultrafine and fine particles at Mauna Loa Observatory, Hawaii. *Journal of Atmospheric Science, 52,* 2242–2257.

Weber, R. J., McMurry, P. H., Mauldin, L., Tanner, D., Eissele, F., Clarke, A. D., & Kapustin, V. N. (1999). New particle formation in the remote troposphere: A comparison of observations at various sites. *Geophysical Research Letters, 26,* 307–310.

Weber, R. J., McMurry, P. H., Mauldin, L., Tanner, D. J., Eisele, F. L., Brechtel, F. J., Kreidenweis, S. M., Kok, G. L., Schillawski, R. D., & Baumgardner, D. (1998b). A study of new particle formation and growth involving biogenic and trace gas species measured during ACE 1. *Journal of Geophysical Research, 103,* 16385–16396.

Weber, R. J., Stolzenburg, M. R., Pandis, S. N., & McMurry, P. H. (1998a). Inversion of ultrafine condensation nucleus counter pulse height distributions to obtain nanoparticle (~3–10 nm) size distributions. *Journal of Aerosol Science, 29,* 601–615.

Whitby, E. R., & McMurry, P. H. (1997). Modal aerosol dynamics modeling. *Aerosol Science and Technology, 27,* 673–688.

Whitby, K. T. (1954). *The mechanics of fine sieving* (Unpublished doctoral dissertation). Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN.

Whitby, K. T. (1955). A rapid general purpose centrifuge sedimentation method for measurement of size distribution of small particles—Part II. Procedures and applications. *ASHAE Journal Section, Heating, Piping, and Air Conditioning, 27,* 139–145.

Whitby, K. T. (1961). Generator for producing high concentrations of small ions. *Review of Scientific Instruments, 32,* 1351–1355.

Whitby, K. T., Algren, A. B., Jordan, R. C., & Annis, J. C. (1957). The ASHAE air-borne dust survey. *ASHAE Journal Section, Heating, Piping, and Air Conditioning, 29,*185–192.

Whitby, K. T., & Clark, W. E. (1966). Electric aerosol particle counting and size distribution measuring system for the 0.015 to 1 μ size range. *Tellus, 18*, 573–586.

Whitby, K. T., Clark, W. E., Marple, V. A., Sverdrup, G. M., Sem, G. J., Willeke, K., . . . & Pui, D. Y. H. (1975). Characterization of California aerosols—I. Size distributions of freeway aerosol. *Atmospheric Environment, 9,* 463–482.

Whitby, K. T., & Liu, B. Y. H. (1967). Generation of countable pulses by high concentrations of subcountable sized particles in the sensing volume of optical counters. *Journal of Colloid and Interface Science, 25,* 537–546.

Whitby, K. T., & Liu, B. Y. H. (1968). Polystyrene aerosols-electrical charge and residue size distribution. *Atmospheric Environment, 2,* 103–116.

Whitby, K. T., Liu, B. Y. H., Friedlander, S. K., Mueller, P. K., Charlson, R. A., Lundgren, D. A., & Noll, K. E. (1969). Los Angeles smog aerosol study. In *7th international conference on condensation and ice nuclei.* Prague, Czechoslovakia, Vienna, Austria.

Whitby, K. T., Husar, R. B., & Liu, B. Y. H. (1972a). The aerosol size distribution of Los Angeles smog. *Journal of Colloid and Interface Science, 39,* 177–204.

Whitby, K. T., Liu, B. Y. H., Husar, R. B., & Barsic, N. J. (1972b). The Minnesota aerosol-analyzing system used in the Los Angeles smog project. *Journal of Colloid and Interface Science, 39,* 136–164.

Willeke, K., & Liu, B. Y. H. (1976). Single particle optical counter: Principle and application. In B. Y. Liu (Ed.), *Fine particles: Aerosol generation, measurement, sampling, and analysis* (pp. 697–729). New York, NY: Academic Press.

Wilson, J. C., & Liu, B. Y. H. (1980). Aerodynamic particle size measurement by laser-doppler velocimetry. *Journal of Aerosol Science, 11,* 139–150.

Wilson, J. C., & McMurry, P. H. (1981). Studies of aerosol formation in power plant plumes—II. Secondary aerosol formation in the Navajo Generating Station plume, *Atmospheric Environment, 15,* 2329–2339.

Wilson, W. E., Han, H.-S., Stanek, J., Turner, J., Chen, D.-R., Johnson, T., & Pui, D. Y. H. (2005). Use of the electrical aerosol detector as an indicator for the total particle surface area deposited in the lung. *Journal of the Air and Waste Management Association, 57,* 211–220.

Wilson, W. E., Spiller, L. L., Ellestad, T. G., Lamothe, P. J., Dzubay, T. G., Stevens, R. K., . . . Cantrell, B. K. (1977). General Motors sulfate dispersion experiment: Summary of EPA measurements. *Journal of the Air Pollution Control Association, 27,* 46–51.

Woo, K. S., Chen, D. R., Pui, D. Y. H., & McMurry, P. H. (2001). Measurement of Atlanta aerosol size distributions: Observations of ultrafine particle events. *Aerosol Science and Technology, 34,* 75–87.

Ye, Y., & Pui, D. Y. H. (1990). Particle deposition in a tube with an abrupt contraction. *Journal of Aerosol Science, 21,* 29–40.

