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Final Report (Part II)

BEHAVIOR OF STACK-GAS PLUMES AT THE TUFTS COVE PLANT

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APPENDIX

This Appendix constitutes Part II of the Final Report on this project and contains more extensive discussions of some aspects of the investigation than were considered necessary in the main part of the report (Part I). The subjects which are included here are as follows:

A. Uncontrolled Influences
  1. Use of Air Instead of Gas
  2. Cold Gas vs Hot Gas
  3. Atmospheric Temperature
  4. Barometric Pressure
  5. Humidity
  6. Variation of Wind Velocity with Height
  7. Summary of Uncontrolled Influences
     Figs. A1 to A6
     Table A1

B. Similarity Between Model and Prototype
  1. Stacks
  2. Buildings
  3. Terrain
  4. Field Observations

C. Velocity-Ratio

D. Frequency and Duration of Intermittent Downwash
     Fig. D1
     Table D1

A. UNCONTROLLED INFLUENCES

There are several conditions at the station which it is not feasible or desirable to duplicate in the wind tunnel and which have been ignored in these tests. Nevertheless, their influences are discussed here to indicate that the errors thus introduced, as listed in Table A1, are not of such magnitude as to vitiate the results of the test and, in general, that they tend to be compensating. The uncontrolled influences are (1) the use of a mixture of air, water-vapor, and oil-vapor instead of a typical stack gas; (2) the use of a cold instead of a hot mixture in simulating the stack gases; (3) the difference between the temperature of the air at the station and that in the tunnel; (4) the difference between the barometric pressures at the station and in the tunnel; (5) the difference in humidity at the station and in the tunnel; (6) the wind velocity varies with height in the free atmosphere but not in the tunnel.

1. Use of Air Instead of Gas.—If air alone were used instead of a typical flue gas, the pressure and temperature remaining the same, the air would be about 3.25% lighter and would therefore have about 3.25% less momentum at the same velocity. It would, however, have a greater flotational effect on the gas. It is not known how much the oil- and water-vapors affect the density of the mixture, but the effect is assumed to be small. It will vary slightly with the temperature of the smoke-generating furnace. The use of the mixture instead of a typical stack gas overestimates the downwash when momentum effects are being considered, and underestimates it when flotational effects are considered, but by a small amount in each case.

2. Cold Gas vs Hot Gas.—On the basis of experience with wind-tunnel models on earlier projects, it had been decided to work with stack gases having the same temperature as the air in the wind tunnel. Controlling the temperature of the stack gases had been found to be a complicated, expensive, and time-consuming process, and one which was not necessary after it had been found that the ratio of the unit momentum of the stack gas to that of the passing wind was a satisfactory parameter with which to characterize the behavior of the gas plume.

There are three regimes of flow which need to be considered in discussing the question of the use of cold gas rather than hot gas in conducting these experiments. The first is that in which the gas has been entrapped in the turbulence of the stack and building and has been brought to the ground. Here the flotational effect of high temperature is useless since the downwash has been completed.

The second regime of flow is that in which the plume has succeeded in escaping the adverse eddies at the tip of the stack and is proceeding in an orderly way downwind. In this regime the plume is free to respond to the flotational forces and to rise to a greater height than would be the case under the influence of the wind and stack-gas velocity alone. The temperature of the plume decreases rapidly due to the diffusion in the ambient atmosphere but the flotational effect of the high temperature is not entirely lost because, although the temperature of the gas plume decreases rapidly, the over-all heat content of the mixture of gas and air is not reduced. The theoretical rate of rise can be computed but, as in the case of idealized diffusion, the basic assumptions are only a rough approximation to nature. Nevertheless, the present theory is the best basis available for determining the additional rise of the plume due to flotation. In this regime of flow there are, then, three influences acting upon the plume, namely, (a) aerodynamic forces, which determine the conformation of the streamlines as the wind is deflected over and around the stacks and building; (b) stack-gas velocity, which adds height to the plume; (c) flotational forces, which add height to the plume. These influences cannot be expressed as linear functions, and their effects, determined separately, are not additive, except as a first approximation.

The third regime of flow is that in which downwash is impending, that is, when the bottom of a plume is below the top of the stack, and all or part of the plume is becoming entrapped in the eddies at the top of the stack. Figure A1 shows results of tests which were conducted in December, 1934. At that time, the photographic method of recording results was not being used but hydrogen sulphide was being used as a tracer as described in Engineering Research Bulletin No. 29, University of Michigan, March 1941, entitled "A Study of Flow Phenomena in the Wake of Smokestacks," Fig. 8, pages 19 through 23. The diagram shows that, in the regime of flow when downwash is impending, the behavior of the plume, within the limits of experimental error, depends only on the velocity-ratio and is independent of gas temperature. This is because the flotational forces are so small, compared to the aerodynamic forces of the adverse eddies. These data, from Project 885, which have not previously been published, are for a range of temperatures from 68° to 285°F. The adverse influences at work in this case are the aerodynamic forces generated by the wind as it passes the stack. Meteorological effects were, of course, not operating in the wind tunnel. However, these aerodynamic forces are capable of bringing the gases to the ground, or to the vortex sheath over the building, and it is with aerodynamic effects that this report is concerned.

Further evidence of the small effect of temperature, in enabling the stack gas to escape adverse aerodynamic forces generated by the stack in the wind, was obtained by replotting in Fig. A3 the data from Fig. A2. The latter figure was originally shown as Fig. 18, in Engineering Research Bulletin No. 29. In Fig. A3 the downwash in stack diameters is plotted against the ratio of stack-gas velocity to wind velocity. The true velocity of the hot gases was reduced to an equivalent velocity at 70°F, which is assumed to be the temperature of the wind tunnel.

It will be seen in Fig. A3 that the wide dispersion of points in Fig. A2 has been reduced to a narrow band with two envelopes, and that the cold gases give points near the right envelope and the hot gases give points near the left envelope. In other words, for a given velocity-ratio there is less depth of downwash of the hot gases than of the cold gases. For example, for a velocity-ratio of 0.5, the range of downwash is between 2.5 and 5.5 stack diameters below the top. This is an extreme range of 3.0 stack diameters, an advantage which may be attributed to the flotational forces of the hot gases. The cold gases have only their momentum as a favorable influence to start them upward against the adverse aerodynamic forces of the eddies generated by the stack. The hot gases have both momentum and flotation. This range can be reduced somewhat if the envelopes are drawn through the average positions of the

400°F points on the left and of the 70°F points on the right, thus making some allowance for experimental errors. This is shown in Fig. A4.

