1.1 A HISTORY OF CLASSIC ATMOSPHERIC DISPERSION FIELD EXPERIMENTS

Steven Hanna*

Hanna Consultants, Kennebunkport, ME

ABSTRACT

This paper introduces a session at the 2010 AMS Annual Meeting on historical atmospheric dispersion models. Other speakers are presenting discussions of specific experiments that they have worked with. The current paper provides an overview of the classic field experiments and the scientific issues that were being investigated. It is shown how the experiments up through the mid-1960s were mostly focused on military applications related to a better understanding of short-range transport and dispersion of releases from chemical and biological weapons. A secondary focus in the 1950s and 1960s was on long range transport and deposition of radiological releases from nuclear weapons. After ambient air quality standards were set and environmental agencies formed in the late 1960s, the emphasis shifted to environmental issues such as short-range dispersion from stack releases at industrial plants. This evolved into experiments investigating longer range (mesoscale and regional) transport and dispersion, which required development of special tracers that could be observed at very low concentrations 1000 km from the source. Special issues such as dispersion in complex terrain and dry and wet deposition and chemical removal began to be studied. Regional air quality problems such as acid rain and ozone transport began to be studied with large field experiments from the 1980s to the present time. Also since the Bhopal tragedy in the 1980s, there has been a special interest in accidental releases of hazardous gases, and many field experiments involving dense gases have taken place. The 2000s have seen many large urban dispersion experiments, related to both environmental, public health, and military concerns.

Computers were invented about halfway through this 100-year history. This has had a profound effect on the size of the experimental data archive. Early data archives consisted of a few pages of tables, while recent data archives consist of TeraBytes of data entries. Naturally, the experiments prior to about 1960 were used mainly to improve parameterizations in one-or-two line analytical dispersion models. More recently, the field experiments are being used mainly to help develop parameterizations in detailed numerical models and to help evaluate the models.

Corresponding author address: Steven R. Hanna, Hanna Consultants, 7 Crescent Ave., Kennebunk-port, ME 04046, hannaconsult@roadrunner.com

1. OBJECTIVES AND BACKGROUND

The objective of this paper is to provide an overview of the so-called classic atmospheric dispersion field experiments. Other papers in this AMS Annual Meeting session cover specific experiments that have been investigated by the speaker. Because of the large numbers of field experiments, this survey groups them into categories based on scientific objective.

Excellent comprehensive surveys of classic dispersion field experiments are available; for example, see the chapters by Islitzer and Slade (1968) and Draxler (1984) in two editions of the DOE review document "Meteorology and Atomic Energy" (renamed Atmospheric Science and Power Production" in the 1984 edition). Pasquill (1974) also has a comprehensive survey in his Chapter 4, including many of the European experiments and examples from the 1920s and 1930s. Since these surveys, there have been a number of new categories of dispersion concerns, such as dense gas releases and regional particulates. These new experiments will also be included in the categories summarized here.

The costs and scope of dispersion field experiments have changed quite a bit since the early 20th century, when L.F. Richardson pedaled his bicycle down to the harbor with turnips hanging from the handlebars. He carefully tossed the turnips in the harbor and observed their relative spread with a simple hand-made device. He used other natural tracers, such as thistledown, in this set of experiments. But despite the low cost and simplicity of these experiments, Richardson knew what he was looking for. He had developed a similarity hypothesis based on fundamental physics, and an outcome of the experiment was the now well-known Richardson power law relation for the horizontal diffusivity of particle clusters, $K = 0.2\ l^{4/3}$, where l is the size of the cluster (Richardson, 1926). Thus the diffusivity increases as the size of the cluster increases (and hence the cluster can be dispersed by eddies with larger and larger sizes).

The early dispersion experiments, such as Richardson's, were not heavily funded by government agencies or industrial consortiums. Instead, the early experiments were intended to answer specific scientific issues raised by a university researcher. Now, there are hardly any altruistic dispersion experiments, done "just for the sake of science". Almost everything is in response to the needs of the public as phrased by funding agencies.

The current paper provides a method of categorizing all dispersion field experiments and then focuses on describing a few of the earlier experiments.

