THE UNIVERSITY OF MICHIGAN

BEHAVIOR OF STACK-GAS PLUMES AT THE PORT SHELDON STATION OF CONSUMERS POWER COMPANY

Final Report (Part A)

for

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under contract with:

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ABSTRACT

Tests were run in the low-speed wind tunnel at The University of Michigan to study the behavior of the gas plumes from the proposed steam-electric power-generating station at Pigeon Lake, Michigan, referred to as the Port Sheldon Station. A model to the scale of 1:500 was used, so designed as to include the plant and the terrain for a distance of some 8375 ft downwind and a distance laterally of 2000 ft on each side of the plume. Six directions were studied, namely, winds from the NW, W, SW, SE, E, and NE. Wind probability studies were also made for the N, NNW, WNW, WSW, SSW, S, SSE, ESE, ENE, and NNE winds.

The wind-tunnel tests were correlated with a five-year sample of the wind records taken by the U. S. Weather Bureau at Grand Rapids, Michigan. The number of hours per year during which the bottom of the plume would be below each of several selected heights at reference points 4000 ft downwind from the plant is shown in the form of graphs in Figs. 49 through 54. A stack-gas temperature of 240°F was used in combination with (1) 30-, 60-, 90-, and 120-fps exit velocity for the stack gas, and (2) 350-, 400-, 450-, and 500-ft stack heights.

OBJECTIVE

The objective of this research is to present predictions of stack-gas plume behavior at the proposed Port Sheldon Plant of the Consumers Power Company of Michigan in such a form that they can be used by the client in selecting the height of the smokestack and the exit velocity of the stack gases.

INTRODUCTION

In a letter dated September 12, 1958, Mr. R. H. Sherlock, Consulting Engineer of Ann Arbor, Michigan, requested Professor R. Clay Porter to submit a proposal for conducting certain parts of a study to determine the probable behavior of the stack-gas plumes at the proposed electric generating station of the Consumers Power Company at Pigeon Lake near Port Sheldon. In accordance with this request, the following program was prepared and incorporated in a contract dated September 15, 1958, between R. H. Sherlock and The University of Michigan. The overall study being conducted by Mr. Sherlock for the Consumers Power Company contains three parts, namely, (A) behavior of stack-gas plumes; (B) ground concentration of SO_2; and (C) deposition of fly-ash. This report pertains only to Part A.

PROGRAM

The program referred to in the letter of September 12, 1958, was as follows:

1. Study the wind history in the area, from data obtained from the U. S. Weather Bureau Station records at Grand Rapids, Michigan, over a period of five years. Construct curves showing the probability of occurrence of various wind velocities from each of six given directions.

2. Design and make a model of the first two units of the proposed plant and nearby buildings, together with the terrain lying in the area to the NW, W, SW, NE, E, SE for a distance of 8375 ft. A scale of 1:500 will be used to fit the model into the working section of the wind tunnel which is 8 ft wide and 20 ft long, as modified.

3. Make changes in the wind tunnel to accommodate the project.

4. Perform the tests, using various combinations of stack height, stack-gas velocity, and stack-gas temperature, in accordance with information to be furnished by the client.

5. Make progress reports verbally, by correspondence, or more formally, as may seem desirable during the progress of the work.

6. Formulate the data into tables and diagrams.

7. Compile a formal report.

THE PLANT AND ITS SITE

The assembly drawings of the plant, and of its location on the company property, were furnished by the Commonwealth Associates, Inc., as were topographic maps showing contours of the terrain, and aerial photographs of the pertinent terrain. The area of the topographic maps showing the terrain which was to be included in the tunnel model was photographed in 9 overlapping photographs of approximately 7 x 12 in. These negatives were enlarged by a mural process to about 8 x 20 ft, after trimming, which is the size of the working space of the tunnel. A total of nine murals was used to cover the areas involved in the six wind directions studied. The distortion and deviation from scale of the finished mural produced errors which were maximum at the corners, but were never in excess of 3/4 in. in length or width.