This range of about two stack diameters is a margin of safety when cold gases are used in the test. However, it would not be safe to rely upon it since it was measured at very low velocity-ratios where the downwash was well established. There is less difference between the downwash of the hot and cold gases in the upper part of the diagrams, that is, in the region where downwash is impending or has little depth below the top of the stack. There is also strong evidence of a change of regime in passing from the condition of downwash to that of free flow. It may be concluded that, after the plume has come under the influence of the eddies at the tip of the stack, the flotational effect of hot gases upon downwash is less than two stack diameters and that it is on the side of safety to ignore it, provided, of course, that the downwash is expressed as a function of the ratio of stack-gas velocity to wind velocity, with temperatures being the same for both of them.

3. Atmospheric Temperature.—When the air in the tunnel is warmer than at the station, it is lighter and the momentum per cubic foot is less for the same wind velocity. The model will thus underestimate the downwash at the station. An extreme condition would exist if the air temperature in the tunnel were 70°F and that at the station - 10°F. The momentum of the wind per cubic foot would then be 1.18 times as great in the field as in the tunnel. Relatively high winds are the cause of the most severe downwash, and these occur more frequently in cold seasons than in warm seasons; this effect will therefore be adverse more frequently than favorable. It will therefore tend to use up at least some of the margin of safety which is always created under Item 2.

4. Barometric Pressure.—The air density, and consequently the momentum of the wind per cubic foot at any fixed velocity, varies with the barometric pressure. If it were assumed that the barometric pressure in the air could change without affecting the pressure of the emerging gas jet, then it could be said that the test would underestimate the downwash at the station during periods of high barometer. But the difference between the air pressure and the gas pressure at the top of the stack would always be small or nonexistent. Furthermore, high winds occur most frequently during low, but rising, barometer, and the maximum change in density will ordinarily not exceed two percent. In addition, the manner of making the wind-velocity measurements in the tunnel and in the field automatically corrects for differences in barometric pressure.

The wind velocity in the tunnel was measured by a standard Pitot-static tube. The calibration of this instrument is such that it does not indicate the true velocity but rather that velocity which, in a standard atmosphere, would produce the same pressure in the manometer. The standard atmosphere has a temperature of 15°C (59°F) and a barometric pressure of 760 mm of mercury (29.92 inches, sea level). The Pitot-static tube measures the velocity head (impact pressure), the value of which is expressed by the formula

$$q = 1/2 \rho V^2 ,$$

where ρ is the density and V is the velocity of the air. It is evident that a constant value of impact pressure will indicate a constant value of velocity only in those cases in which the density is constant. Since the density is affected by changes in temperature and barometric pressure, it is not convenient to compute its value for each set of pressure readings and thus to obtain the true value of the wind velocity. It is more convenient to assume a standard value for the density and thereby to obtain the value of wind velocity which would produce the same pressure in a standard atmosphere.

The U. S. W. B. wind-velocity records were obtained with either cup-anemometers or propeller-type anemometers, and both of them have been calibrated against standard Pitot-static tubes. The field records of velocity may, therefore, be assumed to be reduced to standard atmosphere.

5. Humidity.—The wind tunnel is located in the basement of a large building with forced-draft heating, so the air was usually quite dry. The mixture of air, water-vapor, and oil-vapor, which was used to simulate the stack gases, may be considered to be more moist. Since the density of humid air is less than dry air, it may be said that the momentum effects are such as to cause the tests to overestimate the downwash at the station.

6. Variation of Wind Velocity with Height.—No correction has been applied to the wind records, either on the basis of the vertical velocity gradient in the field, or that in the wind tunnel, or because of the difference between the two gradients. The Pitot-static tube, which was used in the wind tunnel to measure the wind velocity, was placed about 12 inches below the ceiling of the tunnel, as shown in Fig. A5. This corresponds to several hundred feet above the ground. The anemometer at an airport is usually placed at an elevation between 30 and 40 feet above the ground. According to the one-seventh-power theory, which is widely used for the wind-velocity gradient in the free atmosphere, the velocity at the upper level would be about 45% greater than at the lower level, as shown in Fig. A5. However, these relations are based on the fluid drag which accompanies the eddy viscosity found in the free atmosphere, whereas the drag of the floor and walls in the tunnel is based on a relatively finer eddy texture and the increase of velocity is correspondingly more rapid. Surveys of the tunnel velocities have shown that the wind velocity is practically constant over the entire area of the tunnel in the absence of the model, except in the boundary layers at the walls, roof, and floor. These layers are only about one inch thick, and it is therefore certain that the wind velocity at the Pitot tube and at the 30-foot level of the model is practically the same.

Figure A5 also shows the streamlines which would exist at each 100-foot increment of height, based upon theoretical considerations in a perfect gas, if the plant were of indefinite extent at right angles to the flow of the wind. Of course, these streamlines must be considered as merely a first approximation to the conditions which actually occur in the field since the atmosphere is not a perfect gas and possesses viscosity and turbulence of its own, and the plant is not of indefinite extent across the wind. Some flow will always take place around the building as well as over it. The streamlines in the left half of the diagram, that is, the upwind half of the diagram, follow the theoretical considerations given by H. Glauert, Elements of Aerofoil and Airscrew Theory, University Press, Cambridge, England, 1930, pages 23 and 24 (see Fig. A6). The height of the anemometer is indicated in the diagram by a small circle, and the height of the stack (400 feet in Fig. A5) is likewise so indicated. The accompanying wind velocities are shown to be V_1 and V_2, respectively. If the velocity at the Pitot tube is V_1, this will likewise be the velocity at the 30-foot level in the tunnel, but the undisturbed velocity in the field at the 400-foot level will be $V_2 = 1.45\ V_1$ according to the one-seventh-power law. The question arises, is there some other height than 30 feet which will better characterize the flow over the building and which will, therefore, be a better criterion to which downwash can be referred? The theoretical increase of velocity from 30 to 400 feet would be about 45%. If this higher level were chosen, or any other higher level, then all U. S. W. B. wind-velocity records would have to be multiplied by some factor (1.45 at 400 feet) to give the corrected velocity. For example, on one project, when the wind was blowing from the north the critical velocity was 21.8 mph, and downwash would be produced by any velocity which is equal to or higher than this value. The probability curves for the wind velocity in that area showed this to give 0.0015 x 365 x 24 = 13 hours of downwash per year. If, however, the wind records were corrected to 400 feet instead of 30 feet, then every reading of the velocity scale of the probability curve would need to be multiplied by 1.45, and the probability of occurrence would be increased by reference to the new curve.

