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Perspectives on air pollution aerodynamics

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ABSTRACT: This review will examine the application of wind engineering and in particular fluid modeling to air pollution aerodynamics. Since the Industrial Revolution man has had to deal with the polluting consequences of manufacturing, mining, transportation, and power production. Air pollution aerodynamics concerns the interaction of noxious aerosols, gases and particles emitted into the atmosphere with surrounding structures, terrain and vegetation. This interaction can deflect materials toward sensitive areas, concentrate species above acceptable levels, or even mitigate concentration levels and enhance diffusion and dispersion.

1 INTRODUCTION

1.1 *History*

Mankind has noted the impacts of air pollutants from the dawn of recorded history. In Genesis 19:28 of the Old Testament, Abraham "*beheld the smoke of the country go up as the smoke of a furnace.*" Pliny the Elder is recorded to have suffocated from volcanic fumes during the 79 AD eruption of Mount Vesuvius as recorded by Tacitus...hence the designation by geologists that an explosive eruption of magma in a vertical jet is a "Plinian Explosion." In England during the reign of Edward I (1272-1307), the nobility protested the use of highly sulphurous "sea coal", and indeed during Edward II reign (1307-1327) a man was put to torture for the pestilential odors of such coal (Wark et al. 1998).

In 1661 John Evelyn, one of the founders of the Royal Society, wrote a paper on "*Fumifugation: or the Incoveneice of the Aer and Smoke of London Dissapated; together with Some Remedies Humbly Proposed.*" By the 19th century air pollution had been identified as a primary health risk. Killer urban smog incidents due to disperse emission sources occurred in London, UK in 1873 (268 deaths), Glasgow, UK in 1909, Meuse Valley, Belgium in 1930 (60 deaths), Manchester, UK in 1931 (592 deaths), Donora, Pa USA in 1948 (20 died 14,000 ill) and London, UK in 1952 & 1956 (>4000 & 1000 died, respectively).

Specific substance releases also impacted and endangered populations. In 1945 spills of liquid natural gas (LNG) stored at the Cleveland Illuminating Company, USA, killed 44 people and caused $12 M damage (largest US industrial accident when adjusted for inflation). The 1979 nuclear incident at the Three Mile Island reactor, Harrisburg, Pa, forced the public to reconsider the implications of unexpected accidents. In 1984 the disastrous petrochemical releases in Bohpal, India, killed thousands. Then the 1986 release of radioactivity during the Chernobyl reactor accident exposed millions to significant radio nuclides.

But while the large incidents make headlines, there have been literally thousands of less publicized releases of effluents during production, transportation, handling and storage of various chemicals and fuels (Wiekeman 1984). In most cases the hazards of such releases are limited from a few meters to kilometers from the source. In such cases the initial source configuration and its relationship to nearby buildings, vegetation and terrain are critical (Lees 1980).

1.2 *Landmarks in Diffusion Theory*

The German Physiologist, Adoph Fick wrote "*Uber Diffusion*" in 1855 in which he recognized the molecular nature of dispersion at the microscopic scale by adapting the mathematical expressions for heat conduction proposed by Fourier some years earlier. But diffusion theory required the subsequent adoption of the concepts of turbulence by Osborne Reynolds in 1883 and the boundary layer concepts of Ludwig Prandt in 1905 to provide a rationale analytic framework to consider even idealized plume behavior.

In 1921 the Meteorological Department at the Chemical Defense Experimentation Station opened at Porton Downs, UK. Interest in gas warfare during World War I led to many field experiments there on the behavior of plumes and puffs of different gases. Subsequently, these data provided the base for calibration of many models. A few additional tests were carried out during the 1940 wartime years, but remained classified until the 1950s (e.g. Kalinske 1945a,b). Between 1955 and 1970 many field tests were carried out associated with the concern about dispersion from radioactive accidents. These are summarized in the monograph by Slade (1968).

G.I. Taylor proposed his statistical theory of turbulent diffusion in 1920, E. Schmidt and L.F. Richardson proposed three-dimensional K theory plume solutions in 1925, and in 1932 O.G. Sutton produced an eddy diffusion theory based on Taylor's work. Sutton's expressions provided the primary foundation for calculating concentrations (suitability adjusted by ad hoc corrections for stratification, nearby structures, complex terrain, etc.) until the 1950s (Sutton 1953; Wexler 1955; Slade 1968). Additional analytic and statistical approaches have been derived (Lagrangian similarity theories, Langevin equation and Monte Carlo approaches, convective similarity approaches, etc.) which explain plume behavior in stratified atmospheric environments, but have not been widely adopted into any regulatory framework (Csanady 1973; Pasquill & Smith 1983; Randerson 1984).

A "practical" approach suggested by F. Pasquill in 1961 won wide acceptance among regulators around the world. It used a Gaussian framework for dispersion, but assigned dispersion coefficients based on empirical curves derived from curve fits to experimental data and a designation of mixing conditions based on a simple A-F stability scale. (Subsequently this has been called the Pasquill-Gifford method after Frank Gifford added an additional very-stable G category) (Pasquill & Smith 1983). Today there are many variations on this theme adapted for rural/urban/coastal/valley perturbations using expressions regressed against additional field or laboratory data. These expressions have been integrated into large numerical air-pollution programs which consider details of local climatology, release conditions, atmospheric chemistry, etc. (Hanna 1982; Turner 1994; Venkatram & Wyngaard 1988; Zanetti 1990).

It is probably worthwhile at this point to quote a few cynical remarks by Richard Scorer (1978) about the value of analytic and numerical theories:

"Many authors have been taken in by diffusion theory. Their approach has been to develop an analysis assuming that dispersion is diffusion..."

"...sampling time always affects the concentration measured, so that the assumption that eddy diffusion analysis is valid is simply incorrect."

"The concepts of meteorology and fluid mechanics are simple in the extreme, but the computing techniques may be very sophisticated. This is typical of the 'indoor culture' which thinks that our brains rather than our fuel supply differentiates us from our less rich ancestors."

1.3 *Landmarks in Air Pollution Control*

In 1911 the term SMOG was coined by H.A. Des Voeux in a report to the Manchester Conference of the Smoke Abatement League of Great Britain. In 1947 the Los Angeles Air Pollution Control District was formed, and in 1955 Public Law 84-159 became the first US legislation aimed at air pollution control. This initial excursion in legislative control was very narrow in scope primarily because of federal legislature hesitancy to encroach on state's rights. The English Clean Air Act was enacted shortly afterwards in 1956. Subsequent US legislation is discussed in the book by Wark et al. (1998). The US National Air Pollution Control Administration (NACPA) was formed in legislation in 1967 and control was transferred to the US Environmental Protection Agency (EPA) in 1970.

1.4 *Landmarks in Air Pollution Aerodynamics via Fluid Modeling*

Among the earliest studies of plume behavior near buildings was that by Sherlock & Stalker (1940) who studied smoke plumes emitted from stacks above a model of the Crawford Power Station, Chicago Il. They combined their evidence of downwash with local climatological data to predict percent duration of downwash for different wind and stack exhaust velocities. Similarly, Hohenleiten & Wolf (1942) reported plume outlines for models depicting the Riverside Power Station, Baltimore, Md.

