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Final Report (Part I)

BEHAVIOR OF THE STACK GAS PLUMES AT THE MERAMEC PLANT

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Project 2491

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SUMMARY

Tests were performed in the wind tunnel to study the behavior of the gas plumes from the stacks of the present Units 1 and 2, and also the proposed Units 3 and 4 of the Meramec steam-electric generation plant. A model to the scale of 1:600 was used, so designed as to include the plant and the terrain for a distance of 7200 feet downwind and a distance laterally of 2400 feet on each side of the plume. Only one wind direction was studied, namely, winds blowing from the SW and carrying the plume into the area northeast of the plant and parallel to the bluffs along the Mississippi River.

The wind-tunnel results were correlated with a five-year sample of the wind records taken by the U. S. Weather Bureau at Lambert Field Airport. The number of hours per year, during which the bottom of the plume would be below each of several selected heights above the hills, is shown in the form of graphs. A stack-gas temperature of 280°F was used in combination with (1) 60-, 90-, and 120-fps exit velocity for the stack gas, (2) 250- and 300-foot stack heights for Units 1 and 2, and (3) 300-, 350-, and 400-foot stacks for Units 3 and 4. The results are shown in Figs. 6 to 22, inclusive.

INTRODUCTION

Part I of this report gives the results of a study of the behavior of the stack-gas plumes at the Meramec Plant of the Union Electric Company of Missouri, St. Louis, Missouri. Correspondence concerning the possibility of air-pollution studies originated with a letter dated November 28, 1955, from Mr. John K. Bryan to Professor E. Wendell Hewson. He replied in a letter of December 5, in which he included a brief outline of investigations which might be undertaken.

Part II of the report contains additional discussion of the methods used and of their basis and limitations.

A conference was held in St. Louis on December 20 and 21 between representatives of the Company and Professors Hewson and Sherlock. At that time a visit was made to the Meramec Plant and to the area lying to the north and northeast of the plant.

Following a visit to Ann Arbor by Mr. Bryan on January 24, 1956, a program of wind-tunnel studies was outlined and sent in a letter from Professor Sherlock to Mr. Bryan under date of January 25, 1956. A proposal to conduct the study was sent by the Engineering Research Institute of The University of Michigan to the Union Electric Company on January 26, and approved by the Company on February 9, and by the Regents of The University of Michigan on February 28.

Additional conferences for the purpose of observing and discussing the progress of the work were held in Ann Arbor with Mr. Bryan on April 2 and May 7, and with Mr. J. F. McLaughlin on April 2.

This report correlates the information which was obtained in the wind tunnel with the wind history as obtained by the U.S. Weather Bureau at the Lambert Field Airport. Observations were made in the wind tunnel for the wind blowing from the S40°W. This wind carried the plume into the area N40°E of the plant along the bank of the Mississippi River. However, the wind history from Lambert Field has also been worked up in the form of probability curves for all 16 points of the compass and are appended to this report.

PROGRAM

The program contained in the letter of January 25, 1956, and referred to in the proposal dated January 26, was as follows:

1. Make a study of the wind history in the area, from data obtained from the U.S. Weather Bureau at the St. Louis Airport over a period of four or five years. Construct curves showing the probability of occurrence of various wind velocities from each of the eight given directions. If it is necessary to use more recent information, the data will be furnished by the Weather Bureau for each of 16 directions of the compass.

2. Design and make a model of the plant and nearby buildings, including the present Units 1 and 2 and the future Units 3 and 4, together with the terrain lying in the area to the N40°E for a distance of 7200 feet. This will fit into the working section of the tunnel which is 8 feet wide and 14 feet long. A scale of 1:600 will be used. In designing and making the model, provisions shall be made to test the behavior of the gas plume in a direction north of the plant in case this should later prove to be desirable.

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 within the next week.

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

6. Work up the data into tables and diagrams.

7. Compile a formal report.

THE PLANT AND ITS SITE

The assembly drawings of the plant, and its location on the company property, were furnished by the Union Electric Company. They also furnished topographic maps showing contours of the terrain, as published by the U.S Department of the Interior, Geological Survey, as well as aerial photographs of the terrain lying to the north and northeast of the plant. The area of the geological survey map showing the terrain which was to be included in the tunnel model was photographically enlarged to approximately 7 inches x 12 inches and this in turn was traced so as to bring out the topographic contours, as shown in Fig. 1. This tracing was enlarged by a mural process, to the size of 8 feet x 14 feet which is the size of the working space of the tunnel. 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 of an inch in the length or width.

