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THE UNIVERSITY OF MICHIGAN
ANN ARBOR

Final Report (Part I)

A STUDY OF THE BEHAVIOR OF STACK GASES AT FISK STATION

R. H. Sherlock
Professor of Civil Engineering

F. K. Boutwell
Instructor in Mechanical Engineering

Project 2524

COMMONWEALTH EDISON COMPANY
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TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
(Concluded)

Figure

SUMMARY

Tests were performed in the wind tunnel to study the behavior of the gas plumes from Stacks 15, 17-1, 17-2, 18-1, 18-2, and 19 of the steam-electric generating station at Fisk Street, Chicago, Illinois. The model tested was constructed to a scale of 1:400 and represented a distance of approximately 2800 feet upwind and downwind, and 1600 feet to either side of Stack 18-2. Wind directions studied were N, NE, E, SE, S, SW, W, and NW.

Wind-tunnel results were correlated with wind data from the Office Data-Book, U.S. Weather Bureau at Chicago, Illinois, for a five-year sample of winds from 1943 to 1948. The number of hours per year during which the bottom of the plume would be below each of several heights above the station yard is shown in the form of graphs.

For this report, Stacks 17-1 and 17-2 were operated jointly, as were Stacks 18-1 and 18-2. Test conditions were:

Stack	Height (ft)	Exit Velocity (fps)	Temperature (°F)
15	300	36	400
17-1, 17-2	300	60	400
18-1, 18-2	300	60	400
19-A	400	60, 90, 120, 150	290
19-B	425	60, 90, 120, 150	290
19-C	450	60, 90, 120, 150	290

The results are summarized in Figs. 5-14.

INTRODUCTION

Part I of this report gives the results of a study of the behavior of the stack-gas plumes at the Fisk Street station of the Commonwealth Edison Company of Chicago, Illinois. Work was undertaken by authority of the Commonwealth Edison Company, purchase order No. 527983, dated March 21, 1956, to the Engineering Research Institute, which endorsed the project on April 5, 1956.

A conference was held in Chicago on April 4, 1956, with representatives of the Commonwealth Edison Company and the Bechtel Corporation in order to define the scope of the project. At that time a visit was made to the Fisk Street station to determine the various factors to be considered in the layout and construction of the model.

The model was demonstrated in the tunnel during a visit to Ann Arbor by Mr. M. H. Goedjen on July 18, 1956, and the final testing procedure was decided upon at that time.

This report correlates the information which was obtained in the wind tunnel with the wind history as recorded by the U.S. Weather Bureau at Chicago, Illinois. Observations were made in the wind tunnel for the eight segments of the compass — N, NE, E, SE, S, SW, W, and NW. The data from the Weather Bureau have been worked up in the form of probability curves for these points of the compass and are included with this report.

Part II of the report, contained in a separate volume, constitutes an appendix which contains more extensive discussion of some aspects of the investigation than were considered necessary in the main part of the report (Part I).

PROGRAM

The program for the downwash studies was agreed upon at the conference held on April 4, 1956, with representatives of the Commonwealth Edison Company and Bechtel Corporation. Further details were set in subsequent correspondence, and during a conference held at The University of Michigan on July 18, 1956, at which time the model was demonstrated in the tunnel. The test program consisted of:

1. The design and construction of a model of the Fisk Street station and nearby buildings and terrain, including all the present operating units and the future Unit 19. A scale of 1:400 was used and the model so constructed as to fit into the working section of the wind tunnel, which is 8 feet wide and 14 feet long. This represented a distance of some 5600 feet x 3200 feet over which observations could be made in each of the eight wind directions.

2. The necessary changes in the wind tunnel to accommodate the project.

3. The testing of the model in the wind tunnel to determine the critical velocities above which aerodynamic downwash of the stack gases might occur for the stack heights, exit velocities, and gas temperatures as dictated by the client.

4. Making progress reports verbally or by correspondence upon the progress of the work.

5. The compilation of the data and working up a series of tables and diagrams predicting the performance of the plant.

6. The compilation of a final report.

THE PLANT AND ITS SITE

The assembly drawings of the plant, its location on the property, as well as photographs of the general area were furnished by the Commonwealth Edison Company. The general dimensions and location of surrounding structures were also supplied by the Company with details of the proposed additional structure of Unit 19.