The earliest quantitative wind tunnel diffusion study may have been that performed by McElroy et al (1944) who studied a chimney jet in a built-up area. They used two models constructed to scales of 1/200 and 1/400 to study concentrations expected within 150 m of a 12 m square, 77 m high chimney discharging contaminated exhaust air from the proposed Brooklyn-Battery tunnel. Values of emission velocities, V, and wind speeds, U, were varied to produce a range of ratios from 0.3 to 10. Isopleths of maximum concentration ratio (C_{local}/C_{source}) were found as well as points on adjacent buildings. Authors found scale effects were absent, but no attempt was made to simulate the approach boundary layer.

During WW II studies were performed by Kalinske et al (1945a,b) or Rouse (1951) at the University of

Iowa to study the dosage and maximum concentration at various locations in a Japanese urban area as a result of exposure to a wind-borne gas cloud which had been created by a bomb burst in the area. A 1/72 scale model of a typical area was installed on the floor of a 2 m wide x 6 m long x 1.3 m high wind tunnel. The maximum height building was 100 mm, but the buildings covered the entire tunnel floor. A pancake-shaped burst was produced by emitting gas through a graded set of holes in the floor. Wind speeds were about 3 m/s. SO_2 concentrations were measured horizontally and vertically among the downwind buildings and reported non-dimensionally as CL^2U/Q, where U was the undisturbed flow velocity about 254 mm above the floor and L prototype equaled 0.3048 m. Results were compared with field tests over a full-scale Japanese village at the Dugway Proving Ground, Utah USA. Phosgene and NO_2 gas-filled bombs were released at the field site, but test variability made comparisons with the wind tunnel results questionable. The authors concluded results were order-of-magnitude and qualitatively similar. Wind tunnel accuracy was at least as good as the accuracy of single field experiments.

Transverse jets were studied in low-turbulence wind tunnels by Bryant (1949) and Bryant & Cowdrey (1955). Like most early studies plume spreading and trajectories were determined visually which led to difficulties in defining behavior far downstream. It was usually difficult to see differences between transitional and ultimates rise, especially if the plumes were buoyant.

Between 1945 and 1955 wind tunnel diffusion work in the USA was primarily active at the University of Michigan (Sherlock & Lesher 1955) and at New York University (Strom & Halitsky 1954). Most measurements involved photographic examination of smoke visualization above power station complexes.

In the late 50s and 60s fluid modeling studies were conducted in many countries. In the USA the principle efforts were at Colorado State University (CSU); Michigan State University (MSU); and New York University (NYU). The first true Boundary Layer Wind Tunnel was conceived at Colorado State University by Cermak & Albertson (1958) and installed in the Fluid Dynamics and Diffusion Laboratory. At CSU Cermak and coworkers studied point, line, area, and volume sources in a turbulent boundary layer as well as dispersion over buildings [e.g. Children's Hospital, Washington D.C.; Rancho Seco Nuclear Power Station, Ca; Denver Center of Performing Arts; Co], complex terrain [e.g. Point Arguello, Ca; San Bruno Mountain, Ca; Elk Mountain, WY; Stringfellow Dump Site, Riverside, Ca] ,coastal sites [Avon Lake Power Station, OH] , valleys [Wolf Creek pass, CO; Colorado River, CO], islands [San Nicolas Island, CA], dispersion in vegetative canopies, infiltration into buildings, dispersion in stratified flows, dense gas dispersion, and dispersion in urban street canyons. At CSU Martin (1965) investigated dispersion about a model nuclear reactor building and compared model data with field experiments. At NU Strom and coworkers studied dispersion about prismatic and round building shapes [e.g. EAR-2 reactor complex at the National Reactor Test Station, ID; the National Institute of Health, Bethesda, MD.], dispersion in stratified flows, and dispersion in urban street canyons.

In Europe work began with the critical studies by Jensen & Frank (1963) in Denmark which identified the importance of surface roughness and boundary layer turbulence structure during fluid modeling of the atmosphere. They extended their model studies of wind shelter phenomena over scaled surface roughness (including one roughness due to a model city) to diffusion from isolated chimneys, diffusion from chimneys mounted above gable roof buildings, and the effect of chimney cross-section on plume behavior. They expressed concentration measurements non-dimensionally but as $Cz_o^2u^*/Q$, where z_o is the roughness height and u^* is the surface friction velocity.

Mikio Hino (1968) in Japan carried out important numerical and wind tunnel comparisons of plume dispersion over complex terrain. The model experiment was performed at a scale of 1:2500 in a 1.5 m x 3.0 m x 10m long open-circuit Eiffel type wind tunnel. The surface of the model was covered with pebbles to maintain turbulence and the boundary layer, and turbulence grids were placed upwind. Wind profiles measured over the rugged terrain exhibited speedup, separation, and stagnation regions. Experimental plumes were displaced by the terrain, and plume spread and surface concentrations roughly followed trends predicted by his numerical model.

The Fluid Modeling facility was founded by EPA at ESRL in the 1970s where Snyder and coworkers studied a variety of problems associated with dispersion over idealized building shapes, stratified flow over complex terrain [e.g. Rattlesnake Ridge, Az; Cinder Cone Butte, Id], and stack plume behavior.

In England the contributions of Barrett & Hall at the Warren Springs Laboratory, Dept of Environment and the work by Castro and Robins at the Central Electric Generating Board Laboratories at Leatherhead and Southampton must be mentioned These groups developed innovative measuring equipment (e.g. pulsed-hot wire anemometers, fast response gas chromatography) and improved boundary layer simulation methods (e.g. elliptic Counihan spires).

2 SIMILITUDE AND FLUID MODELING CONCEPTS

2.1 *Fluid Modeling of Stack Plumes*

In the early 1900s turbulent jets exhausting into quiescent or cross-flow air streams were studied in wind tunnels. Plume buoyancy effects were recognized but not simulated, and background flow was laminar in character. Authors quickly recognized the importance of exhaust to free stream velocity ratio, but did not generally examine the importance of density ratio, Reynolds number, Froude number, or momentum flux ratios. Sherlock & Stalker (1940) noted plume bifurcation in the cross flow, but attributed the effect to von Karman vortices and deduced incorrectly the horizontal vortices were rotating downward at plume center. Hohenleiten & Wolf (1942) concluded correctly there was an upward motion at the center of the wake. Bryant (1949) and Bryant & Cowdrey (1955) examined the effects of both velocity and temperature of discharge on the shape of smoke plumes.

Among the first to directly address simulation criteria for air pollution aerodynamics were Strom & Halitsky (1954), Halitsky (1962, 1968, 1969), Cermak et al. (1966) and Melbourne (1968). Most experimentalists agreed that to simulate plume or puff trajectory and mixing behavior correctly in the laboratory one must have similarity in approach wind profiles including turbulent behavior, a fully turbulent exhaust jet, and equality of density, momentum, and buoyancy ratios. Unfortunately, simulation of the buoyancy parameter (Froude number) at reasonable tunnel scales implies very low model wind speeds with poor turbulent similarity. The search for an acceptable "partial" simulation has led to many proposals for distorted scaling of density, stack diameter, and exhaust velocities which are not always consistent. Isyumov & Tanaka (1979) compared a number of such schemes, but the suggestions by Snyder (1972, 1981) are most often accepted as the standard simulation criteria.

Stack shape and velocity ratio were examined by Jensen & Franck (1963) in their monograph on wind engineering similarity. They examined circular, square, and rectangular combinations to see the effects of multiple flues and exhaust velocity on stack downwash.