2. CATEGORIES OF CLASSIC DISPERSION EXPERIMENTS

We can survey the literature and make a long list of dispersion field experiments. They can be divided up into categories in many ways. Frank Gifford, the long time director of the NOAA Atmospheric Turbulence and Dispersion Laboratory (ATDL), and analyzer of many dispersion field experiments, used to express this dilemma as "There are many ways to slice the baloney".

The first need is to separate the true "classic" experiments from the run-of-the-mill experiments. Probably the best way to do this is via numbers of citations. The best field experiments will be those that are more heavily used in the long term. With this criterion, the Prairie Grass field experiment from 1956 will rise to the top of any list. It is discussed in detail in Venkatram's paper in this session.

A data set must be complete and understandable to be used. For example, if observed wind speeds are missing, or if averaging time is not obvious, the data are unlikely to be used. As another example, many of the data storage tapes used in the 1970s and 1980s have become unusable. My colleague, Joseph Chang, has been asked by two federal laboratories to provide them with copies of the dispersion datasets that they collected 20 years earlier but their own tapes were lost or had fallen apart. Fortunately, Chang and Hanna (2004) kept an electronic Modelers Data Archive (MDA) containing many of the classic dispersion field experiment data.

There are many alternate ways to define categories; a few are listed below.

Sponsoring agency
Main scientific concern
Release scenario
Health or environmental effect
Pollutant
Distance range
Time duration
Instantaneous or continuous or time-varying release
Point, line, or area source; local or distributed; height of release
Terrain type and land-use
Meteorological conditions
Importance of chemical reactions, deposition

We could make up a 12 dimensional matrix from the above categories and assign a given classic field experiment to each category. This would be "slicing the baloney too thin". For the current overview, eight categories are proposed based on a combination of the above 12 methods as well as my experience with analyses of the field experiments. The next section lists these categories and mentions a few classic field experiments under each category.

3. LISTING OF CLASSIC FIELD EXPERIMENTS FOR EIGHT CATEGORIES

Examples of classic field experiments are given below for eight basic categories. The next section will provide a few more details on experiments in the first three categories, which were in the early time period.

Category 1) Early field experiments intended to investigate specific fundamental dispersion relations.

Richardson's (1926) experiments with turnips fall in this category. These are from an era when atmospheric dispersion research was new and the fundamental scaling relations and power laws were under study by basic researchers. Taylor (1921) and Roberts (1923) also fall in this category.

2) Pre-1960 defense and nuclear related field experiments for near-surface point releases over rural terrain and short distances (< 1km).

There is a large number of these field experiments, as described by Barad (1958, Prairie Grass), Barad and Fuquay (1962, Green Glow), Barad and Schorr (1954), Bowne et al. (1969, woodlot aerosols), Chamberlain (1953, travel and deposition of aerosol clouds), Fuquay et al. (1964, Hanford), Gifford (1957, relative diffusion), Haugen (1959, Prairie Grass), Haugen and Fuquay (1963, Ocean Breeze/Dry Gulch), Hay and Pasquill (1957), Hogstrom (1962), Islitzer and Dumbauld (1963), Record and Cramer (1958, Prairie Grass), Roberts, 1923), and Sagendorf and Dickson (1974, very low wind stable). Pasquill (1974) has an excellent summary of this category.

3) Pre-1980 defense related field experiments for nuclear bomb tests (any elevation) and generally large distances (> 200 km).

Many of these experiments were classified. Some in the open literature include Kellogg (1956, stratospheric puff releases), Machta et al. (1956, travel of atomic debris clouds) and Wilkins (1954, effective diffusivities of atomic bomb clouds)

4) Post-1968 (Clean Air Act) stack plume experiments (flat rural and complex terrain and coastal) at short distances.

Here there are dozens if not hundreds of field experiments. Examples are provided by Briggs (1969, many buoyant plume rise experiments), Chang and Hanna (2004, stack plume flat terrain, complex terrain and overwater field experiments), Hanna and Chang (1993, several power plant experiments in rural and urban terrain), Hanna and Paine (1989, Kincaid power plant dispersion experiment), Hanna et al. (1985, Cameron, Ventura, and Carpenteria overwater/coastal experiments), and Kaimal et al. (1986, CONDORS dispersion experiment in convective conditions).