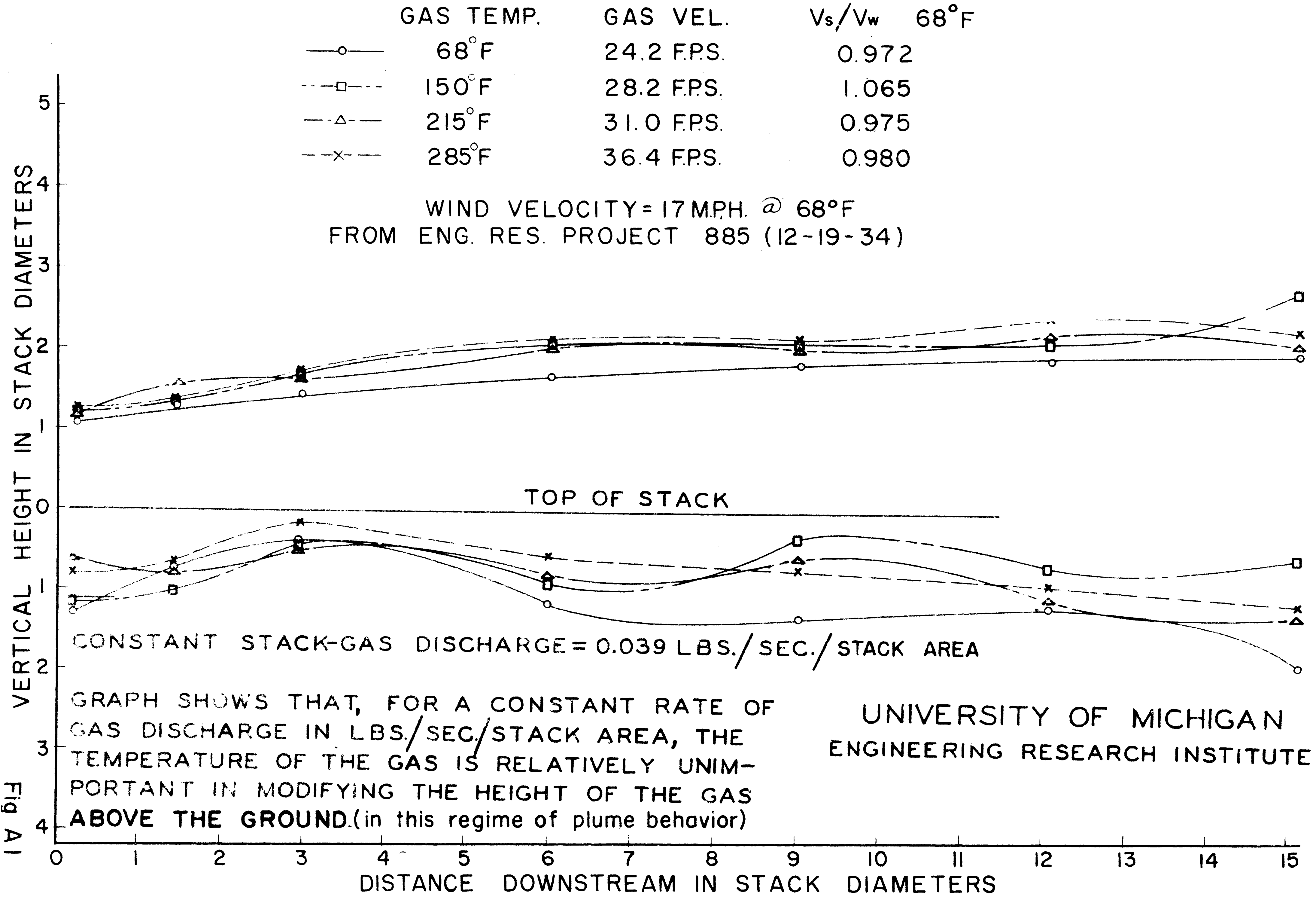
However, the disturbance to the flow in the field is caused mostly by deflection over and around the building rather than at the top of the stack or at any other one height. This effect is different for different wind directions and for different stations, and there is no basis for a refined choice of one height more than some other one, except that an inspection of the streamlines in the diagram shows that the undisturbed wind velocity at 400 feet is undoubtedly too high to characterize the wind which blows over and around the building and 30 feet may be somewhat too low. If 100 feet were chosen as the proper reference height at that station, the velocities would be 19% higher than at 30 feet, and the hours of downwash would need to be changed to 0.0023 x 365 x 24 = 20 hours instead of the 13 hours when 30 feet is used as a reference height.

The only satisfactory way to correct for the variation of wind velocity with height would be to change the velocity gradient in the tunnel so that, to the scale of the model, it agreed with the assumed gradient in the free atmosphere. Of course, the gradient in the free atmosphere changes with meteorological conditions. During a temperature inversion the atmosphere becomes very stable and mixing between the upper and lower layers of the air is suppressed. When the change of atmospheric temperature with height follows the adiabatic law, the atmosphere is thermodynamically neutral, and the streamline flow may be modified either upward or downward according to the aerodynamic forces which may be imposed upon the parcels of flowing air. When the rate of change of temperature with height exceeds the adiabatic lapse rate, the atmosphere is thermodynamically unstable and there is active vertical mixing of the horizontal layers. This meteorological condition promotes diffusion and may result in the stack gases of the plume being brought to the ground. The conditions in the wind tunnel simulate most closely the neutral thermodynamic condition wherein the plume is free to respond to the aerodynamic forces without modification from thermodynamic forces.

Satisfactory techniques for changing the velocity gradient in the tunnel have not been developed. Even though devices are used which cause the wind to enter the working section of the tunnel with the desired vertical velocity gradient, this gradient would not be maintained throughout the length of the working section, even in the absence of the model. The wind would tend to resume the uniform velocity throughout the cross section of the tunnel since this is the condition imposed by the boundary conditions within the working section. Even in the absence of the model it would be necessary to insure vertical mixing which would be compatible with the vertical velocity gradient. This would be very difficult with the model in the tunnel, and it is not at all certain that the results obtained would really approximate the velocity gradient in the field. This additional control was therefore not attempted.

The effect of ignoring this uncontrolled influence is probably to underestimate the frequency of downwash. The error is larger when the wind is blowing at right angles to the long axis of the building than when it is blowing along a diagonal of the building. It would not affect conclusions regarding the relative merits of different shapes of the building, or of different combinations of stack height and gas velocity.

7. Summary of Uncontrolled Influences.—Table A1 shows each of the uncontrolled influences with an indication of the effect upon downwash. If the effect of ignoring the influence was to overestimate the frequency of downwash, then it was considered to be an error on the side of safety and therefore favorable. But if the effect was to underestimate the downwash, it was considered to be adverse. It will be noted that there are 5 favorable and 5 adverse influences, and that the major effects tend to be compensating.