Boundary layer meteorological wind tunnels were first extensively used by Cermak and coworkers to study point, line, area, and volume sources in the 1960s and 1970s (Cermak et al. 1966; Cermak 1974). The behavior of non-stationary or instantaneous emissions in a turbulent shear layer were first measured with a laser-light scattering probe by Yang & Meroney (1973). These data have been used to calibrate Lagrangian similarity models and characterize the effects of shear on vertical and lateral transport.

2.2 *Fluid Modeling of Plumes Interacting with Structures*

Many early model dispersion studies were concerned with plume interaction with fossil-fuel power plant buildings (Hohenleiten & Wolf 1940; Sherlock & Stalker 1942; McElroy et al. 1944; Strom 1953). They recognized the importance of elevating the plume above a minimum height to avoid immediate entrainment and downwash and the broadening effects of wake turbulence on the downwind plume, but they failed to adjust for the effects of approach wind profile on near building flow, separation, re-attachment and the ground-level horse-shoe vortex.

Strom & Halitsky (1954) recognized the need to simulate background turbulence, but tried to solve the problem in an ad hoc manner with the insertion of random hole turbulence generator boards and laterally oscillating table fans upwind of their models. Needless to say, this produced enhanced turbulence, but of no quantifiable intensity or scale related to the atmosphere. Indeed, even the often quoted work by Halitsky (1968) primarily reports measurements for uniform approach flow model studies.

Golden (1961) proposed a minimum building Reynolds number criteria for building emission studies above which near-building concentration distributions would be flow independent. He concluded one should maintain $Re = U_H H/\nu > 11{,}000$ where U_H was approach speed at building height H. Strangely, this conclusion was based on measurements in a uniform approach flow from a release at only one building location and data sampled at only one location on the building surface. Nonetheless, this result has been almost universally quoted for nearly 35 years (Slade 1968; Snyder 1981). More recently work by Castro & Robins (1977), Snyder (1992), and Meroney & Neff (1996) have clarified this matter. It is now known that the criteria is affected by source location, building orientation, and measurement location. Simulations for measurement locations in the middle to far wake region ($x > 1H$ downwind) may only require $Re > 3{,}000$ if a truly turbulent exhaust plume exists. However, surface concentration distributions on the building surface itself may vary with wind speed until Re values exceed 15,000.

Meroney (1982a) summarized progress during the 1970s resulting from fluid model studies, and he provides several simple formulae and figures to calculate first order plume/wake interaction effects on concentrations. Hosker (1984, 1985, 1990) and Hosker & Pendergrass (1987) summarize more recent measurements related to near plume entrainment, wake structure, and the effects of clusters of buildings.

Validation of any plume modeling methodology must depend on direct comparison with prototype measurements. Unfortunately, such joint studies are very limited. In many cases acceptance of results is based on only a few points or just the observation of smoke tracers in the field. The field measurements made around the Phoenix Memorial Reactor at U. of Michigan when compared to wind tunnel measurements by Martin (1965) were among the first to verify that laboratory measurements could be trusted to give reliable predictions. Hatcher & Meroney (1977) and Bouwmeester et al. (1981) compared laboratory and field concentration measurements for plume dispersion near the Experimental Organic Cooled Reactor, Id. and the Rancho Seco Nuclear Power Station, Ca.. Tests included cases with variable stratification and nonstationary wind fields. A comparative analysis showed that combining wind-tunnel measurements with a statistically weighted algorithm method is 40 times more accurate than the conventional Pasquill-Gifford formulae. Graham et al. (1978) compared wind tunnel and aircraft measurements of terrain induced turbulence and dispersion from stacks at the Kingston Steam Plant, TN. One participating meteorologist told me that the results were so similar "*it was probably not even necessary to perform the field measurements.*"

Fackrell & Robins (1982), Li & Meroney (1983a,b) and Wilson (1995) studied intermittent plume behavior about buildings by measuring the concentration fluctuation statistics on building surface and in the wake using fast response concentration katherometers. This led Meroney (1985) to propose a probability based methodology to calculate re-entrainment concentrations about a building. More recently Shin et al. (1991) have extended these early measurements to concentration fluctuations produced by dense gas clouds downwind of enclosure barriers.

2.3 *Fluid Modeling and Natural Ventilation*

Flow visualization through model buildings has frequently been used to evaluate the effect of natural air movement through windows and doors and forced circulation from heating and air vents. Smith (1951) describes an air flow chamber constructed to study fenestration flow patterns. They compared flows through a 10 m full scale building constructed on a rotating turn table to a 1/15 scale model. They found to their surprise that changes as small as 3mm in model window ledge design could completely change internal flow fields. Subsequently, many case studies showing flows around and within different shape structures were reported by Caudill et al. (1951), Caudill & Reed (1952), White (1954), and Evans (1957). Ventilation studies inside industrial style buildings are recorded by Baturin (1972).

Outdoor air moves through a building either due to intentional ventilation (natural or forced) or unintentionally due to infiltration (and exfiltration). Net air exchange in buildings is typically modeled by empirical models based on statistical evaluation of pressurization tests or by semi-empirical models which sum contributions from individual building components. The local building surface pressures due to wind or thermal effects (stack) are estimated from wind tunnel tests (Dick 1949; Straaten 1967; Aynsley 1985). Unfortunately, such methods can not normally account for the effects of wind gustiness, internal pressure fluctuations, or sheltering.

Ventilation rates can be determined from model tests in wind tunnels either by measuring the external pressure distributions and using this data for a theoretical prediction or by measurement of ventilation rates directly. A strong argument for direct measurements is that theory does not account for effects of wind turbulence and internal air movements. Unfortunately, it is hard to specify the actual leakage paths, and it is generally argued that it is not possible to achieve full-scale Reynolds numbers in model cracks at model scale. Meroney et al. (1995) describe an alternative infiltration model strategy which permits simulation of instantaneous flow rates as Q/(AU) for both infiltration and dominant opening flows. Linden (1999) reviews model work examining the joint effect of natural ventilation and buoyant air flows within rooms.

2.4 *Fluid Modeling of Plumes Interacting with Complex Terrain*

In 1929-30 airflow over the Rock of Gibraltar was studied in a National Physical Laboratory wind tunnel to determine safe takeoff and landing patterns from the local airfield. Subsequent measurement of the actual flows around the Rock of Gibraltar with pilot balloons and kites found that the model "*closely forecast what occurred in nature at Gibraltar, in regard to wind directions and the distribution of vortices and vertical currents.*" (Field & Warden 1933; Briggs 1963). Also in 1929 Abe used cold CO_2 sublimated from dry-ice flowing over a 1:50,000 scale model Mt. Fuji, Japan to study mountain wave clouds. Visualization photographs revealed wave like motions near the model mountain peak which correspond to the presence of laminar wave clouds seen over the actual volcano. Then in 1937 Theodore von Karman consulted on wind tunnel studies of flow over a number of mountainous areas in New England at scales ranging from 1:5000 to 1:8000 to identify good wind power sites to erect the 1500 kW wind turbine conceived by Palmer Putnam

(1948). Unfortunately, the researchers failed to consider the effects of the atmospheric shear layer; hence, the results failed to agree with field measurements.

Among the first studies to determine plume behavior perturbed by terrain were those of the Point Arguello and San Nicolas Island, Ca, naval weapon test sites (Cermak et al. 1966; Meroney & Cermak 1966). Concern was expressed that toxic plumes emitted from rocket engine test stands might drift over populated areas downwind. These studies were performed under scaled atmospheric boundary layer conditions and included the effects of stable stratification on plume dispersion. Stable stratification enhanced plume channeling by terrain features and diminished vertical mixing. Extensive field programs of plume motion at both sites were completed. Measurements at Point Arguello agreed qualitatively and quantitatively with wind tunnel values, but the field measurement program at San Nicolas island never recovered any useable data.

