ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

QUARTERLY STATUS REPORT NO. 5

DISPERSION AND PENETRATION OF POLLENS AND INDUSTRIAL CONTAMINANTS

July 1, to September 30, 1954

E. WENDELL HEWSON

This report, not necessarily in final scientific form, is intended only for the internal management uses of the contractor and the Air Force.

Project 2160

GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
CONTRACT NO. AF 19(604)-792

October, 1954

ABSTRACT

A series of field measurements of rates of penetration of ragweed pollen into a prepared room was made during the ragweed season, mid-August to the end of September. These observations suggested that in addition to penetration, sedimentation was a significant factor in determining the air-borne pollen content of the room. Projected studies of sedimentation in the room are expected to permit the meaningful interpretation of the concentration values in terms of penetration rates. This portion of the research has been conducted by E. Wendell Hewson and William H. Hansen.

The aerodynamic analysis of sedimentation from a turbulent air flow is proceeding. The methods being developed will apply directly to the problem presented by pollen deposition on the walls, floor, and ceiling of the test room. A stochastic differential equation has been derived for the general case with certain simplifying assumptions. Steps to permit direct application to the project problems will next be undertaken. This phase is being carried out by V. C. Liu.

DISPERSION AND PENETRATION
OF
POLLENS AND INDUSTRIAL CONTAMINANTS

I. INVESTIGATIONS BEING UNDERTAKEN

The first part of the reporting period was devoted to completing the installation of equipment in two small adjoining rooms on the north side of the roof of the East Engineering Building. One of the two rooms was used as the test room in which the penetration of particulates was measured; the other room housed the recording and other equipment needed for the operation.

A series of runs made with the equipment has shown that, except during the ragweed season, there is insufficient particulate matter in the atmosphere to permit meaningful determinations of rates of penetration using the present techniques.

A full-scale program of measurements was commenced shortly after the beginning of the ragweed season about the middle of August. The atmospheric concentrations increased to high values by late August and early September, thereafter decreasing to very low values in late September. The technique employed was first to reduce the inside concentration of ragweed pollen by means of the high-capacity bag filter constructed for the purpose. This operation was usually carried out first thing in the morning. Thereafter, a series of concentration measurements was taken throughout the day. Simultaneous meteorological measurements were also made.

Since the end of the ragweed season coincides with the end of the reporting period and much datum reduction remains to be completed, only a preliminary and tentative statement of the general results can be given in this report. Part of the time the inside-measured concentrations showed an increase with time, which would be anticipated as the outside pollens diffused into the room. Almost as often, however, there was a decrease in pollen concentration from one measuring period to the next. The most obvious explanation of these decreases is that the pollen particles were settling on the floor and walls, and perhaps on the ceiling, more rapidly than they were diffusing into the room from the outside. The interpretation of these results, therefore, requires a knowledge of the rate of fall-out of the particles. The evaluation of this rate will be undertaken during the next quarter. When this evaluation is complete it should be possible to express the rate of penetration as a function of the measured meteorological variables. These include wind speed and atmospheric turbulence, the latter as measured by a horizontal gust accelerometer.

This settling out of the pollen in the test room involves the impaction of particulates from a turbulent fluid onto solid surfaces. The process is being analyzed by the methods of theoretical aerodynamics. The problem to be solved and the solution being developed are as follows. A theory must be developed which describes the motion of particles suspended in a turbulent fluid. A simplified model, namely, the one-dimensional problem, is used to start with in view of the complicated nature of the problem. This seems to be a logical way to explore the pertinent basic phenomena. The term turbulent fluid, as it is used here, needs to be clarified. What is really meant is a fluid with fluctuating velocity which can be characterized by certain types of spectra.

The forces acting on a particle in a turbulent fluid can be conveniently classified into two kinds. First are the steady forces which include (1) the gravitational force $\vec{G}$ (=$m\vec{g}$), (2) the electrostatic force $\vec{E}$ (=$e\vec{V}_t$) where e = number of unit negative charges carried by the particle and V_t= strength of (earth's) electric field, (3) the radiometer force $\vec{R}$ if the skin temperature of the particle has a gradient, and (4) the drag force due to steady fluid velocity $\vec{U}$. Second are the fluctuating forces which include the Brownian force (or molecular force) $\vec{f}_b(t)$ and the drag force due to the turbulent flow. Hence, the equation of motion of a particle in x-direction is

$$m\frac{d^2x}{dt^2} = G_x + E_x + R_x - \beta\left[\frac{dx}{dt} - U_x - u_x(t)\right] + f_b(t) \qquad (1)$$

where

m = mass of the particle,

$\frac{dx}{dt}$ = velocity of the particle,

u_x = velocity of turbulent flow

$\frac{d^2x}{dt^2}$ = acceleration of the particle,

$\beta = \frac{6\pi\mu r}{1+A\frac{\lambda}{r}}$,

μ = viscosity coefficient of the fluid,

r = radius of the particle,

λ = mean free path of the fluid.