Conferences with the representatives of the Union Electric Company had indicated that the area of greatest interest was that which would be affected by winds from the southwest. An inspection of the geological survey map narrowed the direction down to S40°W. This direction was accordingly used as a centerline of the tunnel and the model was laid out to include 4 feet on each side of this line in the tunnel 2400 feet on each side of the line in the field. The model of the terrain was built up with masonite boards, with each thickness of masonite corresponding to a change of elevation of 10 feet. This is shown in Fig. 3 which is a view in the wind tunnel looking toward the plant from the direction of N40°E, that is, with the wind blowing from the S40°W.

It is expected that eventually there will be 4 units with a total capacity of 840,000 kilowatts. At present there are two units of 140,000-kilowatt capacity each, with each unit having its own steel stack with an exit velocity of 90 fps and with provision for an extension of 50 feet to the stacks in the future if this proves desirable. These are known as Stacks 1 and 2. Stacks 3 and 4 will each serve a unit of 280,000 kilowatts and one of the principal purposes of this project is to furnish information which will serve as a basis for the choice of stack height and exit velocity of the stack gases.

The testing program was as follows:

Scale of model—1:600
Wind direction—from S40°W
Stack-gas temperature—280°F
Stack-gas velocities tested—60, 90, and 120 fps

Series A tests:	Units 1 and 2 operating—Stack height 250 ft
Series B tests:	Units 1, 2, and 3
	Stack height for 1 and 2 = 250 ft
	Stack heights for No. 3 = 300 ft, 350 ft, and 400 ft
Series C tests:	Units 1, 2, 3, and 4
	Stack height for 1 and 2 = 250 ft
	Stack height for 3 and 4 = 300 ft, 350 ft, and 400 ft

The detail drawings for the model of the plant were each 24 inches x 36 inches. An assembly drawing of the same size shows the arrangement of the model and testing equipment in the wind tunnel. Copies of these drawings may be obtained from the authors of this report.

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 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 orientation of the station building with respect to the wind is shown in Fig. 4. The scale of the model (1:600) was selected to give a sufficient coverage of the terrain to insure representative test results. The selected portion of the geological survey map was enlarged photographically and traced as Shown in Fig. 1 to bring out the topographic contours and other significant features of the terrain. The tracing was then used to make mural-type photographs 5 feet wide by 15 feet long. These were glued to plywood and the enclosing rectangle, including the building and stack locations, were drawn to scale on the mural. Ten-foot contour lines were interpolated between the twenty-foot contour lines of the geological survey map, already shown in Fig. 2. Construction of the model contours was made by stacking 3/16-inch masonite boards which had been cut to the topographic contour lines. The photograph of the completed model in the tunnel is shown in Fig. 3. Residences, farm buildings, and trees were not represented in the model since they were considered to be of minor aerodynamic importance in a model of this scale. The model was made in small sections, most of which were rectangular, and of such size that the handling in the tunnel was facilitated.

The smoke plume was photographed through plate-glass windows against a grid on the far side of the tunnel and with an exposure of one second. The grid is shown in Figs. 3, 3(a), and 3(b). It served as a reference for the measurement of the height of the plume above the river. The geological survey map showed that the highest hill has an elevation of approximately 580 feet, thus making it necessary to deduct 200 feet from the readings on the grid in order to obtain the height by which the bottom of the plume cleared the top of the hill. In order to obtain the height of the plume above the highest hill, for example, it was necessary to deduct the 200-foot height of the hill above the river level, as indicated in Fig. 5.

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.

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 "down-wash" 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(a) shows a free-flowing plume which occurs with a high stack-gas velocity in a light wind, and Fig. 3(b) 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 gases low enough so that they penetrate the vortex sheath over the turbulent air above and beyond the building, 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. 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. 3(b) where the "tails" appear as the hazy area on the bottom of the plume as it approaches the hill. 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, 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.

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 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 280°F would have the same plume behavior as one operating with a gas velocity of 43 fps at 70°F. The accompanying wind velocity at 70°F would be 21.5 fps (14.7 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 United States Weather Bureau from records taken at Lambert Field Airport in St. Louis, Missouri. The weather bureau records are divided into sixteen 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. 33 to 48, inclusive. The weather data are shown as small circles 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 southwest winds, which are significant on this project, are shown in Fig. 43. 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 15.7 mph or more."