Joint field and wind tunnel tests of dispersion during valley drainage flows were considered by Yingst et al. (1981). Dispersion over the Geysers Geothermal area, Ca. was simulated using 1:1920 scale models where surfaces were cooled with dry ice. Results compared well for both neutral and drainage flow situations. Weil & Cermak (1981) examined dispersion from a paper plant in a river valley under stable stratification. They found comparable values of dimensionless concentration in the field and laboratory.

Meroney (1980, 1990), Cermak (1984) and Snyder (1985) reviewed the success of terrain flow simulation and associated dispersion experiments. Experiments have been performed in both water and wind tunnels with and without thermal stratification. Simulation criteria and tunnel size place a strong constraint on the ranges of permissible scales and dispersion distances examined. Falvey & Dodge (1977) performed a unique experiment for estimating the dispersion of ground-level generated weather modification nuclides over western Colorado by accounting for Coriolis effects in a stratified rotating water tank simulation. Their measurements explained the unanticipated distributions found during prior field experiments, which are associated with Coriolis driven modifications to mountain-valley flows. Studies included simulations of the Leadville-Climax, San Juan, and Sierra Nevada regions in Colorado.

2.5 *Fluid Modeling of Plumes Interacting with Vegetation*

The earliest measurements of wind flow about vegetation were performed to evaluate crown form and blow down of young tree plantations, not atmospheric dispersion (Tiren 1927). Later tests were also performed to determine vegetation effects on wind profiles related to wind energy prospecting (Meroney 1993). But during the 1960s the US Army supported an extensive wind tunnel program at Colorado State University of flow and dispersion within and above agricultural canopies (e.g. Plate & Cermak 1963; Plate & Quareshi 1965; Kawatani & Meroney 1970). Models were constructed of both stiff and flexible crops (corn vs wheat) using arrays of pegs and flexible plastic strips. Model forests were represented by artificial plastic trees. The specific model trees were chosen based on drag and wake profile measurements made about small live trees inserted into a wind tunnel (Meroney 1968). Concentration measurements were used to develop analytic and numerical models to predict penetration of gaseous plumes into and within canopies during insect and herbicide spray programs.

2.6 *Fluid Modeling of Plumes in Stratified Environments: Stable and CBL Situations*

Most dispersion incidents produce maximum surface concentrations during either stable or unstable stratification. Stable flows lead to plume trapping, plume channeling in complex terrain, plume impingement, and transport of undiluted gas streams far downwind. Unstable flows lead to plume fumigation, adverse descent of elevated plumes to the ground and lift-off of ground level plumes. A number of wind tunnel facilities have been constructed world-wide to focus on the effects of stratification on dispersion (Cermak 1974; Meroney 1998a). Laboratory dispersion tests performed in Australia, England, Germany, Japan and the USA forcefully demonstrate the extent and importance of such phenomena.

Arya (1968) and Ohya et al. (1997) defined the character of stably stratified boundary layers based on wind tunnel measurements of velocity profiles and turbulent spectra. The behavior of continuous gas plumes emitted into a stably stratified boundary layer was studied by Chaudhry & Meroney (1973) who used Arya's boundary layer configuration.

Meroney et al. (1975) simulated the influence of stably stratified flow over a heated shore line to estimate plume fumigation downwind of a shoreline power station. Later, Avissar et al. (1990) examined conditions required to permit joint numerical and laboratory simulation of sea-breeze type phenomena. Kothari et al. (1985) considered the dispersion of gases released into the wake of a model building immersed in a stably stratified flow field. Stratification induced significant changes in the plume entrainment and the growth of the perturbed wake. Orgill (1982) predicted the dispersion of silver-iodide weather modification nuclides in the

Colorado River valley and near Wolf Creek Pass, Co. Grainger & Meroney (1993) examined the dispersion in large open-pit coal mines during night-time inversions situations. Strong stable stratification could lead to dangerous fume trapping in the pit hazardous to mine operations.

Although Willis & Deardorff (1974) considered convectively driven dispersion in their stratified water box experiments, the inclusion of cross flows and boundary layer shear has only been examined fairly recently. During the late 1980s and 1990s teams at Colorado State University, USA; U. of Karlsruhe, Germany, Monash University and CSIRO, Australia have examined ground and elevated source dispersion under unstable stratification convective boundary layer (CBL) conditions in special wind tunnel and water channel facilities. Meroney & Melbourne (1992) presented simulation criteria for CBL situations, and they provided performance envelopes which indicated appropriate simulation ranges for different laboratory facilities. These equipment and measurements are described more fully in the NATO monograph on *Buoyant Convection in Geophysical Flows* (Plate et al. 1998).

2.7 *Fluid Modeling of Plumes in Urban Environments*

The NATO monograph on *Wind Climate in Cities* provides a good starting point to consider the interaction of the urban environment and plume dispersion (Cermak et al. 1995a). Early studies considered generic arrangements of building clusters and streets to determine the influence of street and building alignment on traffic exhaust dispersion (Hoydysh et al. 1974; Wedding et al. 1977). Some experiments included the option of multiple moving vehicle sources (Thompson & Eskridge 1987; Kitabayashi et al. 1976). Others chose to simulate street level sources with line sources (Meroney et al. 1995, 1996).

Most such model studies are performed to help design numerical air pollution models suitable for calculating extreme air pollution episodes due to combined fixed sources and vehicular sources. Klein et al (1994) designed a study to monitor dispersion about a U-shaped building specifically to critique modules in air pollution models used to adjust for air pollution aerodynamics. Leitl et al. (1997) compares the results of various model calculations against the U-shaped building laboratory data.

2.8 *Fluid Modeling of Dense Gas Plumes*

Bodurtha (1961) examined visualizations of the behavior of dense gas plumes in a wind tunnel shear layer to evaluate the plume trajectory and dispersion of gas-relief valves. Hoot & Meroney (1974) measured concentration fields produced by dense plumes emitted into quiescent air and cross-flowing boundary layers. They fit their data to equations derived from integral plume analysis, and proposed relations to calculate plume trajectory, ground touch-down locations, and subsequent surface concentrations (See Bodurtha, 1980).

Concern about safety issues associated with the storage and transport of liquified natural gas (LNG) led to an extensive field and laboratory program on dense gas dispersion during the 1970s and 80s. Large field experiments were performed at China Lake Naval Weapons Test Center, CA and the US Dept. of Energy Field Site, NV, as well as at Porton Downs and Thorney Island, UK, and in The Netherlands. Many of these tests were selected for co-simulation in world wind engineering laboratories (CSU, USA; Warren Springs, UK; EPA Fluid Modeling Facility, USA; U. of Karlsuhe and U. of Hamburg, Germany; TNO, The Netherlands). A summary of such experiments are described by Meroney (1982b, 1987) and Shin et al. (1989) A review of modeling criteria necessary to simulate dense gas plumes including buildings and terrain may be found in Meroney (1986a,b ,1988).

The interaction of dense gas clouds and water spray curtains was examined by Meroney et al. (1984). The study successfully simulated releases of dense CO_2 clouds performed by the Health & Safety Executive, UK. Later Shin et al. (1991) replicated the time-dependent dispersion observed during the Falcon Test Series including the joint effects of barriers and water-spray curtains.