Testing conditions for the various units are outlined below:

Unit	Stack	Height (ft)	Exit Velocity (fps)	Exit Temperature (°F)
15	15	300	36	400
17	17-1	300	60	400
17	17-2	300	60	400
18	18-1	300	60	400
18	18-2	300	60	400
19	19-A	400	60, 90, 120, 150	290
19	19-B	425	60, 90, 120, 150	290
19	19-C	450	60, 90, 120, 150	290

Each of the units was tested for each of the wind directions N, NE, E, SE, S, SW, W, and NW and so required particular attention to the layout details of the plant model. A photograph of the completed model is shown in Fig. 1 and the detail layouts are available from the authors of this report. A general orientation of the main plant with a diagram of the included wind directions is shown in Fig. 2.

WIND TUNNEL

The investigation was conducted in the low-speed wind tunnel, which has a working section 8 feet wide by 5 feet 4 inches high and 14 feet long. The tunnel is a closed-loop, double-return type, with a contraction ratio of approximately 4:1 at the Venturi section. The air is circulated by an adjustable-pitch, axial-flow fan powered by a variable-speed d-c motor. Air velocity in the undisturbed portions of the flow was maintained at a constant rate of 15 fps by controlling the fan speed. An ASHVE Standard Pitot tube was used for the measurement of the wind velocity. It was located approximately above the model of the power plant, at a position that was selected after extensive tests on previous models. This position gives velocities which are representative of the undisturbed velocity of the air at some considerable height above the ground. Unlike the free atmosphere, there is no variation of wind velocity with height in the tunnel but, on the contrary, the wind velocity is practically uniform except in the boundary layer of about one inch at the ceiling floor, and sides of the tunnel. Even with the presence of the model, and the ground board upon which it was mounted, there was a considerable area in the cross section of the tunnel where the velocity was constant. It was in this area that the Pitot tube was placed. It may be said then that the wind velocity shown by the Pitot tube was that of the undisturbed air as it approached the top of the stack, but before it had come under the influence of the turbulence and deflections caused by the buildings and the stacks.

The stack gas (or smoke) is produced in a small furnace by passing an emulsion of oil and water, under pressure from the central compressed-air system, through a stainless-steel coil which is heated to a bright, cherry red. The emulsion is vaporized and the vapor forced through the necessary system pipes, valves, traps, orifice, and a stilling chamber to the stack from which it is emitted at a predetermined velocity.

The furnace was designed to give a vapor which was of the proper density and particle size to have stability and good photographic qualities and to permit visual studies to be made of its behavior. The vapor is cooled to approximately room temperature before being ejected from the stack into the wind stream. The desired velocity-ratios, that is, the ratio of stack-gas velocity to that of the wind velocity, are obtained by changing the stack-gas velocity and by keeping the wind velocity constant at 15 fps. The stack-gas velocity is observed through the readings of a manometer which is connected to a calibrated orifice in the line between the smoke generator and the stack.

MODEL

The construction of the model was made from details taken from the data supplied by the Commonwealth Edison Company. In order to gain the most desirable balance between the physical size of the model and the test section of the wind tunnel, a scale of 1:400 was decided upon. This scale resulted in adequate distance for downwash studies downwind (approximately 2800 feet from the plant) while maintaining enough detail to represent the plant properly.

In order to expedite the tests and to insure the proper contrast for photographing the smoke, Stacks 17-1 and 17-2 were operated jointly as were Stacks 18-1 and 18-2. Stacks 15 and 19 were operated independently because of their larger discharge areas.

The smoke plume was photographed through plate-glass windows against a grid on the far side of the tunnel from the camera. The white smoke is contrasted against the flat black background and the height of the plume can be read directly from the grid as shown in Fig. 3(b). The grid was laid out with the height of the stationyard as a zero reference elevation. All plume measurements are therefore heights above yard elevation as indicated in Fig. 4.

An exposure of one second was made for the photographic studies in order to show the average plume as it leaves the stack and progresses downwind. This corresponds to 5 to 10 minutes of plant operation in actual field conditions. This enables the observer to see an integrated rather than an instantaneous picture of the plume behavior.

STACK-GAS BEHAVIOR

Under favorable weather conditions, the plume from a smokestack will rise gradually as it flows downwind and the gases will be dispersed until only a negligible concentration prevails in the atmosphere. Under such conditions, the gases do not become a cause of annoyance to persons on the ground or of damage to crops and animals.

As the wind blows past a plant, it generates turbulence in the wake of the stacks and of the buildings. The turbulent masses of air immediately above and behind the buildings are separated from the more smoothly flowing

TABLE I. INFLUENCES ON GAS-PLUME BEHAVIOR

Favorable	Adverse
1. Stack height	1. Aerodynamic
2. Gas velocity	2. Terrain
3. Gas temperature	3. Meteorologic

upper layers of air by a vortex sheath. If the gases emitted by the stack come under the influence of the turbulence generated by the stack, the gases may be brought down and penetrate the vortex sheath so that they are brought to the ground by the turbulence of the building. This action we term "downwash" of the gases. Under such conditions, the concentration of obnoxious constituents of the gas on the ground may be very high in the area close to the plant. If the gas escapes the eddies at the plant, it may flow smoothly downwind and come under the adverse influence of the terrain or other obstacles. These may be in the form of hills, valleys, or buildings which set up currents which may entrap the gas, unless the plume approaches these obstructions with sufficient clearance to escape them.