The probability curves for all 16 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. 5. 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. 5, which is merely illustrative and not based on actual data. Here the wind is shown to be from the southwest, the stack is 300 feet high, and the height of the plume for various velocity-ratios is shown by one dot for each wind-tunnel observation. Diagrams based on actual data are shown in Figs. 23

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 280°F					
	V_s' = 60 fps		90 fps		120 fps	
	fps	mph	fps	mph	fps	mph
0.5	86	58.7	129	88	172	117.4
1	43	29.3	64.4	44	86	58.6
1.5	28.7	19.6	43.1	29.3	57.4	39.2
2	21.5	14.7	32.2	22	43	29.4
2.5	17.2	11.7	25.8	17.5	34.4	23.4
3	14.3	9.8	21.5	14.7	28.6	19.5
3.5	12.3	8.4	18.5	12.6	24.6	16.8
4	10.8	7.4	16.2	11.1	21.6	14.8

V_w = Wind velocity, fps at 70°F

V_s = Stack-gas velocity, fps at 70°F

V_s' = Stack-gas velocity, fps at 280°F

$$V_s \text{ at } 70°F = (V_s' \text{ at } 280°F)\ \frac{70 + 460}{280 + 460}$$

$$= 60 \times 0.716 = 43 \text{ fps}$$

$$\text{and } V_w = \frac{43}{V_s \div V_w}$$

to 32, inclusive. Figure 23 may be used for purposes of illustration. It is based upon wind-tunnel readings for 250-foot stacks, with Stacks 1 and 2 operating and with Units 1 and 2 in place (but not Units 3 and 4). The readings of the height to the bottom of the plume were made at a distance of 6000 feet downwind from the stacks. The diagram in Fig. 23 should be read as follows:

"In order to maintain the bottom of the plume at a height of 200 feet, it will be necessary to use a velocity-ratio of 3.25."

The critical velocity-ratio is thus said to be 3.25 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 200 feet. For example, if the stack-gas velocity is 64.4 fps at 70°F (equivalent to 90 fps at 280°F) and the critical velocity-ratio is 3.25 for P = 200 feet,

$$V_W = \frac{64.4}{3.25} = 19.8 \text{ fps}$$
$$= 13.5 \text{ mph.}$$

The critical wind velocity is 13.5 mph, and any velocity greater than that will drive the plume below 200 feet within a distance of 6000 feet downwind from the stacks. The manner of obtaining the values of 64.4 and 19.8 fps is shown in Table II.

Having obtained the value of the critical wind velocity, (19.8 fps = 13.5 mph) it is then necessary to turn to the probability curve of Fig. 43, from which it will be possible to pick out the percentage of hours of the year (0.99 percent = 86.7 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 (200 feet) for which the critical wind velocity was obtained. This is illustrated in Diagram (3) of Fig. 5.

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, (86.7 hours) as shown in Diagram (4) of Fig. 5.

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 the plume sweeping the tops of the hills. One hundred eighty-nine such runs were required to complete the program. 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 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

The results are summarized by the diagrams in Figs. 6 to 22, inclusive. In Figs. 6 to 19, inclusive, the intermittent downwash in hours per year is plotted vertically and the stack-gas velocity is plotted horizontally. A separate curve is shown for each plume height above the top of the hill. In Figs. 20, 21, and 22 the hours of downwash are plotted vertically and the stack height horizontally, with a separate curve for each of several plume heights. In all cases a constant gas temperature of 280°F was used.

In Fig. 6, Stacks 1 and 2 were operating with a height of 250 feet and with only the present plant (Units 1 and 2) in place. It will be seen that if it is desired to maintain the bottom of the plume at a height of 200 feet above the hill, there will be about 260 hours per average year when the wind velocity will be such that the plume will be lower than 200 feet. This is based on the assumption that the plant will be operating for an entire year at 60-fps exit velocity. If it is assumed that the plant will be operating for the entire year with a stack-gas velocity of 120 fps, there will be only about 20 hours per year when the plume will be lower than 200 feet, and zero hours per year when the plume will be less than 100 feet above the hill. All of this applies to the area northeast of the plant in the 22.5° segment of the compass, since these data refer to SW winds only.

In Fig. 7 the same conditions prevailed except that Unit 3 with its building and stack had been added. Stacks 1 and 2 were still the only ones operating. All other conditions were the same. It will be seen that if a stack-gas velocity of 60 instead of 120 fps is used, the hours per year when the plume will be below 100 feet will be increased from about 40 to about 330,