Conferences with the representatives of the Consumers Power Company and Commonwealth Associates had indicated the areas of greatest interest. An inspection of the topographic map narrowed the choice of directions down to the six tested, NE, E, SE, NW, W, SW. These directions were accordingly used as centerlines of the tunnel and the model was laid out to include 4 ft on each side of these lines in the tunnel, corresponding to 2000 ft on each side of the line in the field. The model terrain was built up with 1/4-in. plywood sheets, with each thickness corresponding to a change of elevation of 10.4 ft. Figure 1 shows the model of the entire area tested. The Frontispiece, which is a view in the wind tunnel looking toward the plant from the SE, also illustrates the model construction. Rough-cut sponge rubber was used to simulate the heavily forested areas surrounding the plant.

The testing program was as follows:

Scale of model - 1:500
Wind direction - from NE, E, SE, NW, W, SW
Stack-gas temperature - 240°F

Plume behavior was observed for the proposed plant:

(a) For each wind direction (NE, E, SE, NW, W, SW)
(b) For each stack height (350, 400, 450, and 500 ft)
(c) For stack No. 1 only
(d) For selected ratios of stack-gas velocity to wind velocity, $R = V_s/V_w$ (1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0)

The detail drawings for the model of the plant were each 24 x 36 in. An assembly drawing of the same size shows the arrangement of the model in the wind tunnel. Copies of these drawings may be obtained from the authors of this report. Figure 2 shows the significant terrain included in the model as well as the orientation of the Port Sheldon Station.

WIND TUNNEL

The investigation was conducted in the low-speed wind tunnel, which has a working section 8 ft wide by 5 ft 4 in. high, and 14 ft long except when modified. 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 8 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 is a considerable area in the cross section of the tunnel where the velocity is 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 a low-carbon-content oil, under pressure from the central compressed-air system, through a stainless-steel coil which is heated to a bright, cherry red. The oil is vaporized and the vapor is 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 ratio, that is, the ratio of stack-gas velocity to that of the wind velocity, is obtained by changing the stack-gas velocity and by keeping the wind velocity constant at 8 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 orientation of the station building is shown in Figs. 2 and 3. The scale of the model (1:500) was selected to give a sufficient coverage of the terrain to insure representative test results. The selected portions of the topographic maps were photographed to bring out the topographic contours and other significant features of the terrain in the area under study. The negatives were then used to make mural-type prints of the selected area to model scale, as illustrated in Fig. 4. These were glued to plywood and the enclosing rectangle of the plant area, including the building and stack locations, was drawn to scale on the mural. Construction of the model contours was made by stacking 1/4-in. plywood sheets which had been cut to the topographic contour lines. The completed model is shown in Fig. 1. Residences, farm buildings, and trees were only approximately represented in the model since they were considered to be of small aerodynamic importance in a model of this scale. Principal buildings and large structures were represented in accordance with available data as illustrated in Fig. 4. The model was made in small sections, most of which were rectangular, and of such size that the handling in the tunnel was facilitated, and so that the six directions could be tested without making duplicate sections.

The smoke plume and a reference grid were photographed through plate-glass windows with an exposure of two seconds. The grid is shown in Figs. 5 and 6 as well as in the Frontispiece. It served as a reference for the measurement of the height of the plume above the station yard (elev. 600 ft above sea level).

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. Unfortunately, however, there are several adverse natural influences which arise occasionally to disturb this orderly dispersion of the stack gases (see Table I).

TABLE I

INFLUENCES ON GAS-PLUME BEHAVIOR

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

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 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. These large-scale thermal effects should 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 6 shows a free-flowing plume which occurs with a high stack-gas velocity in a light wind, and Fig. 5 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 stack. If this first step brings the gasses low enough so that they penetrate the vortex sheath over the turbulent air above and beyond the building, the second step occurs and the gasses 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. At the site of this project it is particularly undesirable for the plume to be broken up in this manner since such a disturbance of its regular shape interferes with its ability to escape the turbulence generated by the terrain over which it must pass.

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. The action of a ragged plume is illustrated in Fig. 5 where the "tails" appear as the hazy area on the bottom of the plume and cause its ragged appearance. The tails and part of the remainder of the plume are drawn down so that they sweep along the surface of the hill.

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, 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.

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 70 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 stack.

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 240°F would have the same plume behavior as one operating with a gas velocity of 45.42 fps at 70°F. The accompanying wind velocity at 70°F would be 22.71 fps (15.48 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.