5) Urban point and line source experiments

This category includes 1960s urban dispersion experiments such as McElroy and Pooler (1968, St. Louis) and Hilst and Bowne (1966, Ft. Wayne), as well as more recent urban experiments such as Hanna and Chang (1993, Indianapolis), Chang and Hanna (2004, Urban 2000 and JU2003), Hanna and Franzese (2003, Urban 2000 and Los Angeles), and the recent Manhattan dispersion experiments (MSG05 and MID05). Other urban experiments occurred in London (DAPPLE) and Basel (BUBBLE). In addition, there have been several European field experiments involving pollutant emissions from traffic in street canyons and tunnels. These experiments take place in Europe rather than the US because the European NOx standard is four times more stringent than in the U.S.

6) Mesoscale-regional experiments with point sources of tracers and large distances (out to 100 km or more)

These experiments were made possible by the development of perfluorocarbon tracers that can be observed at very low concentrations (Ferber et al., 1981). Initially, this scale was studied by Lagrangian tracers such as tetroons (Angell and Pack, 1960). Classic tracer experiments at this range are CAPTEX (Ferber et al., 1986), ANATEX (Draxler and Heffter, 1989) and ETEX (JRC, 1998).

7) Urban, mesoscale, and regional ozone and related pollutants field experiments

This category was initiated in the 1970s after the realization that acid rain, ozone, small particles, mercury and other pollutants were an urban through regional-scale phenomenon. Emissions are scattered broadly and chemical reactions and deposition are important. Field experiments on this scale are very expensive and generally involve many groups and many instrument systems. An example is the South Central Coast Cooperative Aerometric Monitoring Program (SCCCAMP, see Hanna et al., 1991). Every year there are one or two of these experiments. As a recent example, the Texas Air Quality Study (TexAQS) has had two field programs on the 2000s.

8) Hazardous industrial chemical experiments at short distances ($x < 1$ km).

After the Bhopal accident in India, many field experiments took place where hazardous gases were released. The more dangerous gases are denser than air and/or are emitted as a gas-aerosol mixture. Impacts are generally greatest in the near field (distances less than about 1 km). Chang and Hanna (2004) have collected many of these experiments in their Modelers Data Archive. Also see Hanna et al. (1993) and Hanna and Chang (2001). Currently the DHS is planning additional field experiments involving large releases of pressurized liquefied gases such as chlorine and anhydrous ammonia.

4. SOME DETAILS ON EARLY EXPERIMENTS

Other papers in this AMS conference are discussing subsets of the above eight categories of dispersion experiments. Therefore, this paper will focus on the early experiments in categories 1 through 3 above. Pasquill's (1974) Chapter 4 is titled "Experimental studies of atmospheric diffusion", and is used as the basis for this section. Note that Pasquill considered "diffusion" and "dispersion" to be the same phenomenon (the entry under "dispersion" in his index says "see diffusion"). Pasquill points out on p 166 that the early dispersion field experiments fall into three main groups:

1) Optical outline methods, using a suitable form of smoke.
2) The measurement of trajectories of individual marked particles
3) Measurement of the concentration of a tracer element introduced into the air"

Roberts (1923) discussed the use of photographs and other optical analyses of smoke to study diffusion. The puffs that he was studying were formed from anti-aircraft shell bursts. A breakthrough by Gifford (1957) allowed observations of the maximum optical outlines of smoke plumes and puffs to be used to estimate the plume standard deviation, σ, as long as the shape of the cross-wind distribution could be assumed (the Gaussian shape was assumed in his test scenarios).