GRAPH SHOWS THAT, FOR A CONSTANT RATE OF GAS DISCHARGE IN LBS./SEC./STACK AREA, THE TEMPERATURE OF THE GAS IS RELATIVELY UNIMPORTANT IN MODIFYING THE HEIGHT OF THE GAS **ABOVE THE GROUND.** (in this regime of plume behavior)

Fig A1

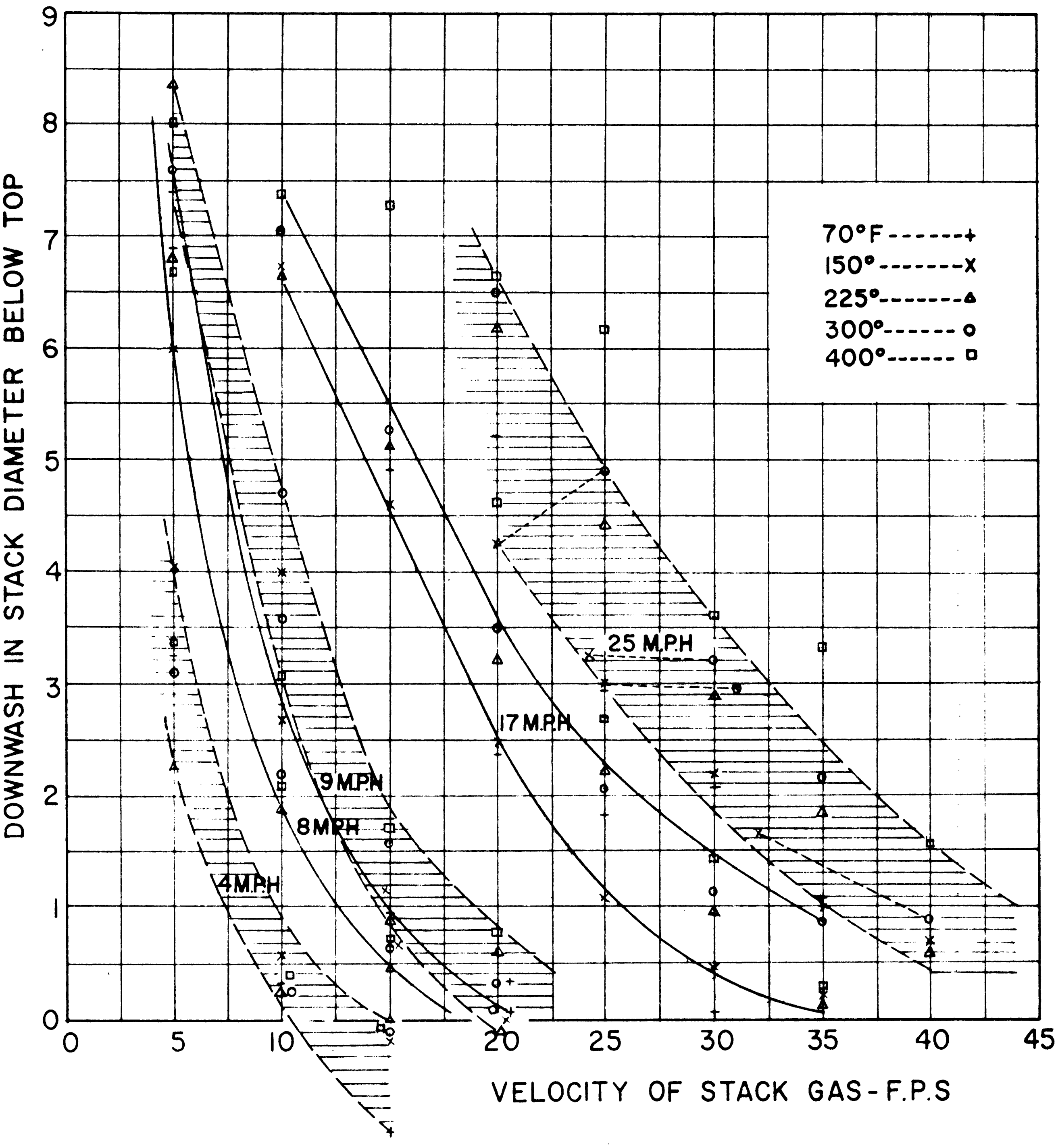
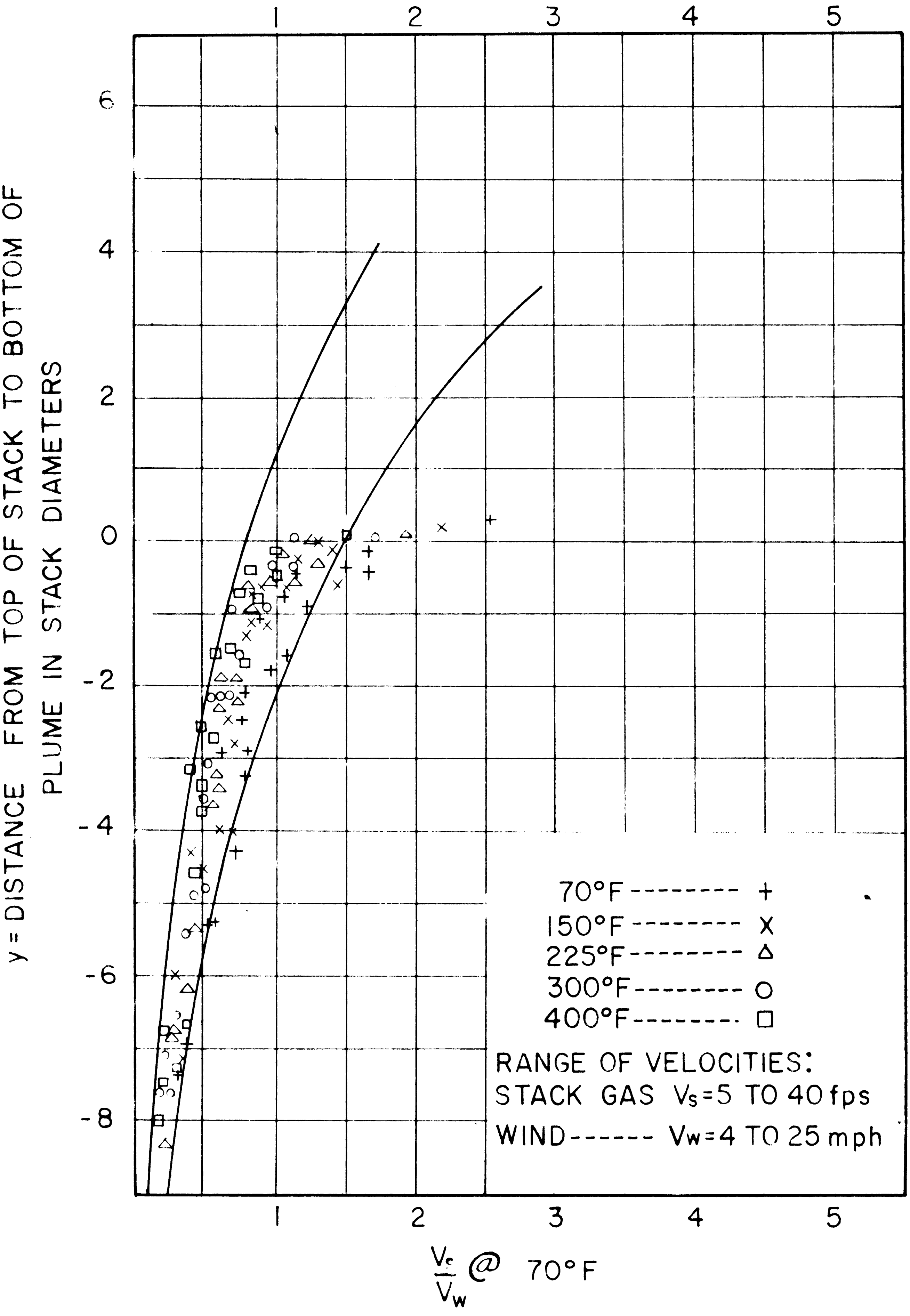
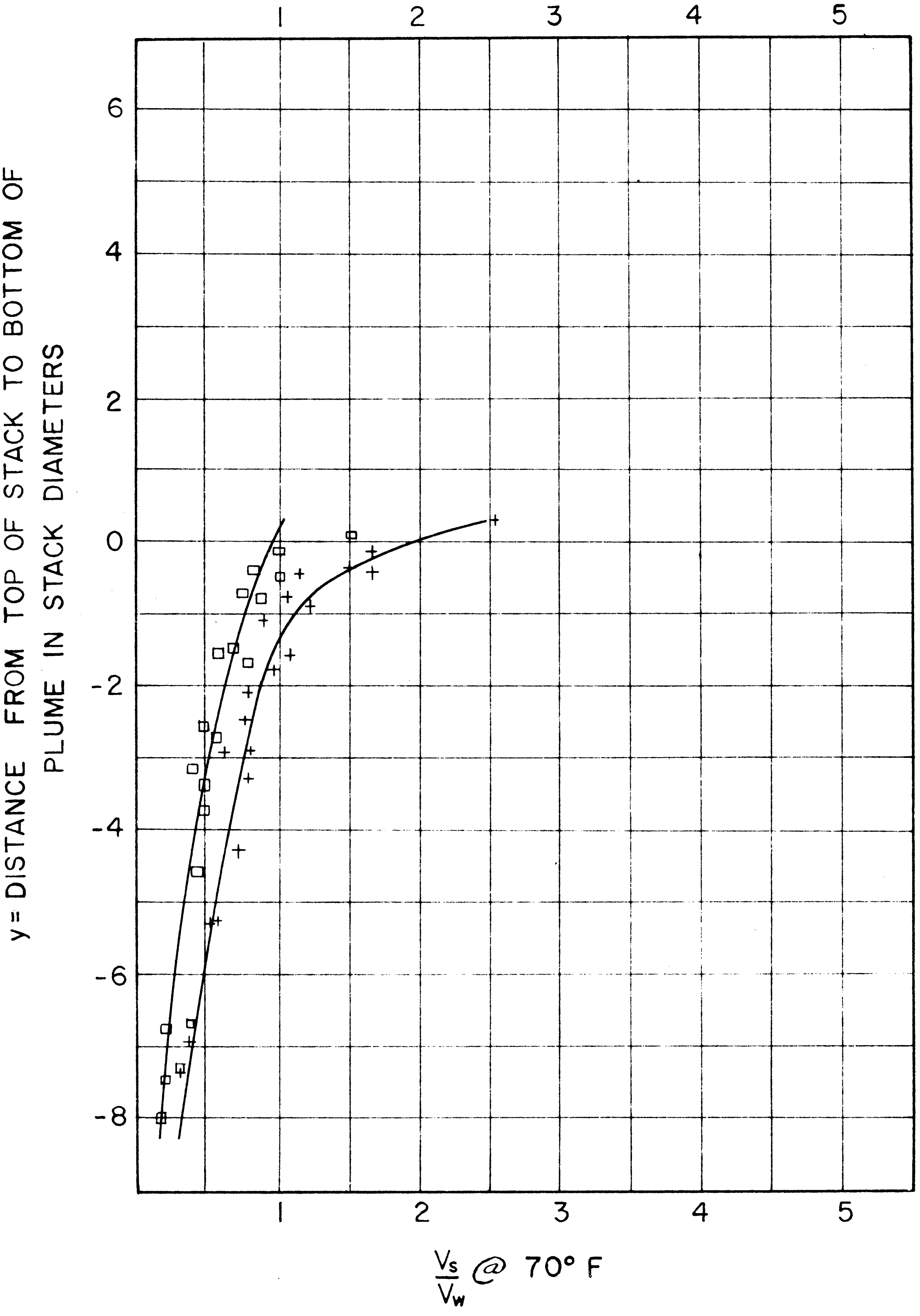