WIND HISTORY

A five-year sample of hourly wind velocities was obtained from the U. S. Weather Bureau from records taken at the Grand Rapids, Michigan, weather station. The wind records are divided into 16 points of the compass, thus covering a 22.5° segment for each wind direction. The probability curves based on this five-year sample are shown in Figs. 7-12 for the directions tested in the tunnel and Figs. 13-15 for the remaining directions. A Pearson Type III statistical curve representing the wind data is shown as a solid line. The data for northwest winds, which are significant on this project, are shown in Fig. 7. The curve should be read as follows:

> "During 2.0% of all the hours in an average year the wind will be from the northwest with a velocity of 13.0 mph or more."

The probability curves for only 6 wind directions are included in this report individually, but other directions are presented for reference. These have been taken from the hourly recording of wind speed and direction for the period starting March, 1950, and ending with February, 1955, some 43,800 entries. A wind-rose showing the percentage frequency distribution of winds is presented as Fig. 16. This plot is cumulative and can be read as in the following example. Considering SW winds, and referring to Fig. 16, we see that SW winds can be expected for approximately 8.6% of the time. Winds will be from the SW and will have a speed of between 0-3 mph for approximately 1.3% of the time, between 0-7 mph for 3.2% of the time, etc.

The orientation of the Port Sheldon Station and the surrounding areas is presented in Fig. 17. Various cities may be located with reference to the plant location and wind direction from this figure.

SEQUENCE OF PROCEDURES

The sequence of procedures used in obtaining the final results can be illustrated as in Fig. 18. For a given set of operating conditions involving stack height, wind direction, wind velocity, stack-gas velocity, and stack-gas temperature, a "run" can be made in the wind tunnel in which the plum behavior is photographed over the model. The stack-gas velocity and wind velocity are both reduced to a standard temperature of 70°F for the computation of the velocity-ratio (stack-gas velocity, V_s, to wind velocity, V_w) for the tunnel test. The resulting photograph for each run can be studied to determine the height of the plume corresponding to that particular velocity-ratio (R) and set of other operating conditions. A series of such runs for one stack height, wind direction, and operating stack can then be plotted as in Fig. 18(1), each velocity-ratio representing a different wind speed. The relation between the wind velocity and the stack-gas velocity can be represented as in Fig. 18(2) for any particular value of the stack-gas velocity. For instance, 90-fps stack-gas velocity at 240°F corresponds to a velocity of

$$V_s = V_s' \times \frac{T_{70}}{T_{240}} = 90\left(\frac{460 + 70}{460 + 240}\right) = 68.13 \text{ fps at } 70°\text{F} \quad ,$$

and since $R = V_s/V_w$, the plot of V_w vs. R can be made. To relate plume height P and V_w, a criterion of P must be established usually at a height sufficient to cause the plume to clear any obstruction by a suitable margin (P' as indicated in Fig. 18). If, for example, a plume height of P = 400 ft were desired, Fig. 18(1) would indicate that for this stack and wind direction, R = 3.3 would be critical and any value of $R < 3.3$ would result in a lower plume (therefore $R_{critical} = R_c = 3.3$). Figure 18(2) shows that, for a stack-gas temperature of 240°F and stack-gas velocity of 90 fps, $V_w = 14$ mph, corresponding to R = 3.3. Any wind velocity greater than 14 mph would result in a plume lower than 400 ft, and therefore $V_w = 14$ mph for this example is critical. A wind probability curve for this direction such as that illustrated in Fig. 18(3) enables the number of hours to be predicted when any particular wind velocity may be exceeded. For instance, in the example above $V_w = 14$ mph was critical. Figure 18(3) shows that the wind velocity would be in excess of this figure in this direction for about 3.7% of the hours per year. This would result in the plume being lower than our desired criterion of 400 ft for .037 x 8760 = 324 hours per year. Such a condition is called "downwash" in this report.

If a series of stack heights were tested, all other conditions remaining the same, a different number of hours of downwash might be expected from each stack height for the same plume criterion, P. These data could be presented as in Fig. 18(4) which shows that while stack height "a" might have resulted in 324 hours of downwash per year, stack heights b, c, and d might result in a fewer number of hours of downwash. It is understood that each stack height and operating condition must be duplicated in the wind-tunnel tests in order that curves similar to Fig. 18 may be drawn.