Laboratory studies continue to be a primary source of data for safety analysis in the petro-chemical industry due to the cost and complicated nature of successful field experiments. Recent references incorporating the results of fluid modeling related to air-pollution aerodynamics and industrial safety include Fannelöp (1994) and Hanna & Drivas (1996).

3 SUMMARY OF RESEARCH NEEDS

3.1 *Limitations of Similitude*

It is important to remember that models are "virtual" reality and only as accurate or realistic as our own imagination. When we insist on modeling at reduced length scale ratios simulation criteria often require metrology decisions which may enhance one flow characteristic while degrading another. We will never fully be able to answer the question "*Just how reliable are the results*?" Simulation must be limited by uncertainties in our understanding of the physical phenomena, uncertainties about the initial or boundary conditions, uncertainties about our measuring equipment, uncertainties about our prototype observations, and uncertainty about what we really want to know.

We must also take care that our search for agreement and correlation does not itself lead to "*spurious*" errors and self deception (Meroney 1998b). A data presentation suggested by scaling variables and simulation criteria may itself misrepresent the results.

Despite the limitations noted above, careful fluid modeling is often still the best and only reliable predictive tool available! Every caution which can be applied to fluid modeling must also be applied to analytic and numerical modeling. Wind tunnels are, in effect, analog computers which have the advantage of "near-infinitesimal" resolution and "near-infinite memory." A fluid modeling study employs "real fluids" not models of fluids; hence, the fluid model is implicitly non-hydrostatic, turbulent, includes variable fluid properties, non-slip boundary conditions, and dissipation. Real fluids permit flow separation and recirculation.. All conservation equations are automatically included in their correct form without truncation or differencing errors, and there are no missing terms or approximations.

3.2 *Air Pollution Aerodynamics in the 21st Century*

The primary role of fluid modeling during the next century will not always be the direct measurement of data to be used during engineering design of specific facilities. Fluid modeling is often not fast or flexible enough to perform the sensitivity studies commonly required to make engineering decisions about very complex systems. Instead fluid modeling should be used:

1. To explore atmospheric dispersion interactions not yet fully understood,
2. To tune and justify turbulence models incorporated into CFD models,
3. To devise new analytic models suitable for inclusion in larger numerical systems, and
4. To validate computational modules as they are incorporated into computer design codes.

The proliferation of conference titles and sessions focusing on CFD and Wind Engineering suggests that this refocus is already underway. Consider the titles of recent conferences and workshops (e.g. Int. Symposium on Computational Wind Engineering I and II held in Tokyo, Japan and Fort Collins, Co in 1992 and 1996, respectively).

Apology: Many outstanding scientists have contributed to the growth of our understanding of Air Pollution Aerodynamics. Contributions have been recorded in many journals, reports, and proceedings. Many are in languages other than English and archived in limited locations. My presentation reflects my own experience, resources, preferences and memory. It was certainly not my intention to ignore or forget anyone's contribution, but the limited scope of this review is evident. I trust some value will be found by every reader.

REFERENCES

Abe, M. 1929. Mountain Clouds, Their Forms and Connected Air Currents, Part II. *Bull. Centr. Met. Obs., Japan.* 7(3):93-145.

Arya, S.P.S. 1968. *Structure of a Stably Stratified Boundary Layer.* Ph.D. Dissertation, Civil Engineering, Colorado State University.

Avissar, R., M.D. Moran, G. Wu, R.N. Meroney, & R.A. Pielke 1990. Operating Range of Numerical and Physical Models for the Simulation of Coastal Marine Flows. *Boundary Layer Meteorology.* 50:227-275.

Aynsley, R.M. 1985. Estimating Comfort Cooling from Natural Wind inside Buildings Using Boundary Layer Wind Tunnels. *ASHRAE Transactions.* 91(2) Paper No. HI-85-35 #2 pp. 13.

Baturin, V.V. 1972. Air Change. *Fundamentals of Industrial Ventilation.* Oxford: Pergamon Press Ch. 13, pp. 283-347.

Birdsall, J.B & R.N. Meroney 1995. Model Scale and Numerical Evaluation of Tracer Gas Distribution Due to Wind Forced Natural Ventilation. *Wind Engineering: Retrospect and Prospect.* New Delhi:Wiley Western Limited IV:1693-1703.

Bodurtha, F.T. 1961. The Behavior of Dense Stack Gases. *J. Air Pollut. Control Assoc.* 11(9):431-437.

Bodurtha, F.T. 1980. *Industrial Explosion Prevention and Protection.* New York: McGraw-Hill Book Co. pp. 186.

Bouwmeester, R.J.B., R.N. Meroney, & K.M. Kothari 1981. An Algorithm to Estimate Field Concentrations in the Wake of a Power Plant Complex under Nonsteady Meteorological Conditions from Wind-tunnel Experiments. *Journal of Applied Meteorology.* 30:92-101.

Briggs, J. 1963. *Airflow around a model of the Rock of Gibraltar.* Meteorological Office, Scientific Paper No. 18, London: HMSO.

Bryant, L.W. 1949. The Effects of Velocity and Temperature of Discharge on the Shape of Smoke Plumes from a Funnel or Chimney in a Wind Tunnel. *Proc. Inst. Mechanical Engineers* (London). 169:371-400.

Bryant, L.W. & C.F. Cowdrey 1955. The Effects of Velocity and Temperature of Discharge on the Shape of Smoke Plumes from a Tunnel or Chimney: Experiments in a Wind Tunnel. *Proc.*

Inst. Mech. Eng. (London). 169:371-400.

Castro, I.P. & A.G. Robins 1977. The flow around a surface-mounted cube in uniform and turbulent streams. *J. Fluid Mechanics* .79(2):307-335.

Caudill, W.W., S.E. Crites & E.G. Smith 1951. *Some General Considerations in the Natural Ventilation of Buildings.* Texas Engineering Experiment Station Research Report No. 22, Texas A.& M. College, College Station, TX pp. 46.

Caudill, W.W. & B.H. Reed 1952. *Geometry of Classrooms as Related to Natural Lighting and Natural Ventilation.* Texas Engineering Experiment Station Research Report No. 36, Texas A.& M. College, College Station, TX pp. 57.

Cermak, J.E. 1974. Applications of Fluid Mechanics to Wind Engineering–A Freeman Scholar Lecture. *Journal of Fluids Engineering.* 97:9-38.

Cermak, J.E. 1978. *Dispersion of Pollutants in the Urban Environment.* ASCE Spring Convention and Exhibition Pittsburgh, Pa. Preprint 3269 pp. 29.

Cermak, J.E. 1984. Physical Modelling of Flow and Dispersion Over Complex Terrain. *Boundary-Layer Meteorology.* 30:261-292.

Cermak, J.E. 1995. Physical Modelling of Flow and Dispersion over Urban Areas. *Wind Climate in Cities.* Amsterdam: Kluwer Academic Publishers pp. 383-403.

Cermak, J.E. & M. Albertson 1958. Use of Wind Tunnels in the Study of Atmospheric Phenomena. *Air Pollution Control Association.* Paper No. 58-32, Annual Meeting APCA pp. 18.

Cermak, J.E., A.G. Davenport, E.J. Plate & D.X. Viegas (eds) 1995. *Wind Climate in Cities.* Durecht, the Netherlands pp. 772.