In setting up the above equation we assume that the drag force on the particle, due to the relative velocity between the particle and the fluid, is given by Stokes' formula with a Cunningham correction factor. This implies that the scale of turbulence is so large compared to the diameter of the particle that the local flow around the particle can be considered as laminar, and also that the Reynolds number of the flow for the particle is low enough to be in the Stokes range.

To analyze Equation 1, first the following transformation is introduced

$$\left.\begin{aligned} x' &= x - \left(\frac{G_x + E_x + R_x}{\beta} + U_x\right) t \\ \frac{dx}{dt} &= \frac{dx'}{dt} + \frac{G_x + E_x + R_x}{\beta} + U_x \\ \frac{d^2x}{dt^2} &= \frac{d^2x'}{dt^2} \quad . \end{aligned}\right\} \qquad (2)$$

Substitute Equations 2 into 1, so that

$$m \frac{d^2x'}{dt^2} + \beta \frac{dx'}{dt} = \beta\, u_x(t) + f_b(t) \quad . \qquad (3)$$

Equation 3 is a stochastic differential equation. "Solving" a stochastic differential equation like Equation 3 is not the same as solving an ordinary differential equation. For one thing Equation 3 involves the function $\beta u_x(t)$ and $f_b(t)$, each of which has only statistically defined properties. To treat Equation 3, the method of generalized harmonic analysis is used.* Let the right-hand side of Equation 3 be represented

---

* N. Wiener, Acta Math, 55 (1930).

by a stationary random function $U'(t)$ with $\overline{U'} = 0$. Consider $U'(t)$ to be truncated so that it becomes zero outside the interval $(-T,T)$. Let the truncated function be $U'_T(t)$. Under certain restrictions $U'_T(t)$ can be represented as a Fourier integral.

$$U'_T(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} F(w)\, e^{iwt}\, dw \qquad (4)$$

$$F(w) = \frac{1}{\sqrt{2\pi}} \int_{-T}^{T} U'_T(t)\, e^{-iwt}\, dw \qquad (5)$$

From the Parseval theorem

$$\int_{-\infty}^{\infty} U'^2_T(t)\, dt = \int_{-T}^{T} U'^2_T(t)\, dt = \int_{-\infty}^{\infty} \left|F(w)\right|^2 dw\ ; \qquad (6)$$

hence,

$$\overline{U'^2} = \frac{1}{2T} \int_{-\infty}^{\infty} \left|F(w)\right|^2 dw = \int_{0}^{\infty} \frac{|F(w)|^2}{T}\, dw \quad . \qquad (7)$$

For a stationary random function $\overline{U'^2(t)}$ tends to a constant, so $\frac{|F(w)|^2}{T}$ tends to a definite limit. Let

$$p(w) = \lim_{T\to\infty} \frac{|F(w)|^2}{T}\ ; \qquad (8)$$

then

$$\overline{U'^2(t)} = \int_{0}^{\infty} p(w)dw \quad . \qquad (9)$$

The power spectrum of $U'(t)$ is called $p(w)$. The element $p(w)dw$ gives the contribution to $\overline{U'^2(t)}$ from simple harmonic elements with frequencies ranging from w to $w+dw$.

Consider the equation

$$m \frac{d^2x'}{dt^2} + \beta \frac{dx'}{dt} = U'(t) \quad , \qquad (10)$$

where $U'(t)$ is an arbitrary forcing function represented by a Fourier integral

$$U'(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} F(w)\, e^{iwt}\, dw \quad . \tag{11}$$

From generalized harmonic analysis

$$x'(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \frac{F(w) e^{iwt}}{Z(iw)}\, dw \quad , \tag{12}$$

$$\frac{dx'}{dt} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} (iw) \frac{F(w) e^{iwt}}{Z(iw)}\, dw \ , \tag{13}$$

where $Z(iw) = -mw^2 + i\beta w$, if the integral converges.

$$\overline{x'^2(t)} = \int_0^{\infty} \frac{p(w)}{|Z(iw)|^2}\, dw \quad , \tag{14}$$

$$\overline{\left(\frac{dx'}{dt}\right)^2} = \int_0^{\infty} w^2 \frac{p(w)}{|Z(iw)|^2}\, dw \ , \tag{15}$$

where $p(w)$ is the power spectrum of $U'(t)$.