This report presents the tunnel data in Figs. 19 through 48 in the form of Fig. 18(1). Selecting Fig. 39 at random, we note that this represents winds from the NE, stack height of 350 ft. For a plume height of 400 ft, we note that $R_c = 3.00$. If $V_s = 90$ fps, then a $V_w = 68.13/R = 68.13/3 = 22.7$ fps is the critical wind velocity (22.7 fps = 15.5 mph). Figures 43-48 are cumulative curves showing the influence of stack height in modifying the relation between plume height and velocity-ratio for each of the several directions.

Probability curves from the meteorological data for winds from the NE, E, SE, SW, W, and NW are given in Figs. 7-15. Selecting the probability curve for NE winds (Fig. 12), it is noted that winds will equal or exceed 15.5 mph for some 0.27% of the hours per year, or for a total of $.0027 \times 8760 = 23.6$ hours. This is plotted in Fig. 54 for $V_s' = 90$ fps, 350-ft stack height and 400-ft plume height. Similarly, all the points in Figs. 49 through 54 have been plotted to describe the plume behavior for the various conditions of operation.

Table II is a useful conversion table for relating wind velocities with stack-gas velocities of 30, 60, 90, and 120 fps through use of the velocity-ratio (V_s/V_w) corrected to 70°F from the assumed stack-gas operating temperature of 240°F.

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 5 and 6 show two runs, one with satisfactory plume behavior and the other with the plume sweeping the ground. Some 400 such runs were required to complete the program. Whole velocity-ratios (1.0, 2.0, 3.0, 4.0, 5.0) were always run twice to provide a check on the accuracy of the work done. The other ratios (1.5, 2.5, 3.5, 4.5) were not repeated. Table II shows the relation between each velocity-ratio and the corresponding wind velocity in the field, when a stack-gas temperature of 240°F is assumed.

Since it was easier to change the stack-gas velocity than to change the wind velocity, a constant wind velocity of 8 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 sec, and one particular 2-sec interval was selected for the time exposure of the camera. Two seconds in the tunnel corresponds to a period of about 5 to 10 min at the plant site, depending on the

TABLE II

EQUIVALENT WIND VELOCITY IN FIELD, V_w AT 70°F
(Operating Conditions, V'_s at 240°F)

$V_s \div V_w$ at 70°F	$V'_s = 30$ fps		$V'_s = 60$ fps		$V'_s = 90$ fps		$V'_s = 120$ fps	
	fps	mph	fps	mph	fps	mph	fps	mph
1.0	22.71	15.48	45.42	30.97	68.13	46.45	90.84	61.94
1.5	15.14	10.32	30.28	20.65	45.42	30.97	60.56	41.29
2.0	11.36	7.75	22.71	15.48	34.07	23.23	45.42	30.97
2.5	9.08	6.19	18.17	12.39	27.25	18.58	36.34	24.78
3.0	7.57	5.16	15.14	10.32	22.71	15.48	30.28	20.65
3.5	6.49	4.42	12.98	8.85	19.47	13.27	25.95	17.69
4.0	5.68	3.87	11.36	7.75	17.03	11.61	22.71	15.48
4.5	5.05	3.44	10.09	6.88	15.14	10.32	20.19	13.77
5.0	4.54	3.10	9.08	6.19	13.63	9.29	18.17	12.39

Stack-gas temperature = 240°F

$$\text{Temperature conversion factor} = \frac{70 + 460}{240 + 460} = \frac{530}{700} = 0.757$$

$$\begin{aligned} V_s \text{ at } 70°\text{F} = V'_s \text{ at } 240°\text{F} \times 0.757 &= (30)(.757) = 22.71 \text{ fps} \\ &= (60)(.757) = 45.42 \text{ fps} \\ &= (90)(.757) = 68.13 \text{ fps} \\ &= (120)(.757) = 90.84 \text{ fps} \end{aligned}$$

$$\text{Mph} = V_s \text{ at } 70°\text{F} \times 0.68181$$

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wind velocity at the site. A 2-sec exposure was too long to show the instantantaneous 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 min at the plant site 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

Figures 19-48 show the results of the wind-tunnel tests and Figs. 7-12 show the wind probability curves for the six directions tested. The results of combining these two categories of information are summarized by the diagrams of Figs. 49-54 inclusive. In Figs. 49-54, the intermittent downwash in hours per year is plotted vertically and the stack-gas velocity is plotted horizontally. Each graph of Figs. 49-54 is for a particular stack height. A separate curve is shown for each of several plume heights above the station yard (elev. 600 ft) measured at points 4000 ft downwind from the plant. A constant stack-gas temperature of 240°F was assumed throughout the testing program.