Pasquill (1974) and Draxler (1984) describe the development of improved tracer materials and how gradually the tracer option above became the dominant component of dispersion field experiments. Pasquill (1974) claims that "The first known measurements of this type were carried out on Salisbury Plain, England, at the War Office

Chemical Defence Experimental Establishment, Porton, in 1923". "A hand pump was used to draw the smoke-laden air through a small orifice backed by a filter paper. The stain on the filter paper was compared with a series of standard stains". A team of observers was arranged at specific locations, allowing cross-wind concentration distributions to be measured. "In later work, the vertical distribution was explored by stationing the observers at various heights on a tower". This early use of smoke and gaseous tracers could be used only to distances of about 1 km at most because of the hazardous nature of the tracers. In the early 1950s, fluorescent particle tracers, such as zinc cadmium sulphide, allowed dispersion experiments to be extended to 100 km or more. The Prairie Grass experiment used sulfur dioxide gas. However, we now know that many of these tracers were subject to significant removal due to deposition. Thus inert gases such as SF_6 are now widely used. The development of perfluorocarbon tracers (PFTs) allowed the dispersion experiments to extend past 1000 km, since they have a small global background and can be observed to very small concentrations. The global background obviously will provide a limit to all types of tracers.

Of course, the development and improvements in data acquisition systems and computers allowed much more efficient data collection and storage and analysis. For example, observations from the original Prairie Grass experiments were originally available only in hard-copy reports (e.g., Haugen, 1959). Now we have field data archives with sizes in the gigabytes and terabytes. The largest sizes are associated with experiments using fast response instruments such as 10 Hz sonic anemometers and/or remote sounders.

The early (1920s through 1940s) dispersion experiments in England with tracers showed that the cross-wind distribution of material had an approximate Gaussian shape (e.g., Sutton, 1953, p 275). The dispersion field experiments in Europe and the U.S. were almost exclusively carried out using funding from the Departments of Defense. We note that most of the analyses that were carried out were to check the basic theoretical formulations proposed by Taylor (1921), Richardson (1926), and other scientists. For example, the theory says that the cross-wind spread is proportional to σ_θ, which is the standard deviation of the wind direction observations. **Figure 1** is copied from Pasquill's book (1974, p 181) and shows observed cloud-width plotted versus the "lateral width of a bi-directional-vane trace" (equal to about 4 σ_θ). The field observations, which show a nice linear relation, were at Cardington, England, in 1934.

The vertical distribution of concentration for releases at ground level was also investigated in these early experiments. The hypothesis was that the concentration dropped off with height according to the formula:

$$C(z = z_1)/C\ (z = 0) = \exp\ (-bz_1^{s}) \qquad (1)$$

Pasquill's (1974, p 205) Table 4.VIII presents values of the parameter, s, derived from 7 experiment trials at Porton in 1923-1924, 29 trials from Cardington in 1931, and 41 trials from Prairie Grass in 1956. Stabilities were usually close to neutral. For these three sites, s was found to be 1.15 at Porton, 1.5 at Cardington, and 1.49 (with a range from 1.21 to 1.77) at Prairie Grass. Note that a Gaussian distribution would have s = 2.

The U.S. military and atomic energy agencies began a series of short distance dispersion experiments in the 1950s where releases were near the ground. The MIT Round Hill Field Station (in New England) and a flat site in O'Neill, Nebraska (the Prairie Grass site) were used for intensive field experiments. The top U.S. micrometeorologists and dispersion specialists were employed to plan and carry out the experiments, and analyze and report the results (Cramer et al. 1958, Barad 1958, Haugen, 1959). Similar experiments, but sometimes involving releases from towers, were carried out at other military sites and AEC labs such as the Hanford site (e.g., Barad and Fuquay 1962 – the Green Glow experiment; Fuquay et al. 1964, Haugen and Fuquay 1963 – the Ocean Breeze and Dry Gulch experiments, Islitzer and Dumbauld 1963).

In the 1960s, because of issues raised by the use of chemical agents in the Viet Nam war, several dispersion experiments were carried out to study aerosol dispersion and deposition, especially in forests and in urban areas (e.g., Hilst and Bowne 1966 – releases of aerosols from airplanes flying 100 m above Fort Wayne IN; Bowne et al. 1968 – releases of aerosols over woodlots). Of course, dispersion of smoke and aerosol puffs was of interest to the defense community throughout the 20^{th} century (e.g., Chamberlain 1953, Barad and Schorr 1954, Gifford 1957, Hay and Pasquill 1957, Smith and Hay 1961). **Figure 2**, from Smith and Hay (1961) and reproduced as Figure 9.17 in Draxler (1984, p 385), shows the observed spread of clusters of particles as a function of turbulence intensity. The observations again support a linear relation, as postulated by the theory.