If it is assumed that the turbulence fluctuation force, $\beta u_x(t)$, and the Brownian force, $f_b(t)$, are random functions independent of each other,

$$p(w) = p_u(w) + p_b(w) \quad , \tag{16}$$

or

$$\begin{aligned} \overline{x'^2} &= \overline{x_u^2} + \overline{x_b^2} \\ &= \int_0^{\infty} \frac{p_u(w)}{|Z(iw)|^2}\, dw + \overline{x_b^2} \quad ; \end{aligned} \tag{17}$$

$$\overline{\left(\frac{dx'}{dt}\right)^2} = \int_0^{\infty} \frac{w^2 p_u(w)\, dw}{|Z(iw)|^2} + \overline{\left(\frac{dx}{dt}\right)_b^2} \quad , \tag{18}$$

where x_b and $\left(\frac{dx}{dt}\right)_b$ are the particle displacement and the velocity fluctuation due to Brownian force, respectively.

When the turbulent velocity distribution is Gaussian (or normal) then Equation 17 or 18 is all we need to calculate the probability distribution of x' or $\frac{dx'}{dt}$, respectively. These probability distributions are the basic relations in our theory of motion of particles in turbulent fluid flow. At this point it is desirable to discuss further the assumption concerning the turbulent velocity distribution, which greatly simplifies the analysis. Experimental evidence* does show that the turbulent air motion generated by passing through a square-mesh grid in a wind tunnel has a velocity distribution very close to the Gaussian. This, of course, only represents a special type of turbulent flow.

It is intended that the analysis should continue by applying the basic relations, namely, the probability distribution of x' and $\frac{dx'}{dt}$, to specific problems of sedimentation, impaction, etc., which have been raised by the experimental program of the project.

II. SCIENTIFIC ACTIVITIES

On August 16, Mr. J. Reinheimer of Project Big Ben, University of Pennsylvania, visited the project. The day was spent with project personnel discussing various aspects of the research.

On September 8, the project director acted as chairman of one session of a symposium on atmospheric pollution held during the 131st National Meeting of the American Meteorological Society in Columbus, Ohio. The papers read and topics discussed during the session were closely related to a number of aspects of the research being undertaken by the project.

III. RESEARCH FACILITIES

Actual construction of the penthouse laboratory on the roof of the East Engineering Building commenced early in September. The

---

*A. A. Townsend, Proc Camb Phil Soc, 43, 560 (1947).

laboratory should be ready for occupancy by the end of the next reporting period.

The development of the special test room facility for penetration measurements has been mentioned above.

IV. PERSONNEL AND ADMINISTRATION

Mr. Martin Harwit, Assistant in Research, who had been employed for the summer months only, resigned from his project duties at the end of August.

The amount of time that Mr. William H. Hansen has devoted to the project has decreased during the summer owing to an increased need for his services by the project with which he had been associated earlier. His experience and skills will still be available to the present project, but he will be able to devote only a strictly limited amount of time to it.

Two Assistants in Research were employed on a full-time basis during the summer to assist with the intensive program of measurements undertaken during the ragweed season. They are:

José F. Asuncion, who received the B.S. in civil engineering in 1948 from the Mapua Institute of Technology, Phillipines. He is at present studying for a bachelor's degree in electrical engineering. His experience and abilities in experimental work have been directly applicable in the work of the project.

Gunvant C. Sutaria, who has a B.S. in chemistry and a B.S. in chemical engineering, both from the University of Bombay. He is at present completing the requirements for a M.S. in chemical engineering. His previous experience in particulate counting under the microscope has been most useful.

A third Assistant in Research, Mr. Alan H. Molof, was also employed on a half-time basis during the height of the ragweed season. Mr. Molof received a M.S. in chemical engineering in 1951 and a M.S. in sanitary engineering in 1953, both from the University of Michigan. He is at present working on his Ph.D. in sanitary engineering. Mr. Molof has had research experience and training which were valuable in the program.

Since the middle of September Messrs. Asuncion and Sutaria have changed from a full-time to a half-time basis and Mr. Molof is spending only a very few hours per month on project work.

Negotiations have been completed for Dr. A. Nelson Dingle to take a position at the University of Michigan. Dr. Dingle will devote full time to the project research. He is one of the very few meteorologists who have given detailed attention to the behavior of pollens in the atmosphere and he may be expected to make a major contribution to the successful prosecution of the research.

V. FISCAL INFORMATION

Actual expenditures up to the end of September, 1954, were approximately $34,250 and encumbrances $1,750 for a total of $36,000. Balance as of that date is approximately $24,000.

This encumbrance is for the Instruments Corporation recording anemometer and wind vane, delivery of which has been promised for October, 1954.