Four diagrams are presented upon each of Figs. 49-54. Each of these represents a particular stack height of 350, 400, 450, or 500 ft and presents the hours of intermittent downwash for varying stack-gas velocities and plume-height criteria. Referring to Fig. 50, for example, which represents west winds, the following information is presented. Assuming that a plume height of 300 ft above the base of the stack is to be considered and a stack-gas velocity of 60 fps is desirable, for a stack height of 350 ft an intermittent downwash of about 620 hours is predicted. If the stack height were increased to 450 ft, other criteria remaining the same ($P = 300$ ft, $V_s = 60$ fps), the intermittent downwash to be expected would be about 400 hours. An increase of stack-gas velocity to 120 fps results in a downwash of some 170 hours for a 350-ft stack or 30 hours for a 450-ft stack height using the same plume height of 300 ft as a criterion. Combinations of stack height, stack-gas velocity, and plume height can thus be evaluated. Indicated on the figures is the total number of hours that winds can be expected for the given direction on a yearly basis, in the case of west winds, 957 intermittent hours. Figures 49 and 51-54 similarly allow evaluation for winds from the NW, SW, SE, E, and NE, respectively.

It is again to be noted that the plume height as indicated in the foregoing figures refers to height to the bottom of the plume above the station yard. It is significant that winds from the east and northeast carry the plume across the sand dune which itself, in places, is as much as 190 ft above the station yard. The actual clearance of the plume above the ground is therefore dependent upon the ground elevation beneath it. For the wind directions studied, this is not particularly significant except for the NE and E winds since the terrain is essentially flat for all other directions and the plume height as recorded is approximately equal to the clearance. Reference should be made to Figs. 2 and 18 for further clarification of this point.

Figures 19-48 show the behavior of the plume from wind-tunnel data and indicate the plume height from a given stack at an equivalent distance downwind of 4000 ft from the stack with varying velocity-ratios. Composite curves for different stack heights are shown in Figs. 43-48. The composite curves show the influence of increasing the stack height upon the plume behavior. These curves serve as a basis for this report as previously indicated, and may also be used as a starting point for the computation of the ground concentration of SO_2 if it is later decided to proceed with Part B of the overall studies of stack-gas plume behavior.

Downwash is the condition wherein the bottom of the plume has been forced down below some height which has been selected as a desirable minimum, based on the size of the obstructions to be cleared and a reasonable allowance for atmospheric diffusion. The word "intermittent" is used because, within any hour having an average velocity of a particular value, there will be portions of the hour when the velocity will be below that value, and downwash may not occur. Consequently, the indicated number of hours of downwash is on the pessimistic side since some of the hours will not include 60 min of downwash. It is not possible to say by what margin it is pessimistic since the conditions under which a particular average may be obtained vary so widely.

It should be noted also that the indicated number of hours will not be consecutive. It is possible to analyze the meteorological records to determine the probable number of consecutive hours in each case of downwash. This was done on one project in the midwest United States and it was predicted that the duration of the cases would vary from 1 to 15 hours, with an average of 2.8 consecutive hours.

The results are further pessimistic because, in reality, the flotational effect of the hot gases will increase the clearance of the plume above the terrain. However, it should be repeated that this is true only under those conditions wherein the plume has succeeded in escaping the turbulence created by the buildings or by the terrain and is free to respond to the flotational forces.

In conclusion, it may be stated generally that:

(a) higher stacks improve the behavior of the plume;
(b) higher stack-gas velocities improve the behavior of the plume;
(c) the introduction of additional building masses modifies the behavior of the plume because of the deflection of greater masses of air and because of the introduction of greater or lesser degrees of streamlining, and it is possible that in a few situations the addition of a building mass may result in better plume behavior rather than worse behavior;
(d) the downwash of the gas within any hour may be intermittent because of the way in which the averages are taken; and
(e) the hours of downwash are not always consecutive.

The magnitude of the influences under items (a), (b), and (c) are shown by the respective diagrams, but those under items (d) and (e) have not been evaluated.