Cermak, J.E., V.A. Sandborn, E.J. Plate, G.H. Binder, H. Chuang, R.N. Meroney and S. Ito 1966. *Simulation of Atmospheric Motion by Wind-tunnel Flows.* Civil Engineering Report CER66JEC-VAS-EJP-GJB-HC-RNM-SI17, Colorado State University Fort Collins, CO pp. 111.

Chaudhry, F.H. & R.N. Meroney 1973. A Laboratory Study of Diffusion in a Stably Stratified Flow. *Atmospheric Environment.* 7(4):443-454.

Csanday, G.T. 1973. *Turbulent Diffusion in the Environment.* Dordrecht, the Netherlands: D. Reidel Publishing Co. pp. 258.

Dick, J.B. 1949. Experimental Studies in Natural Ventilation of Houses. *Institution of Heating and Ventilating Engineers.* 17 (173): 420-466.

Evans, B.H. 1957. *Natural Air Flow Around Buildings.* Texas Engineering Experiment Station Research Report No. 59, Texas A.& M. College, College Station, TX pp. 16.

Fackrell, J.E. & A.G. Robins 1982. Concentration fluctuations and fluxes in plumes from point sources in a turbulent boundary layer. *J. Fluid Mech.* 117:1-26.

Falvey, H.T. & R.A. Dodge 1977. *Atmospheric Simulation Using Stratified Liquid Models.* Bureau of Reclamation Rept. REC-ERC-77-8 US Dept. of the Interior pp. 96.

Fannelöp, T.K. 1994. *Fluid Mechanics for Industrial Safety and Environmental Protection.* Amsterdam: Elsevier pp. 544.

Field, J.H. & R. Warden 1929. A Survey of Air Currents in the Bay of Gibraltar, 1929-1930. *Geophysics Memoirs.* No 59 London:Her Majesty's Stationary Office, UK pp. 84.

Golden, J. 1961. *Scale Model Techniques.* M.Sc. Thesis, College of Engineering, New York University New York pp. 48.

Graham, N.E., G.H. Taylor, E.L. Hovind, R.L. Petersen, J.E. Cermak, & P.C. Sinclair 1978. *An Analysis of Terrain-Induced Aerodynamic Disturbances Near the Kingston Steam Plant, Kingston, Tennessee.* North American Weather Consultants Rept. No. AQ-78-22 pp. 169.

Grainger, C. & R.N. Meroney 1993. Dispersion in an Open-cut Coal Mine in Stably Stratified Flow. *Jrnl. of Boundary Layer Meteorology.* 63:117-140.

Halitsky, J. 1962. Diffusion of Vented Gas Around Buildings. *J. Air Pollution Control Association.* 12(2): 74-80.

Halitsky, J. 1968. Gas Diffusion Near Buildings Ch. 5-5 of *Meteorology and Atomic energy 1968.* US Atomic Energy Commission TID-24190 Oak Ridge, TN Ch 5-5: 221-255.

Halitsky, J. 1969. *Validation of Scaling Procedures for Wind Tunnel Model Testing of Diffusion Near Buildings.* New York University, Dept. of Meteorology & Oceanography Tech. Report No. TR-69-8 pp. 205.

Hanna, S. 1982. *Review of Atmospheric Diffusion Models for Regulatory Purposes.* World Meteorological Organization Tech. Rept. No. 581 Geneva, Switzerland pp. 44.

Hanna, S.R. & P.J. Drivas 1996. *Guidelines for use of Vapor Cloud Dispersion Models.* 2nd ed. New York: Center for chemical Process Safety, AIChE pp. 304.

Hatcher, R.V. & R.N. Meroney 1977. Dispersion in the Wake of a Model Industrial Complex. Proceedings of *Joint Conference on Applications on Air Pollution Meteorology*, AMS-APCA, Salt Lake City pp. 348-346

Hino, M. 1968. Computer Experiment on Smoke Diffusion Over a Complicated Topography. *Atmospheric Environment.* 2: 541-558.

Hohenleiten, H.L. von & E.F. Wolf 1942. Wind-Tunnel Tests to Establish Stack Height for

Riverside Generating Station. *Trans. ASME.* 64: 671-683.

Hoot, T. & R.N. Meroney 1974. The Behavior of Negatively Buoyant Stack Gases. *67th APCA Proceedings*. Denver, Colorado.

Hosker, R.P. Jr. 1984. Flow and Diffusion Near Obstacles. Ch. 7 in *Atmospheric Science and Power Production.* D. Randerson (ed) US Dept. of Energy Tech. Report DOE/TIC-27601 Ch. 7: 241-326.

Hosker, R.P. Jr. 1985. Flow around Isolated Structures and Building Clusters: A Review. *ASHRAE Transactions.* 91: Pt. 2 HI-85-34 No. pp. 22.

Hosker, R.P. Jr. 1990. The Effects of Buildings on Local Dispersion: A Summary. *Second Interdisciplinary Conf. On Urban Air Quality.* Boulder: CO October 29-31, 1990 pp. 21.

Hosker, R.P. Jr. & W.R. Pendergrass 1987. *Flow and Dispersion Near Clusters of Buildings.* US NOAA Tech. Memorandum ERL-ARL-153 Silver Spring, MD pp. 106.

Hoydysh, W.G., R.A. Griffiths & Y. Ogawa 1974. A Scale Model Study of the Dispersion of Pollution in Street Canyons. *67th Annual Meeting of Air Pollution Control Association.* Paper #74-157 pp. 26.

Isyumov, N. & H. Tanaka 1979. Wind Tunnel Modelling of Stack Gas Dispersion–Difficulties and Approximations. *Wind Engineering: Proceedings of the 5th Int. Conf.* Oxford:Pergamon Press 2:987-1002.

Jensen, M. and N. Franck 1963. *Model-Scale Tests in Turbulent Wind: Part I, Phenomena Dependent on the Wind Speed: Shelter at Houses - Dispersal of Smoke.* Copenhagen: The Danish Technical Press pp. 102.

Kalinske, A.A., R.A. Jensen & C.F. Schadt 1945a. *Wind Tunnel Studies of Gas Diffusion in a Typical Japanese Urban District.* OSRD NDRC Div. 10 Informal Rep. No. 10.3A-48 Lib. of Congress, Wash. D.C.

Kalinske, A.A., R.A. Jensen & C.F. Schadt 1945b. *Correlation of Wind Tunnel Studies with Field Measurements of Gas Diffusion.* OSRD NDRC Div. 10 Informal Rep. No. 10.3A-48A Lib. Of Congress, Wash. D.C. pp. 13.

Kawatani, T. & R.N. Meroney 1970. Turbulence and Wind Speed Characteristics within a Model Canopy Flow Field. *Journal of Agricultural Meteorology.*7:143-158.

Kitabayashi, K., K. Sugawara & S. Isomura 1976. A Wind Tunnel Study of Automobile Exhaust Gas Diffusion in an Urban District. *Proc. 4th Int. Clean Air Congress.* Tokyo, Japan pp. 192-196.

Klein, P. M. Rau, R. Röckle, & E.J. Plate 1994. Concentration estimation around point sources located in the vicinity of U-shaped buildings and in a built-up area. *2nd Int. Conf. Air Pollution.* Barcelona, Spain.

Kothari, K.M., J.A. Peterka and R.N. Meroney 1985. Wind Flow Patterns About Buildings. *J. of Wind Engineering and Industrial Aerodynamics.* 21:21-38.