Even if the gases escape the influence of the eddies near the plant or of the currents deflected by downwind obstacles, there are thermal influences in the atmosphere which may bring the gases to the ground before they have been sufficiently dispersed. Vertical-convection cells are common and frequently extend to the ground and may extend upward hundreds or, in some cases, even thousands of feet. Their effect in dispersing the gases is very great, but unfortunately they frequently bring the gases to the ground before the concentration of obnoxious constituents has been reduced to within satisfactory limits. The effects must be superimposed upon the idealized diffusion but are unfortunately unpredictable insofar as model tests are concerned. These meteorological effects are therefore not considered in this report although they may be approximated on theoretical considerations. It is assumed that the flotational effects which are discussed later at least partially offset the effects of the convection cells.

BASIC PLUME

A clearly defined standard of reference must be used in speaking of the conditions which are most easily simulated in the wind tunnel, namely, a neutral or stable atmosphere which is relatively free from the vertical mixing caused by convection cells. The flow patterns which are observed in the tunnel under these conditions are referred to here as the "basic plume."

Figure 3(b) shows a free-flowing plume which occurs with a high stack-gas velocity in a light wind, and Fig. 3(a) shows the downwash which can occur with low stack-gas velocity in a strong wind. It should be noted here that the aerodynamic downwash will usually occur in two steps, the first of which is caused by the eddies at the top and in the wake of the stacks. If this first step brings the gases low enough so that they penetrate the vortex sheath over the turbulent air above and beyond the building, the second step occurs and the gases may be brought to the ground. This may affect only the lower portion of the plume so that the regular shape of the basic plume becomes partly ragged with sweeping "tails" at irregular intervals, or it may include all or most of the plume. In the case of Stacks 15, 17, and 18 the stacks are so low and the volume of the buildings and other obstructions so great that the vortex sheath, for the wind directions considered, lies above the top of the stacks and there is only the second step of downwash.

UNFAVORABLE TERRAIN

When the wind is blowing over a hill it will be deflected upward and the height to which this effect extends may be several times the height of the hill. If the plume approaches the hill in an undisturbed manner at a height sufficient to escape the turbulent boundary layer on the surface of the hill, it may actually be deflected upward and thus escape contact with the hill.

However, if the plume has already been made ragged by the action of the stack and building turbulence, or if it has not reached a sufficient height to pass over the turbulent boundary layer of the hill, the plume will be dragged into the boundary layer and impinge upon the surface of the hill. An intermediate condition occurs when the tails are being drawn down so that they sweep along the surface of the hill. Under these conditions the high concentrations of obnoxious constituents of the gas are only transitory or intermittent.

GAS TEMPERATURE

The higher temperature of the stack gases in relation to the ambient atmosphere introduces flotational forces which, under favorable conditions, will cause the plume to rise, even though the temperature of the plume decreases rapidly due to diffusion in the atmosphere. The flotational effect of the high temperature is not entirely lost, however, since the overall heat content of the mixture of gas and air is not reduced. The theoretical height of rise can be computed, but, as in the case of idealized diffusion, the basic assumptions are only a rough approximation to nature.

In those cases where the plume has not escaped the adverse aerodynamic effects at the top of the stack and in the wake of the building, or has not escaped the turbulent boundary layer on the face of a hill, the flotational forces are so small compared to the aerodynamic forces that they should be neglected. This matter is further discussed in Part II of the Final Report, page 2.

In those situations where the stacks are of sufficient height, and the exit velocity is sufficiently great, so that the plume is unlikely to be entrapped in the turbulence of a hill, the temperature of the gas may be ignored and considered simply as an additional margin of safety. The higher temperature of the plume will cause the plume to rise and to clear the hill by a greater margin than is indicated by the wind-tunnel test. Also in such situations, if a gust velocity becomes momentarily high, or if the atmosphere is unstable so that a small amount of vertical mixing occurs, small fragments of the plume may reach the ground.