DOWNWASH IN STACK DIAMETER BELOW TOP
VELOCITY OF STACK GAS - F.P.S
0
1
2
3
4
5
6
7
8
9
0
5
10
15
20
25
30
35
40
45
70°F ------ +
150° ------- X
225° ------- ▲
300° ------ o
400° ------ ◘
4 M.P.H
8 M.P.H
9 M.P.H
17 M.P.H
25 M.P.H

Fig A2



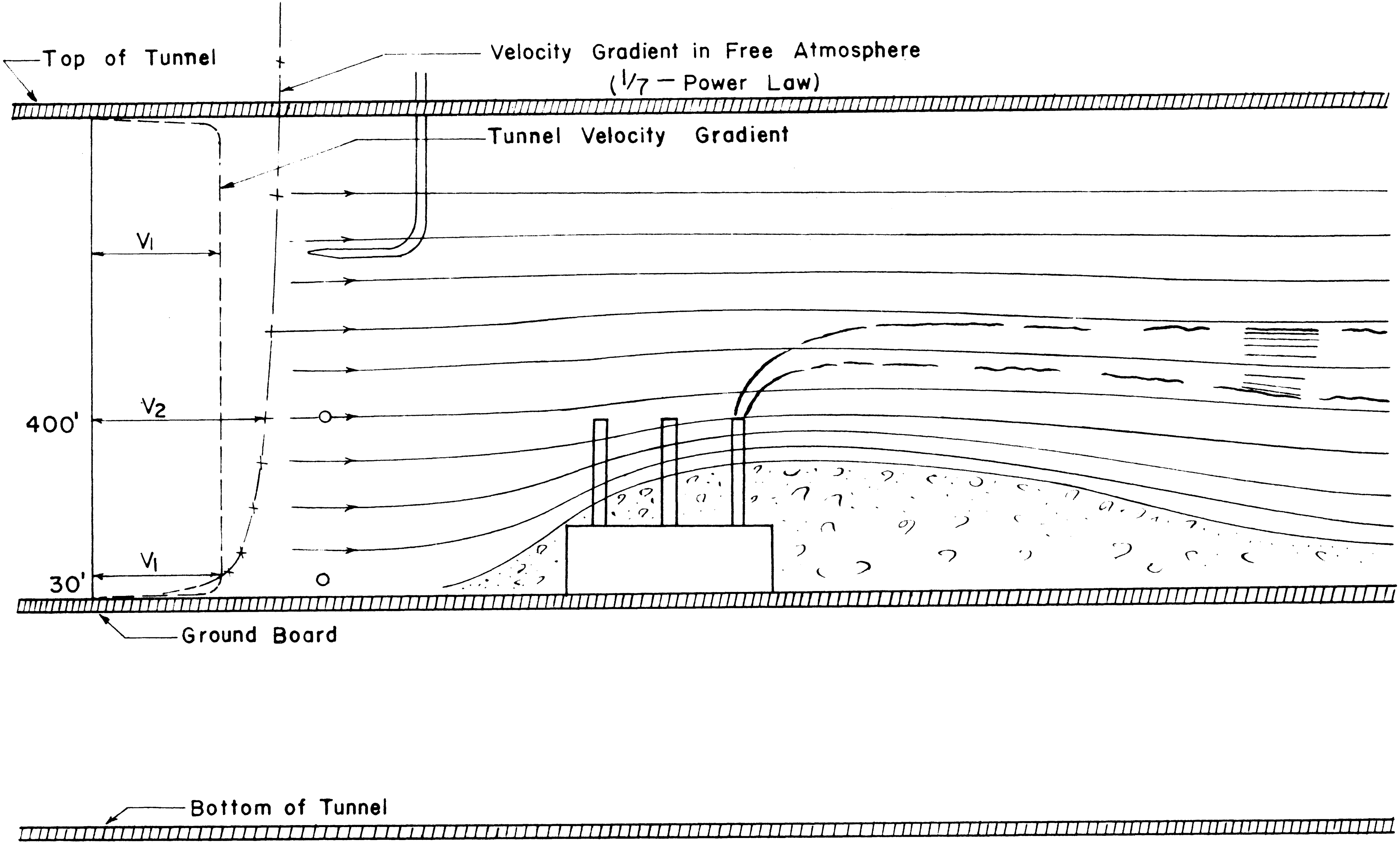
REPLOT OF DATA FROM FIG 18, BULLETIN 29

Fig A 3



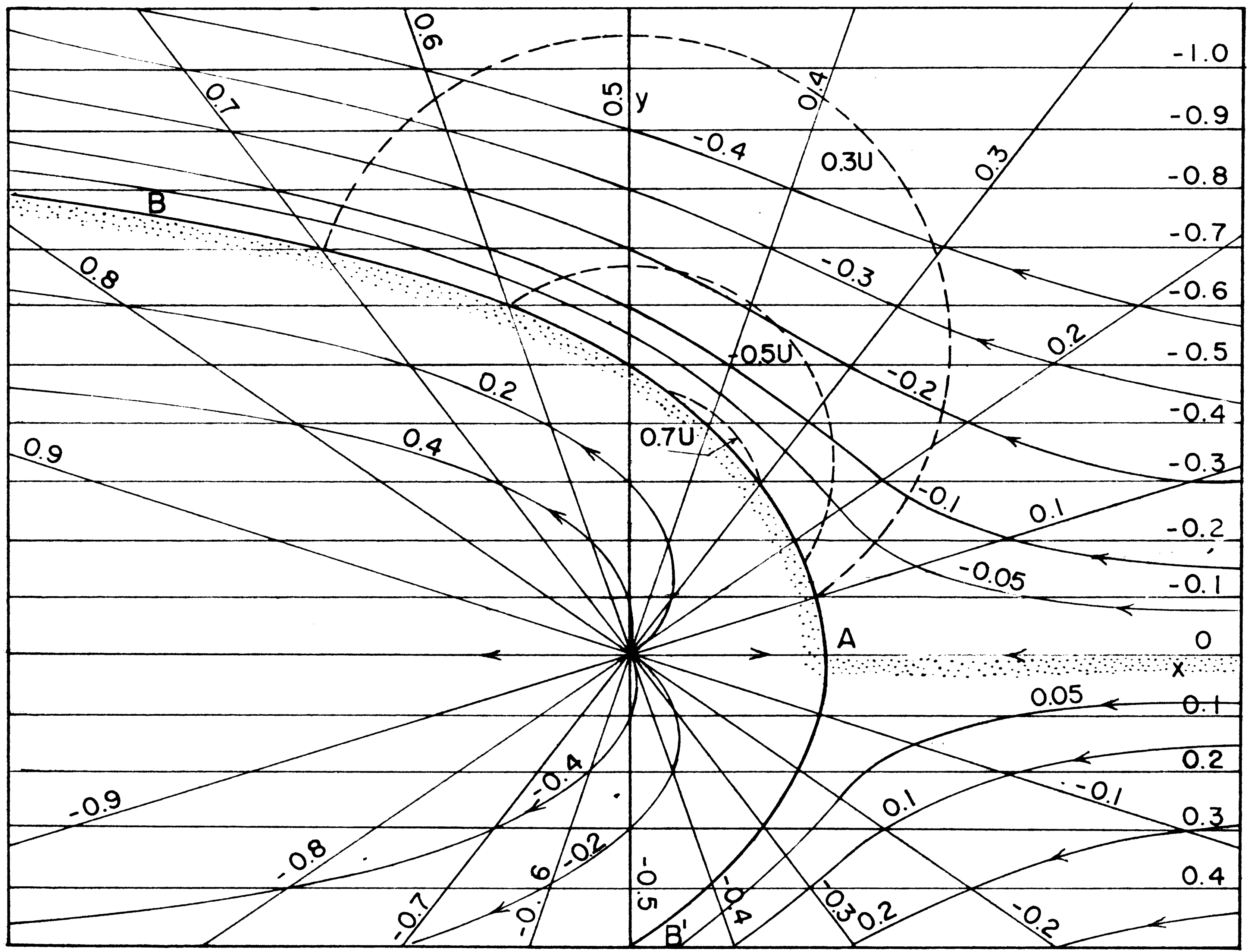
REPLOT OF DATA FROM FIG 18, BULLETIN 29

Fig A4



STREAMLINES AND VELOCITY PROFILES IN WIND TUNNEL AND IN FIELD

Fig A5



Streamlines in a Perfect Gas (after H. GLAUERT)