As noted earlier, after WW II there was a major research effort to understand the transport and dispersion and deposition of radiological releases from atomic bombs and from nuclear reactors. Understandably, only a few of the results of the research made it into the open literature. Kellogg's (1956) paper was titled "Diffusion of smoke in the stratosphere". He released a mixture of $TiCl_4$ and water from trains of balloons at elevations from about 23,000 to 63,000 feet and tracked the cloud with phototheodelites. The resulting observations of visible smoke puff diameter were plotted against time of travel and the averaged curve is given in **Figure 3** (Pasquill, 1964, Fig 4.16 on p 214). The puff diameter grows to about 110 m after five minutes of travel. Wilkins (1954) and Machta et al. (1956) discuss effective coefficients of diffusivity for atomic bomb clouds at distances out to several thousand miles. The bomb cloud transport and dispersionmodels used at the time made use of diffusivities.

5. FURTHER COMMENTS

The characteristics of dispersion experiments have been shown to evolve over the past century. Capabilities have grown because of the development of improved tracers and samplers, electronic data acquisition devices, and electronic archival and analysis methods. Experiment costs and sizes of data archives have also grown, in an exponential fashion.

The goals of the field experiments have continually shifted to follow the available funding sources. It was seen that, up through about 1965, the primary interest was in military applications. There was also a large interest in spread of atomic bomb debris in the two or three decades after WWII. More recently, interest has shifted to environmental (air pollution) concerns. But a common characteristic of any series of dispersion experiments is that the funding for the experiments and the analysis ends before the scientists think they have solved the problem.

Often it is cost effective to search through the archives and use data from previous field experiments that are related to your interests. This means that the field experiment archives must be accessible and fully explained. In some cases, current researchers convert the old hard copy data reports to electronic format. Examples are given in other papers in this conference session. For example, Venkatram discusses his analyses of the Prairie Grass and St' Louis dispersion experiments, and Chang discusses the Modelers Data Archive, which contains electronic files from dozens of dispersion experiments (see Chang and Hanna, 2004).

ACKNOWLEDGEMENTS

This research has been sponsored by the National Science Foundation under grant 0750878, and by contracts from the Defense Threat Reduction Agency (DTRA) and the American Petroleum Institute.

REFERENCES

Angell, J. K. and D. Pack, 1960: Analysis of some preliminary low level constant balloon (tetroon) flights. *Mon. Wea. Rev*. **88**, 235.

Barad, M.L., 1958: Project Prairie Grass, a Field Program in Diffusion. Gephys. Res. Paper No. 59. AFCRL, Bedford, MA.

Barad, M. and J.J. Fuquay (eds), 1962: The Green Glow Diffusion Program. Geophys. Res. Paper No. 73, Vols 1 and 2.

Barad, M. and B. Shorr, 1954: Field studies of the diffusion of aerosols. *Am. Ind. Hyg. Assoc. Quart.* 15 (2) 136-140.

Bowne, N.E., H.D. Entrekin, K.W. Smith and G.R. Hilst, 1969: Aerosol Diffusion over Woodlot Complexes. Report TRC-7236-343A, USDPG, Dugway, UT

Briggs, G.A., 1969: Plume rise. USAEC Critical Review Series, TID-25075, 80 pp.

Chamberlain, A.C., 1953: Aspects of travel and deposition of aerosol and vapour clouds. A.E.R.E., HP/R1261 HMSO.

Chang, J. and S. Hanna, 2004: Air quality model performance evaluation. *Meteorol. and Atmos. Phys.* **87**. 167-196

Cramer, H.E., F. Record and H. Vaughan, 1958: The study of the diffusion of gases in the lower atmosphere. MIT Dept of Meteorology Final report under Contract AF 19604-1058.

Draxler, R., 1984: Atmospheric Science and Power Production. DOE/TIC-27601 (DE84005177), Chapter 9: Diffusion and Transport Experiments. pp 367-422.