GAS VELOCITY

Early investigations on previous projects established the great value of high stack-gas velocity as a device to reduce downwash. The function of the exit velocity is to provide sufficient favorable momentum to enable the gases to escape entrapment by the eddies generated by the stack and thus to prevent the gas from being brought down through the vortex sheath and into the turbulence of the building. Such prevention is usually accomplished by a gas momentum per unit volume which accompanies a velocity of about 60 fps and a temperature of about 300°F. Under such circumstances, the favorable momentum of the emerging gas will be sufficient to overcome the unfavorable momentum of the passing wind in all except storms of gale intensity. The unfavorable momentum of the wind is reflected in the strength of the eddies above and behind the stacks.

The ratio of the velocity of the stack gases to that of the passing wind can be used as a measure of the relative momenta, provided that gas and air have both been reduced to an equivalent common temperature. This is called the velocity-ratio. If, for example, the model tests indicate that a certain plume behavior can be expected with a velocity-ratio of 2.0, a plant operating with a gas velocity of 60 fps at 290°F would have the same plume behavior as one operating with a gas velocity of 42.4 fps at 70°F. The accompanying wind velocity at 70°F would be 21.2 fps (14.5 mph), as shown in Table II. The results reported on this project are based on an acceptance of this principle and on the belief that what is observed in the wind tunnel on this basis will be repeated in the field. This belief has been supported by observations in the field on other projects. A more detailed discussion of this subject appears in Part II of the Final Report, pages 18 and 19.

TABLE II. EQUIVALENT WIND VELOCITY IN FIELD, V_w AT 70°F

$V_s \div V_w$ at 70°F	Operating Conditions, V_s' at 290°F					
	V_s = 60 fps		90 fps		120 fps	
	fps	mph	fps	mph	fps	mph
0.5	84.8	57.8	127.2	86.8	169.6	115.6
1	42.4	28.9	63.6	43.4	84.8	57.8
1.5	28.3	19.3	42.4	28.9	56.5	38.5
2	21.2	14.5	31.8	21.7	42.4	28.9
2.5	17.0	11.6	25.4	17.3	33.9	23.1
3	14.1	9.6	21.2	14.5	28.3	19.3
3.5	12.1	8.3	18.2	12.4	24.2	16.5
4	10.6	7.2	15.9	11.0	21.2	14.5

V_w = Wind velocity, fps at 70°F
V_s = Stack-gas velocity, fps at 70°F
V_s' = Stack-gas velocity, fps at 290°F

$$V_s \text{ at } 70°\text{F} = (V_s' \text{ at } 290°\text{F}) \frac{70 + 460}{290 + 460}$$

$$= 90 \times 0.707 = 63.6 \text{ fps}$$

$$\text{and } V_w = \frac{63.6}{V_s' \div V_w}$$

WIND HISTORY

The results of the wind-tunnel tests are correlated with a statistical analysis of wind data from the Office Data-Book, U.S. Weather Bureau at Chicago, Illinois, for a five-year sample of winds from 1943 to 1948. The probability curves based on this five-year sample are shown in Figs. 47 through 54. The weather data are plotted as points and a fitted Pearson Type III statistical curve is shown as a solid line. The values of average velocity, standard deviation, and coefficient of skewness are also shown on each diagram. The data for southeast winds, for example, are shown in Fig. 50. The curve should be read as follows:

> "During 0.5% of all the hours in an average year the wind will be from the southwest with a velocity of 13.9 mph or more."

The probility curves for the 8 wind directions are included in this report so that they may be available to the client in other cases.

SEQUENCE OF COMPUTATIONS

The sequence of procedures used in obtaining the final results is shown in Fig. 4. The first step, of course, is to obtain from the wind-tunnel photograph the height of the bottom of the plume for a given set of operating conditions involving stack height, wind direction, wind velocity, stack-gas velocity, and stack-gas temperature. The stack-gas velocity and the wind velocity are both reduced to a standard temperature of 70°F and the velocity-ratio (V_s/V_w) is obtained from these equivalent velocities.

These data are then plotted in the form shown in Diagram (1) of Fig. 4, which is merely illustrative and not based on actual data. Here the wind is shown to be from the southeast, the stack is 425 feet high, and the height of the plume for various velocity-ratios is shown by one "x" for each wind-tunnel observation. Diagrams based on actual data are shown in Figs. 15 through 46. Figure 30 may be used for purposes of illustration. It is based upon wind-tunnel readings for a 450-foot stack. The readings of height to the bottom of the plume were made at a distance of 2300 feet downwind from the stacks. The diagram of Fig. 30 should be read as follows:

> "In order to maintain the bottom of the plume at a height of 300 feet, it will be necessary to use a velocity-ratio of 2.69."