Fig A6

TABLE A1
Summary of Uncontrolled Influences

	Effect upon Downwash of Stack Gases	
	Favorable	Adverse
(1) Air mixture instead of Stack Gas: (Difference in composition density)		
Due to Momentum	Downwash is overestimated by tests	
Due to Flotation		Downwash is underestimated by tests
(2) Cold Air instead of Hot Air for Stack Gases:		
Due to Flotation	MAJOR EFFECTS Plume height is underestimated by tests.	
(3) Atmosphere is Warmer at Station than in Tunnel: (Seldom occurs during storms)	(MINOR) Downwash is overestimated by tests	
Atmosphere is Colder at Station (Usual during storms)		Downwash is underestimated by tests
(4) High Barometer at Station (Seldom during storms) (Small effect)		(MINOR) Downwash is underestimated by tests
Low Barometer at Station (Frequent, but small effect)	(MINOR) Downwash is overestimated by tests	
(5) High Humidity at Station (Usual case, small effect)	(MINOR) Downwash is overestimated by tests	
Low Humidity at Station (Seldom during strong winds)		(MINOR) Downwash is underestimated by tests
(6) Wind Varies with Height in Free Air but not in Tunnel		MAJOR EFFECTS Downwash is underestimated by tests

B. SIMILARITY BETWEEN MODEL AND PROTOTYPE

The model used in the wind-tunnel tests is usually made to a scale of 1:300 or 1:400, compared to its prototype in the field. Where it is desired to include a large area of terrain, the scale is usually 1:600. The model is geometrically similar to the prototype, except for details which are considered to be aerodynamically unimportant. The question arises as to whether the downwash of gases shown by the models in the wind tunnel reproduces to scale that of the gases at the full-size station. The results of tests presented to the client, usually in the form of diagrams, carry with them the implication that the downwash observed with models is substantially that which would be observed in the field for the same wind velocity, stack-gas velocity, and gas temperature, that is, that there are no important errors introduced because of aerodynamic or temperature scale effects. The validity of this conclusion, however, is by no means self-evident, and the reasons underlying the assumptions are therefore set forth in the following discussion.

Similitude here must be divided into two parts, corresponding to the two stages of downwash, namely, that involving the cylindrical stacks where sharp edges are encountered only as the air flows over the top of the stack and that involving the sharp-edged buildings. The two parts will be treated under the separate subheadings of (1) "Stacks" and (2) "Buildings." There are also the questions of similarity of terrain and of the comparison between wind-tunnel predictions and field observations. These will be discussed under subheadings (3) and (4).

In aeronautics and hydraulics, attention is usually focused upon intensities of pressures acting upon the surface of the obstruction rather than upon the details of flow which accompany them, and upon this basis, the laws of similitude have been quite thoroughly developed and validated by experience. Reynolds number, which characterizes the relative importance of the viscous and the inertia forces, is the appropriate parameter to use when dealing with the pressures exerted by the air at the surface of the cylindrical stack. On this project, however, downwash involves parcels of air which are remote from the surfaces of the stack, where viscous forces are negligible and inertia forces are of dominant importance. Furthermore, consideration of the aerodynamic intensities of pressure as a basis for determining similarity of downwash, would constitute a very complicated and indirect method of approach. This is because we are interested in knowing (a) if an observed depth of downwash at the model will be reproduced to scale at the full-size station; (b) if the wind velocity and the stack-gas velocity require scale reduction factors; and (c) if the stack-gas temperatures involve scale effects between model and prototype.

1. Stacks.—A stack presents a rounded surface to the wind. When a cylinder, such as a smokestack, is placed in an air stream with its axis normal to the direction of flow, the air is forced to flow around it and tends to

resume the undisturbed conditions of flow as soon as possible downstream from the obstruction. If the air were a perfect gas, there would be no losses due to viscosity or friction, and the air would resume its undisturbed condition of flow immediately at the downwind surface of the cylinder. In that case, there would be an increase in the velocity and kinetic energy of the fluid layers adjacent to the side of the cylinder, with a corresponding decrease in the static pressure, so that at the widest portion of the cylinder these layers would have gained the exact amount of kinetic energy necessary to permit them to return to their original line of flow against the increasing static pressure on the downstream side. Actually, however, the air is viscous, and the conditions of flow are different from those for an imaginary perfect gas. In this case the boundary layers lose energy through friction and viscosity on the upstream side and are eventually forced to separate from the surface of the cylinder on the downstream side, thus enclosing a region in which the static pressure is lower than that of the free-flowing air but is higher than that of the fast-moving enclosing layers. Due to its momentum, each layer is able to support a difference in pressure between the enclosed dead-air space and the air outside the layer. However, this difference in pressure cannot be supported indefinitely and the layers turn inward and roll into vortices or eddies with their axes of rotation parallel to the axis of the cylinder. They flow downstream and eventually disintegrate as the velocities in the component parts of the wake approach the velocities in the undisturbed air stream. It has been shown theoretically that the vortices or eddies which are shed by a cylinder are dynamically stable only when they are arranged in a staggered configuration. This configuration has come to be known as "the Karman Trail," and the reality of its existence under laboratory conditions has been established by many investigators.

A real vortex has an interior pressure substantially lower than that of the surrounding air so that the air flows into its core if either or both ends are open. The vortex nevertheless does not immediately collapse as a result of this inflow but tends to retain its configuration because its angular momentum and the viscosity of the air slow down the disintegration. Also, there is enough outflow at appropriate places along the vortex cylinder to compensate for the destructive action of the inflowing air at the ends. Consequently, the vortices continue in existence throughout long distances downstream from their origin. Such large-scale vortices and their end-flows and outflows in the free atmosphere have been found by Sherlock and Stout (*J. Aero. Sci.*, December, 1937).

The smokestacks are cylinders past which the air stream flows and builds up a vortex trail. However, both the laboratory work and the theoretical work on cylinders were done with two-dimensional flow, that is, with cylinders so arranged as to prevent flow around the ends. In the case of the smokestacks, the top ends of the trailing vortices may occur in the open air at the level of the stack gases. The flow into the vortices may carry with it gases which are later discharged by the vortices downstream at a lower level. If this lower level is in the region of the turbulence caused by the station buildings, then the gas will be mixed with the turbulent mass of air and at least part of it will reach the ground.