Lees, F.P. 1980. Emission and Dispersion. Ch. 15 of *Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control, Vol. 1.* London: Butterworts Press Ch. 15: 413-476.

Ladle, B., R.N. Meroney, P. Klein & M. Rau 1997. Concentrations and Flow Distributions in the Vicinity of U-Shaped Buildings: Wind-tunnel and Computational Data. *J. Wind Engineering & Industrial Aerodynamics.* 67-68:745-756.

Li, W.W. & R.N. Meroney 1983a. Gas Dispersion Near a Cubical Model Building, Part I: Mean Concentration Measurements. *J. of Wind Engineering and Industrial Aerodynamics.* 12:15-33.

Li, WW & R.N. Meroney 1983b. Gas Dispersion Near a Cubical Model Building, Part II: Concentration Fluctuation Measurements. *J. of Wind Engineering and Industrial Aerodynamics.* 12:5-47.

Linden, PF. 1999. The Fluid Mechanics of Natural Ventilation. *Ann. Rev. Fluid Mech.* 31:201-238.

Martin, J.E. 1965. *The Correlation of Wind Tunnel and Field Measurements of Gas Diffusion Using Krypton-85 as a Tracer.* Ph.D. Thesis, Univ. of Michigan, Ann Arbor (Also Michigan Phoenix Memorial Laboratory MMPI Report 272).

McElroy, G.E., C.E. Brown, L.B. Berger & H.H. Schrenk 1944. *Dilution of Stack Effluents.* US Bureau of Mines Tech. Paper 657 US Gov. Print. Ofc.

Melbourne, W.H. 1968. Wind Tunnel Modelling of Buoyant Chimney Plumes. *3rd Australasian Conference on Hydraulics and Fluid Mechanics, The Institution of Engineers, Australia.* Paper No. 2631 pp. 81-85.

Meroney, R. N. 1968. Characteristics of Wind and Turbulence in and above Model Forests. *Journal of Applied Meteorology.* 4(5):780-788.

Meroney, R.N. 1980a. Physical Simulation of Dispersion in Complex Terrain and Valley Drainage Flow Situations. *Proceedings of the 11th NATO-CCMS Int. Tech Meeting on Air Pollution Modeling and Its Application.* Amsterdam, the Netherlands pp. 303-322.

Meroney, R.N. 1980b. Wind-Tunnel Simulation of the Flow Over Hills and Complex Terrain. *J. of Industrial Aerodynamics.* 5:297-321.

Meroney, R.N. 1982a. Turbulent Diffusion Near Buildings. Ch. 10 in *Engineering Meteorology* ed. E.J. Plate Amsterdam: Elsevier Ch 11: 481-525.

Meroney, R. N. 1982b. Wind-tunnel Experiments on Dense Gas Dispersion. *J. of Hazardous Materials.* 6: 85-106.

Meroney, R. N. 1985. Gasp! Wheeze! Ugh! Where is that smell coming from? Symposium on Air Flow Around Buildings ASHRAE Annual Meeting, Paper HI-85-34 No. 3, *ASHRAE Transactions.* 91(2):1708-1721.

Meroney, R.N. 1986a. *Guideline for Fluid Modeling of Liquefied Natural Gas Cloud Dispersion: Vol. I: Instruction Guide.* Gas Research Institute Report No. GRI-86/0102.1, Chicago, Il. pp. 62.

Meroney, R.N. 1986b. *Guideline for Fluid Modeling of Liquefied Natural Gas Cloud Dispersion: Vol. II: Technical Report Document.* Gas Research Institute Report No. GRI-86/0102.2, Chicago, Il. pp. 264.

Meroney, R.N. 1987. Validation of Fluid Modeling Techniques for Assessing Hazards of Dense Gas Cloud Dispersion. *Journal of Hazardous Materials* . 15:377-417.

Meroney, R.N. 1988. Guidelines for Fluid Modeling of Dense Gas Cloud Dispersion. *Journal of Hazardous Materials.* 17:23-46.

Meroney, R.N. 1990. Fluid Dynamics of Flow Over Hills and Mountains: Insights Obtained Through Physical Modeling. Ch.7 of *Current Directions in Atmospheric Processes Over Complex Terrain.* American Meteorological Society Monograph 23(45):45-172.

Meroney, R.N. 1993. *Wind-Tunnel Modeling of Hill and Vegetation Influence on Wind Power Availability Task 1: Literature Review.* for US Windpower, Livermore, Ca. Civil Engineering Report CER92-93-RNM-1 pp. 151.

Meroney, R.N. 1998a. Wind Tunnel Simulation of Convective Boundary Layer Phenomena: Simulation Criteria and Operating Ranges of Laboratory Facilities. *Buoyant Convection in Geophysical Flows.* E.J. Plate, E.E. Fedorovich, D.X. Viegas, & J.C. Wyngaard (eds) Amsterdam: Kluwer Academic Publishers pp. 313-326.

Meroney, R.N. 1998b. Spurious or Virtual Correlation Errors Commonly Encountered in Reduction of Scientific Data. *J. of Wind Engineering and Industrial Aerodynamics.* 77-78:543-553.

Meroney, R.N. & J.E. Cermak 1966. *Wind Tunnel Modeling of Flow and Diffusion over San Nicolas Island.* Pacific Missile Range Report PMR-MR-68-1, Point Mugu, California pp.106.

Meroney, R. N., J.E. Cermak, & B.T. Yang 1975. Modeling of Atmospheric Transport and Fumigation at Shorelines. *Boundary Layer Meteorology.* 9(1):69-90.

Meroney, R.N., D.E. Neff & B. Birdsall 1995. Wind-tunnel Simulation of Infiltration Across Permeable Building Envelopes: Energy and Air Pollution Exchange Rates. *7th International Symposium on Measurement and Modeling of Environmental Flows.* San Francisco, CA, November 12-17, 1995 pp. 8.

Meroney, R.N. & D.E. Neff 1996. Reynolds Number Independence of the Wind-tunnel Simulation of Transport and Dispersion about Buildings. (Unpublished internal memorandum) 21 pp.

Meroney, R.N., D.E. Neff & G. Heskestad 1984. Wind-tunnel Simulation of a U.K. Health and Safety Executive Water Spray Curtain Dense Gas Dispersion Test. *Boundary-Layer Meteorology.* 28:107-119.

Meroney, R.N. & W.H. Melbourne 1992. Operating Ranges of Meteorological Wind Tunnels for the Simulation of Convective Boundary Layer (CBL) Phenomena. *Boundary-Layer Meteorology.* 61:145-174.

Meroney, R.N., M. Pavageau, S. Rafailidis & M. Schatzmann 1996. Study of Line Source Characteristics for 2-D Physical Modelling of Pollutant Dispersion in Street Canyons. *J. Wind Engineering & Industrial Aerodynamics.* 62:37-56.

Meroney, R.N., S. Rafailidis & M. Pavageau 1995. Dispersion in Idealized Urban Street Canyons. *Air Pollution Modeling and Its Application XI.* S.E. Gryning & F.A. Schiermeier (eds) NATO Challenges of Modern Society, New York: Plenum Press 21:451-458.

Ohya, R., D.E. Neff & R.N. Meroney 1997. Turbulence Structure in a Stratified Boundary Layer under Stable Conditions. *Boundary Layer Meteorology.* 83:139-161.