The critical velocity-ratio is thus said to be 2.69 for this set of conditions. Therefore, if the stack-gas velocity is maintained constant at a particular value, it will be possible to solve for the critical wind velocity which will hold the bottom of the plume at a height of 300 feet. For example, if the stack-gas velocity is 63.6 fps at 70°F (equivalent to 90 fps at 290°F) and the critical velocity-ratio is 2.69 for P = 300 feet,

$$\begin{aligned} V_W &= \frac{63.6}{2.69} = 23.6 \text{ fps} \\ &= 16.1 \text{ mph.} \end{aligned}$$

The critical wind velocity is 16.1 mph, and any velocity greater than that will drive the plume below 300 feet within a distance of 2300 feet downwind from the stacks. The manner of obtaining the values of 63.6 and 23.6 fps is shown in Table II.

Having obtained the value of the critical wind velocity (23.6 fps = 16.1 mph), it is then necessary to turn to the probability curve of Fig. 50, for which it will be possible to pick out the percentage of hours of the year (0.23 percent = 20 hours) when the critical velocity will be exceeded. This will also be the percentage of hours when the height of the bottom of the plume will be equal to or lower than the height (300 feet) for which the critical wind velocity was obtained. This is illustrated in Diagram (3) of Fig. 4.

Knowing the percentage of hours when the critical conditions will be exceeded, it is possible to compute the number of hours per year during which the critical conditions will be exceeded (20 hours) as shown in Diagram (4) of Fig. 4.

TEST PROCEDURES

A "run" is a wind-tunnel test for which a photograph is available showing the behavior of the gas plume under a particular set of conditions. Figures 3(a) and 3(b) show two runs, one with satisfactory plume behavior and the other with downwash. Each set of conditions was run twice in order to provide a check on the accuracy of the work done. Table II shows the relation between each velocity-ratio and the corresponding wind velocity in the field.

Since it was easier to change the stack-gas velocity than to change the wind velocity, a constant wind velocity of 15 fps was used in the tunnel for all runs, and the various velocity-ratios were obtained by varying the stack-gas velocity. During each run smoke was ejected at the proper velocity from the stack for a period of about 15 seconds and one particular second was selected for the time exposure of the camera. One second in the tunnel corresponds to a period of about 5 to 10 minutes at the plant site, depending on the wind velocity at the site. A one-second exposure was too long to show the instantaneous structure of the plume and accounts for the "paint-brush-stroke" appearance of the plume in the pictures. Instead, it gave an integrated history of the plume behavior for a period of about 5 to 10 minutes at the plant sites and made it possible to obtain readings which were more representative of the long-time behavior of the plume under each particular velocity-ratio.

DISCUSSION OF RESULTS

The results are summarized by the diagrams in Figs. 5 through 14. In Figs. 5 through 11, intermittent downwash in hours per year is plotted against wind direction for each of the several combinations of the stacks, gas velocities, and plume heights as indicated. In these instances the expected downwash is plotted with reference to the desired plume height, P. In Fig. 5, for instance, on the left diagram, there is shown the expected intermittent hours per year during which the plume height will be equal to or less than 100 feet. On the right diagram there is indicated the expected intermittent number of hours per year that the plume will be at a height equal to or less than 200 feet. It is to be noted that for this and subsequent figures the expected number of hours of downwash is often indicated by notation where the graph is not continuous or where difficulty in reading may occur. In Fig. 5 the height of the plume for winds from the N would be $P \leq 100$ feet for 780 hours per year and $P < 200$ feet for more than 2400 hours per year for the velocity-ratios tested.

The results for the three worst wind directions for Stack 19 are summarized in Figs. 12 through 14. Here the expected downwash is plotted against the stack velocity for stack heights of 400, 425, and 450 feet. Again, intermittent downwash is defined as the hours per year during which the average plume height is expected to be below the designated elevation, P. These figures demonstrate very clearly the effect of increasing stack height and/or stack-gas velocity. It is to be noted that an addition to the stack height does not necessarily affect the plume height to the same relative degree for all directions. For instance, in Fig. 12, for winds from the S, only a small improvement is noted for the 450-foot stack as compared to the 425-foot stack while a very marked improvement is indicated in Fig. 13 for SW winds for the same change in height. Note that in Fig. 13, SW winds, that the 450-foot stack height delivers a plume which can be expected to be above 400 feet for a considerable number of hours per year, even at a stack velocity of 60 fps. This is the only instance where the arbitrary reference height, P, for downwash was plotted equal to or below 400 feet.

Figures 15 through 46 are enclosed as supporting data for Figs. 5 through 14 and represent the wind-tunnel results. For these figures the plume height is measured to the bottom of the plume by means of the reference grid, as previously mentioned.