Draxler, R.R. and J.L. Heffter, 1989: Across-North America Tracer Experiment (ANATEX) Vol. 1 Description, Ground Level Sampling at Primary Sites and Meteorology. Tech Memo ERL ARL-167.

Ferber, G.J., K. Telegadas, J.L. Heffter, C.R. Dickson, R.N. Dietz, and P.W. Krey, 1981: Demonstration of a long-range atmospheric tracer system using fluorocarbons. NOAA Tech Memo ERL-ARL-101.

Ferber. G.J. et al., 1986: Cross-Appalachian Tracer Experiment (CAPTEX '83). Tech Memo ERL ARL-142.

Fuquay, J.J., C.L. Simpson, and T.H. Hinds, 1964: Predictions of environmental exposure from sources near the ground based on Hanford experimental data. *J. Appl. Meteorol*. **3**, 761-770.

Gifford, 1957: Relative atmospheric diffusion of smoke puffs. *J. Meteorol*. **14**, 410-414.

Gifford, F.A., 1968: Meteorology and Atomic Energy 1968, USDOE, Chapter 3: An Outline of Theories of Diffusion in the Lower Layers of the Atmosphere, pp 66-116.

Hanna, S.R., R.E. Britter and P. Franzese, 2003: A baseline urban dispersion model evaluated with Salt Lake City and Los Angeles tracer data. *Atmos Environ*. **37**, 5069-5082.

Hanna, S.R. and J.C. Chang, 1993: HPDM improvement and testing at three field sites. *Atmos. Environ*. **27A**, 1491-1508.

Hanna, S.R. and J.C. Chang, 2001: Kit Fox dense gas dispersion field experiments and HEGADAS model testing. *Atmos Environ*. **35**, 2231-2242.

Hanna, S.R., J.C. Chang and D.G. Strimaitis, 1993: Hazardous gas model evaluation with field observations. *Atmos. Environ*. **27A**, 2265-2285.

Hanna, S.R. and R.J. Paine, 1989: Hybrid Plume Dispersion Model (HPDM) development and evaluation. *J Appl. Met*. **28**, 206-224.

Hanna, S.R., L.L. Schulman, R.J. Paine, J.E. Pleim and M. Baer, 1985: Development and evaluation of the Offshore and Coastal Diffusion Model. *J Air Poll Control Assoc*. **35**, 1039-1047.

Hanna, S.R., D.G. Strimaitis, J.S. Scire, G.E. Moore and R.C. Kessler, 1991: Overview of results of analysis of data from the South Central Coast Cooperative Aerometric Monitoring Program (SCCCAMP). *J. Appl. Met*. **30**, 511-533.

Hilst, G.R. and N.E. Bowne, 1966: A study of the diffusion of aerosols released from aerial line sources upwind of an urban complex. Final Report, prepared by The Travellers Res Center Inc, Hartford, CT for the US DPG, 231 pp.

Haugen, D.A. (Ed.), 1959: Prairie Grass, A Field Program in Diffusion. Geophy. Res Papers No 59, Vol III, Report AFCRC-TR-58-235 (ASTIA Doc No AD-217076, USAF Cambridge Res Center.

Haugen, D.A. and J.J. Fuquay, 1963: The Ocean Breeze and Dry Gulch Diffusion Programs, USAEC report HW-78435 (AFCRL-63-791), USAF Cambridge Res Center.

Hay, J.S. and F. Pasquill, 1957: Diffusion from a fixed source at an elevation of a few hundred feet in the atmosphere. *J. Fluid Mech* **2**, 299-310.

Hogstrom, U., 1964: An experimental study on atmospheric diffusion. *Tellus*, **16**, 205-251.

Islitzer, N. and K. Dumbauld, 1963: Atmospheric diffusion-deposition studies over flat terrain. *Int. J. Air Water Poll* **7**, 999-1012.

Islitzer, N. and D. Slade, 1968: Meteorology and Atomic Energy 1968, USDOE, Chapter 4: Diffusion and Transport Experiments, pp 117-188.