Orgill, M.M. 1971. *Laboratory Simulation and Field Estimates of Atmospheric Transport-Dispersion Over Mountainous Terrain.* Ph.D. Thesis Civil Engineering, Colorado State University pp. 327

Pasquill, F. & F.B. Smith 1983. *Atmospheric Diffusion.* 3rd ed. New York: John Wiley pp. 437.

Plate, E.J. & J.E. Cermak 1963. *Investigations to Develop Wind Tunnel Techniques for Measuring Atmospheric Gaseous Diffusion in Model Vegetative Surfaces.* Civil Engineering Report CER63EJP-JEC28 Colorado State University pp. 155.

Plate, E.J. & A.A. Quareshi 1965. Modeling of Velocity Distributions Inside and Above Tall Crops. *J. of Applied Meteorology.* 4(3):400-408.

Plate, E.J., E.E. Fedorovich, D.X. Viegas, & J.C. Wyngaard editors 1998 *Buoyant Convection in Geophysical Flows* Amsterdam: Kluwer Academic Publishers pp. 504.

Putnam, P.C. 1948. *Power From The Wind.* New York: Van Nostrand Reinhold Company pp. 236.

Randerson, D. (ed). *Atmospheric Science and Power Production.* US Dept. of Energy Report DOE/TIC-27601 pp. 859.

Rouse, H. 1951. Air-Tunnel Studies of Diffusion in Urban Areas. *Meteorological Monograph.* Vol. I No. 4: 39-41

Scorer, R.S. 1978. *Environmental Aerodynamics.* London: John Wiley & Sons pp. 488.

Sherlock, R.H. & E.J. Lesher 1955. Design of Chimneys to Control Down-Wash of Gases. *Trans. ASME.* 77:1-9.

Sherlock, R.H. & E.A. Stalker 1940. The Control of Gases in the Wake of Smoke Stacks. *Mechanical Engineering.* 52:455-458.

Shin, S.H.& R.N. Meroney 1989. Surface Pattern Comparability of Wind-tunnel Simulations of the Thorney Island Dense Gas Dispersion Trials. *Air Pollution Modeling and Its Application VII.* H. van Dop (ed). New York:Plenum Press pp. 77-88.

Shin, S.H., R.N. Meroney & T. Williams 1991. Wind Tunnel Validation for Vapor Dispersion from Vapor Detention System. *International Conference and Workshop on Modeling & Mitigating the Consequences of Accidental Releases of Hazardous Materials.* New Orleans, LA, May 21-24, 1991.

Slade, D.H. 1968. *Meteorology and Atomic energy 1968.* US Atomic Energy Commission TID-24190 Oak Ridge, TN pp. 455.

Smith, E.G. 1951. *The Feasibility of Using Models for Predetermining Natural Ventilation.* Texas Engineering Experiment Station Research Report No. 26, Texas A.& M. College, College Station, TX pp. 26.

Snyder, W.H. 1972. Similarity Criteria for the Application of Fluid Models to the Study of Air Pollution Meteorology. *Boundary-Layer Meteorology.* 3:113-134.

Snyder, W.H. 1981. *Guideline for Fluid Modeling of Atmospheric Diffusion.* US Environmental Protection Agency Report EPA-600/8-81-009 pp. 199.

Snyder, W.H. 1985. Fluid Modeling of Pollutant Transport and Diffusion in Stably Stratified Flows Over Complex Terrain. *Ann. Rev. Fluid Mech.* 17:239-266.

Snyder, W.H. 1992. Some Observations of the Influence of Stratification on Diffusion in Building Wakes. *Institute of Mathematics and Its Applications, Meeting on Stably Stratified Flows.* Sept. 21-23, 1992, U. of Surrey, Guildford, UK pp 25.

Straaten, J.F. van 1967. Natural Ventilation. *Thermal Performance of Buildings.* Amsterdam:Elsevier Ch. 14:229-297.

Strom, G.H. 1953. *Wind Tunnel Study of Air Pollution by Avon Plant.* for Cleveland Electric Illuminating Company (Contained as Appendix within EERL Tech Rept. 103 New York University May 1971) pp. 19.

Strom, G.H. & J. Halitsky 1954. Important Considerations in the Use of the Wind Tunnel for Pollution Studies of Power Plants. *Air Repair.* 4(2): 25 pp. (Also Paper No. 54-SA-41, ASME Semi-Annual Meeting, Pittsburgh, Pa., June 20-24, 1954).

Sutton, O.G. 1953. *Micrometeorology.* New York: McGraw-Hill Book Co. pp. 343.

Thompson, R.S. & R.E. Eskridge 1987. Turbulent Diffusion Behind Vehicles: Experimentally Determined Influence of Vortex Pair in Vehicle Wake. *Atmospheric Environment.* 21(10): 2091-2097.

Tiren, L. 1927. Einige Intersuchungen ober die Schaftform. *Meddel. Statens Skogsforsoksanstalt.* 24(4):81-152.

Turner, D.B. 1994. *Workbook of Atmospheric Dispersion Estimates: An Introduction to Dispersion Modeling.* 2nd Ed. Boca Raton: Lewis Publishers of CRC Press pp. 174.

Venkatram, A. & J.C. Wyngaard (eds) 1988. *Lectures on Air Pollution Modeling.* Boston: American Meteorological Society pp. 397.

Wark, K., C.F. Warner & W.T. Davis 1998. *Air Pollution: Its Origin and Control.* 3rd ed. Menlow Park, Ca: Addison-Wesley pp. 584.

Wedding, J., D.J. Lombardi & J.E. Cermak 1977. A wind-tunnel study of gaseous pollutants in city street canyons. *J. Air Pollution Control Association.* 27:557-566.

Weil, J.C. & J.E. Cermak 1981. Plume Dispersion about the Windward Side of a Hill at Short Range: Wind Tunnel vs Field Measurements. *Proceedings of 5th Symposium on Turbulence, Diffusion and Air Pollution.* Boston: American Meteorological Society pp. 159-160.

Wexler, H. 1955. *Meteorology and Atomic energy.* Weather Bureau, US Dept. of Commerce pp. 171.

White, R.F. 1954. *Effects of Landscape Development on the Natural Ventilation of Buildings and Their Adjacent Areas.* Texas Engineering Experiment Station Research Report No. 45, Texas A.& M. College, College Station, TX pp. 17

Wiekeman, B.J. 1984. Vapour Cloud Explosions–An analysis Based on Accidents. *J. Hazardous Materials.* 8: 294-311.

Willis, G.E. & J.W. Deardorff 1974. A laboratory model of the unstable planetary boundary layer. *J. Atmos. Sci.* 31:1297-1307.

Wilson, D.J. 1995. *Concentration Fluctuations and Averaging Time in Vapor Clouds.* New York: Center for Chemical Process Safety, AIChE pp. 189.

Yang, B.T. & R.N. Meroney 1972. *On Diffusion from an Instantaneous Point Source in a Neutrally Stratified Turbulent Boundary Layer with a Laser light Scattering Probe.* US Office of Naval Research, Project THEMIS Tech. Report No. 20, pp. 236.

Yingst, J.C., R.N. Swanson, M.L. Mooney, J.E. Cermak, & R.L. Petersen 1981. Review of Five Wind-Tunnel Modeling Results in Complex Terrain. *Proceedings of 5th Symposium on Turbulence, Diffusion and Air Pollution.* Boston: American Meteorological Society pp. 148-149.

Zannetti, P. 1990. *Air Pollution Modeling: Theories, Computational Methods and Available Software.* New York: Van Nostrand Reinhold pp. 454.