Ye, Y., Pui, D. Y. H., Liu, B. Y. H., Opiolka, S., Blumhorst, S., & Fissan, H. (1991a). Thermophoretic effect of particle deposition on a free standing semiconductor wafer in a clean room. *Journal of Aerosol Science, 22,* 63–72.

Ye, Y., Tsai, C. J., Pui, D. Y. H., & Lewis, C. (1991b). Particle transmission characteristics of an annular denuder ambient sampling system. *Aerosol Science and Technology, 14,* 102–111.

Yeh, H. C., & Liu, B. Y. H. (1973a). Aerosol filtration by fibrous filters—I. Theoretical. *Journal of Aerosol Science, 5,* 191–204.

Yeh, H. C., & Liu, B. Y. H. (1973b). Aerosol filtration by fibrous filters—II. Experimental. *Journal of Aerosol Science, 5,* 205–217.

Yook, S. J., Fissan, H., Asbach, C., Kim, J. H., Dutcher, D. D., Yan, P. Y., & Pui, D. Y. H. (2007b). Experimental investigations on particle contamination of masks without protective pellicles during vibration or shipping of mask carriers. *IEEE Transactions, 20,* 578–584.

Yook, S.-Y., Fissan, H., Asbach, C., Kim, J. H., van der Zwaag, T., Engelke, T., . . . & Pui, D. Y. H. (2007c). Experimental investigations of protection schemes for extreme ultraviolet lithography masks in carrier systems against horizontal aerosol flow. *IEEE Transactions, 20,* 176–186.

Yook, S.-J., Fissan, H., Asbach, C., Kim, J. H., Wang, J., Yan, P.-Y., & Pui, D. Y. H. (2007a). Evaluation of protection schemes for extreme ultraviolet lithography (Euvl) masks against top-down aerosol flow. *Aerosol Science, 38,* 211–227.

Yook, S. J., Fissan, H., Engelke, T., Asbach, C., Kim, J. H., van der Zwaag, T., . . . & Pui, D. Y. H. (2008b). Controlled deposition of SiO_2 nanoparticles of NIST-traceable particle sizes on mask surface inspection system characterization. *IEEE Transactions on Semiconductor Manufacturing, 21,* 238–243.

Yook, S. J., Fissan, H., Engelke, T., Asbach, C., van der Zwaag, T., Kim, J. H., . . . & Pui, D. Y. H. (2008a). Classification of highly monodisperse nanoparticles of NIST-traceable sizes by TDMA and control of deposition spot size on a surface by electrophoresis. *Journal of Aerosol Science, 39,* 537–548.

Zhang, R. Y., Khalizov, A. F., Pagels, J., Zhang, D., Xue, H. X., & McMurry, P. H. (2008). Variability in morphology, hygroscopicity, and optical properties of soot aerosols during atmospheric processing. *Proceedings of the National Academy of Sciences, USA, 105,* 10291–10296.

Zhang, X., McMurry, P. H., & Hering, S. (1993). Mixing characteristics and water content of submicron aerosols measured in Los Angeles and at the Grand Canyon. *Atmospheric Environment, 27A,* 1593–1607.

Zhang, X. Q., Turpin, B. J., McMurry, P. H., Hering, S. V., & Stolzenburg, M. R. (1994). Mie theory evaluation of species contributions to 1990 wintertime visibility reduction in the Grand Canyon. *Journal of the Air and Waste Management Association, 44,* 153–162.

Zhang, Z., & Liu, B. Y. H. (1991). Performance of TSI 3760 condensation nuclei counter at reduced pressures and flow rates. *Aerosol Science and Technology, 15,* 228–238.

Zhang, Z., & Liu, B. Y. H. (1992). Experimental study of aerosol filtration in the transition flow regime. *Aerosol Science and Technology, 16,* 227–235.

Zhang, Z. Q., & Liu, B. Y. H. (1989). On the empirical fitting equations for aspiration coefficients for thin-walled sampling probes. J*ournal of Aerosol Science, 20,* 713–720.

Zhao, J. Eisele, F. L., Titcombe, M., Kuang, C., & McMurry, P. H. (2010). Chemical ionization mass spectrometric measurements of atmospheric neutral clusters using the cluster-CIMS. *Journal of Geophysical Research, 115,* D08205.

Zhao, J., Liu, B. Y. H., & Kuehn, T. H. (1991). The formation of water aerosols during pump-down of vacuum process tools. *Solid State Technology, 34,* 85–89.

Ziemann, P. J., Kittelson, D., & McMurry, P. H. (1996). Effects of particle shape and chemical composition on the electron impact charging properties of submicron inorganic particles. *Journal of Aerosol Science, 27,* 587–606.

Ziemann, P. J., Liu, P., Kittelson, D. B., & McMurry, P. H. (1995a). Electron impact charging properties of size-selected, submicrometer organic particles. *Journal of Physical Chemistry, 99,* 5126–5138.

Ziemann, P. J., Liu, P., Kittelson, D. B., & McMurry, P. H. (1995b). Particle beam mass spectrometry of submicron particles charged to saturation in an electron beam. *Journal of Aerosol Science, 26,* 745–756.

Ziemann, P. J., & McMurry, P. H. (1997). Spatial distribution of chemical components in aerosol particles as determined from secondary electron yield measurements: Implications for mechanisms of multicomponent aerosol crystallization. *Journal of Colloid and Interface Science, 193,* 250–258.

Ziemann, P. J., & McMurry, P. H. (1998). Secondary electron yield measurements as a means for probing thin organic aerosol particles. *Aerosol Science and Technology, 28,* 77–90.