JRC, 1998: ETEX – The European Tracer Experiment. EUR 18143 EN, Joint research Center, Eur. Com (with WMO and IAEA), 106 pp.

Kaimal, J.C. et al., 1986: Project CONDORS: Convective Diffusion Observed by Remote Sensors. NOAA/ERL BAO Rep No. 7, Boulder, CO, 305 pp.

Kellogg, W.W., 1956: Diffusion of smoke in the stratosphere. *J. Meteorol*. **13**. 241-251.

Machta, L., R.J. List and L.F. Huber, 1956: World-wide travel of atomic debris. *Science*. **124**, 474.

McElroy, J.L and F. Pooler, 1968: The St. Louis Dispersion Study. Vol II-Analysis. NAPCA Pub. No. AP-53, USDHEW, Arlington, VA, 50 pp.

Pasquill, F., 1974: Atmospheric Diffusion – The Dispersion of Windborne Material from Industrial and Other Sources, Second Edition, John Wiley and Sons, London, 447 pp.

Record, F.A. and H.E. Cramer, 1958: Preliminary analysis of Project Prairie Grass diffusion mea. *J. Air Poll. Control Assoc*., **8**, 240-244.

Richardson, L.F., 1926: Atmospheric diffusion shown on a distance-neighbor graph. *Proc. Roy. Soc. (London), Series A,* **110,** 709-737.

Roberts, O.F.T., 1923: The theoretical scattering of smoke in a turbulent atmosphere. *Proc. Roy. Soc. A* **104**, 640-654.

Sagendorf, J.F. and C.R. Dickson, 1974: Diffusion under low wind speed stable conditions. NOAA-T-ERL-ARL-52, NOAA, NTIS.

Smith, F.B. and J.S. Hay, 1961: The expansion of clusters of particles in the atmosphere. *Q. J. Roy. Meteorol. Soc.* **87**, 82-92.

Sutton, O.G., 1953: Micrometeorology. McGraw-Hill, New York.

Taylor, G.I., 1921: Diffusion by continuous movements. *Proc. London Math Soc, Ser. 2*. **20**, 196-202.

Wilkins, E.M., 1954: Effective coefficients of diffusivity for atomic bomb clouds at one thousand to two thousand miles. *Trans. Am. Geoph. Union*, **39**, 58-68.

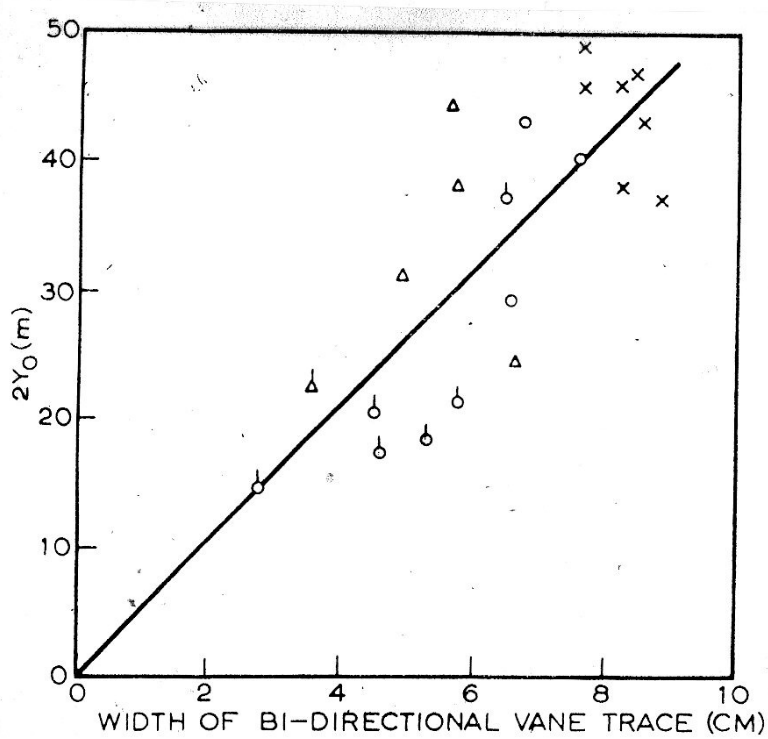

FIG. 4.4. Relation between cloud-width ($2Y_0$) from a maintained point source, and turbulence as indicated by the lateral width of a bi-directional-vane trace. The different symbols refer to different dates, the primed symbols to the more stable conditions. (Unpublished data from smoke experiments at Cardington, England, 1934)

Figure 1. From Pasquill (1974, p 181)

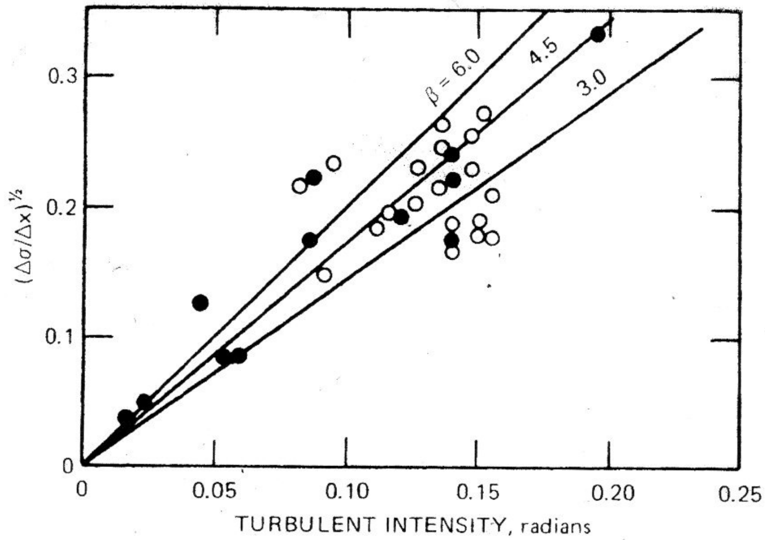

Fig. 9.17 Experimental values for the spread of clusters of particles. ○, crosswind spread from instantaneous point sources at distances to 300 m; ●, vertical spread from aircraft-released line sources at distances of 3 to 100 km; —, based on Eq. 9.17 for the indicated values of β, the Lagrangian–Eulerian time-scale factor. [From F. B. Smith and J. S. Hay, The Expansion of Clusters of Particles in the Atmosphere, *Q.J.R. Meteorol. Soc.*, **87**: 82-101 (1961).]

Figure 2. From Draxler (1984, p 385)

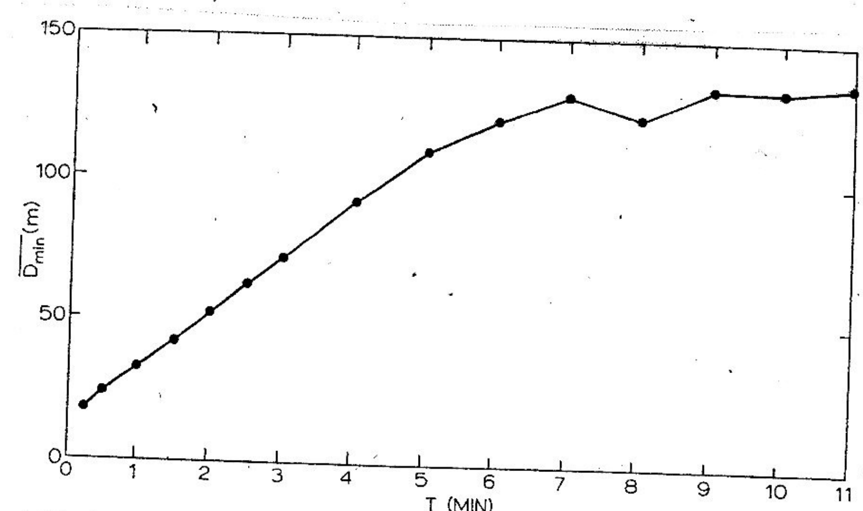

FIG. 4.16. Growth of the visible diameter of a smoke-puff as a function of time of travel *T*. Average curve from eighteen releases at heights ranging from 23,600 to 63,000 ft over New Mexico. (Kellogg 1956)

Figure 3. From Pasquill (1974, p 215)