In the case of the three-dimensional flow at the top of the smokestack, there is also developed a pair of tip vortices whose sense of rotation is upward outside of the wake and inward and downward within the wake. These tip vortices are known to be very powerful and are typical of those which form at the tips of many different kinds of obstructions, including airplane wings. However, when the velocity of the emerging gas is high compared to that of the passing wind, the gases continue upward with sufficient momentum to constitute an obstruction to the flow of the wind and act as a continuation of the stack. There is, however, an attrition at the surface of the plume as the wind flows past, with a consequent entrainment of the smoke which renders the boundary layers visible. The rolling up of the boundary layers here follows the same pattern as behind the stack as long as the plume remains vertical, but as the plume bends over under the influence of increasing wind the incipient trailing vortices approach a horizontal position with a sense of rotation which is opposite to that of the tip vortices at the top of a stack from which no plume is emerging. When, however, the velocity of the emerging gas is low compared to the velocity of the passing wind, as evidenced by a small value of the velocity ratio, the plume levels off so rapidly that the tip vortices at the top of the stack are re-established, and the gases become entrained and are delivered to the eddies behind the stack. There is thus a difference in the mechanism of flow under the conditions of a free-flowing plume compared to that of a plume which has become entrained in the stack eddies.

It is probable that the mechanism by which the gases are brought down is even more complicated than is here described. Nevertheless, there can be no question that the downwash occurs largely in two steps which are substantially as follows: (1) the plume becomes entrained in the eddies created by the stack; (2) the gases are discharged by the stack eddies into the turbulent mass of air in the wake of the station building within which it is dispersed and brought to the ground.

A detailed discussion of the question of similitude between the model stacks and their prototypes in the field is given in Engineering Research Bulletin No. 29, pages 7 to 16, pages 38 to 43, and Figs. 20 through 32. The conclusions reached as a result of the studies described there are as follows: "It may be concluded for these variables that whatever differences exist between the detailed structure of flowing air behind the model stacks and their prototypes in the field, these differences do not destroy the characteristics of the downflow which are essential to downwash. There may be differences in the relative frequency of the eddies, or in the paths which they follow downstream, or in the relative size and strength of the individual eddies, but the effect of their presence upon air downflow is practically the same in both cases."

2. Buildings.—It has been shown experimentally by other investigators that scale effects need not be considered in relation to the pressures on

the roof and sides of sharp-edged buildings. The separation of the surface layers always occurs at the corners and there is therefore no critical value of Reynolds number at which the coefficients of air resistance undergo changes in these regions; the coefficients will depend only upon the shape and proportions of each building and its model. It was assumed on this project that the type of flow which accompanies these pressures would likewise remain the same for model and prototype, and that this similarity would apply also to questions of downwash within the wake.

3. Terrain.—Hills and valleys constitute an adverse influence on the behavior of the gas plume at some plants. In some cases the contours are sufficiently rounded so that the question of similarity between model and prototype may be raised. On one such project, where the brow of the main hill was gently rounded, it was decided to make the tests using, first, a rounded and, second, a sharp edge for the brow of the hill. There was no measurable difference in the behavior of the plume in the two situations. It must be noted that these remarks apply only to the aerodynamic influences of the terrain upon the plume, and that there are meteorological influences which may also be acting and greatly modify the results.

4. Field Observations.—There were several previous projects on which it was possible to observe qualitatively the behavior of the gases in the field and to compare them with the behavior in the wind tunnel. On one project it was possible to make quantitative observations of the plume in the field and to plot the actual behavior against the predicted behavior. The results are not yet available for publication but the agreement between actual behavior and the predicted behavior was good, thus supporting the conclusions based on other evidence that there is no scale effect, that is, that the behavior of the plume in the wind tunnel reproduces to scale the behavior of the plume in the field.

C. VELOCITY-RATIO

In the wind-tunnel investigation upon which the predictions of stack-gas downwash were based, it was assumed that the ability of the stack gases to escape the adverse aerodynamic effect of the station structures depends upon the ratio of the momentum of the stack gas to that of the wind. In both cases the momentum per unit volume is used. The ratios of these momenta at the station can be replaced by the corresponding velocity-ratios which have been reduced to their proper values at some standard temperature, in this case 70°F. This can be shown as follows:

> If M_s', m_s', and V_s' are respectively the momentum per cubic foot, the mass per cubic foot, and the velocity of the stack gas, all at stack gas temperature and at atmospheric pressure, and M_w', m_w', and V_w' are respectively the momentum per cubic foot, the mass per cubic foot, and the velocity of the wind, all at atmospheric temperature and pressure, and m_s, V_s, m_w, V_w are the corresponding properties at atmospheric pressure and 70°F and K_s and K_w are the factors for reducing the actual properties to those at 70°F

$$K = \frac{460 + 70}{460 + t}$$

then

$$\frac{M_s'}{M_w'} = \frac{m_s' \ V_s'}{m_w' \ V_w'}$$

$$= \left[\frac{m_s'}{K_s}\right] \left[\frac{K_w}{m_w'}\right] \left[\frac{V_s' \ K_s}{V_w' \ K_w}\right]$$

$$= \frac{m_s}{m_w} \ \frac{V_s}{V_w}$$

and, if we ignore the distance downwind which the gas travels after leaving the stack before attaining atmospheric temperature and pressure, then at the top of the stack $m_s = m_w$ and

$$\frac{M_s'}{M_w'} = \frac{V_s}{V_w} \quad .$$

In the present project cold gases were used, that is, a mixture of air from the compressed-air system in the building with water-vapor and oil-vapor, and the downwash is recorded as a function of the ratio of the stack-gas velocity to the wind velocity, V_s/V_w. In the absence of scale effects this permitted the use of velocities which were convenient in the tunnel rather than velocities which will occur at the station. For example, when the temperature was 70°F for both wind and gas in the tunnel and $V_s = 64$ fps with $V_w = 32$ fps (21.8 mph), then $V_s/V_w = 2$. This was assumed to produce the same downwash effect as $V_s/V_w = 120/60 = 2$.

On one project the validity of this assumption was continually tested during the first 150 runs by making two tests for every given ratio, one with the wind at 32 fps and the other at 42 fps. When it was definitely seen that there was no measurable difference in the downwash, the repetition on that project was discontinued.

At the station in the field the stack-gas velocity and stack-gas temperature are kept constant while the wind varies with time. The various values of the velocity-ratio are thus produced by the changes in the wind velocity. However, in the wind tunnel it is more convenient to change the stack-gas velocity than to change the wind velocity and the different values of the velocity-ratio are thus obtained by varying the stack-gas velocity. From time to time, on different projects, the validity of this method was tested by varying the velocity-ratio both ways and observing that there was no measurable difference in the results obtained by the two methods.

An additional validation of the velocity-ratio as a parameter to characterize downwash is contained in Figs. A2, A3, and A4, previously discussed. These observations were made under the very unfavorable conditions when the bottom of the plume was level with the top of the stack or far below it and yet, when the velocity-ratio is used as the characterizing parameter in Figs. A3 and A4, the spread of the data caused by flotational forces and experimental errors is very small indeed.

D. FREQUENCY AND DURATION OF INTERMITTENT DOWNWASH

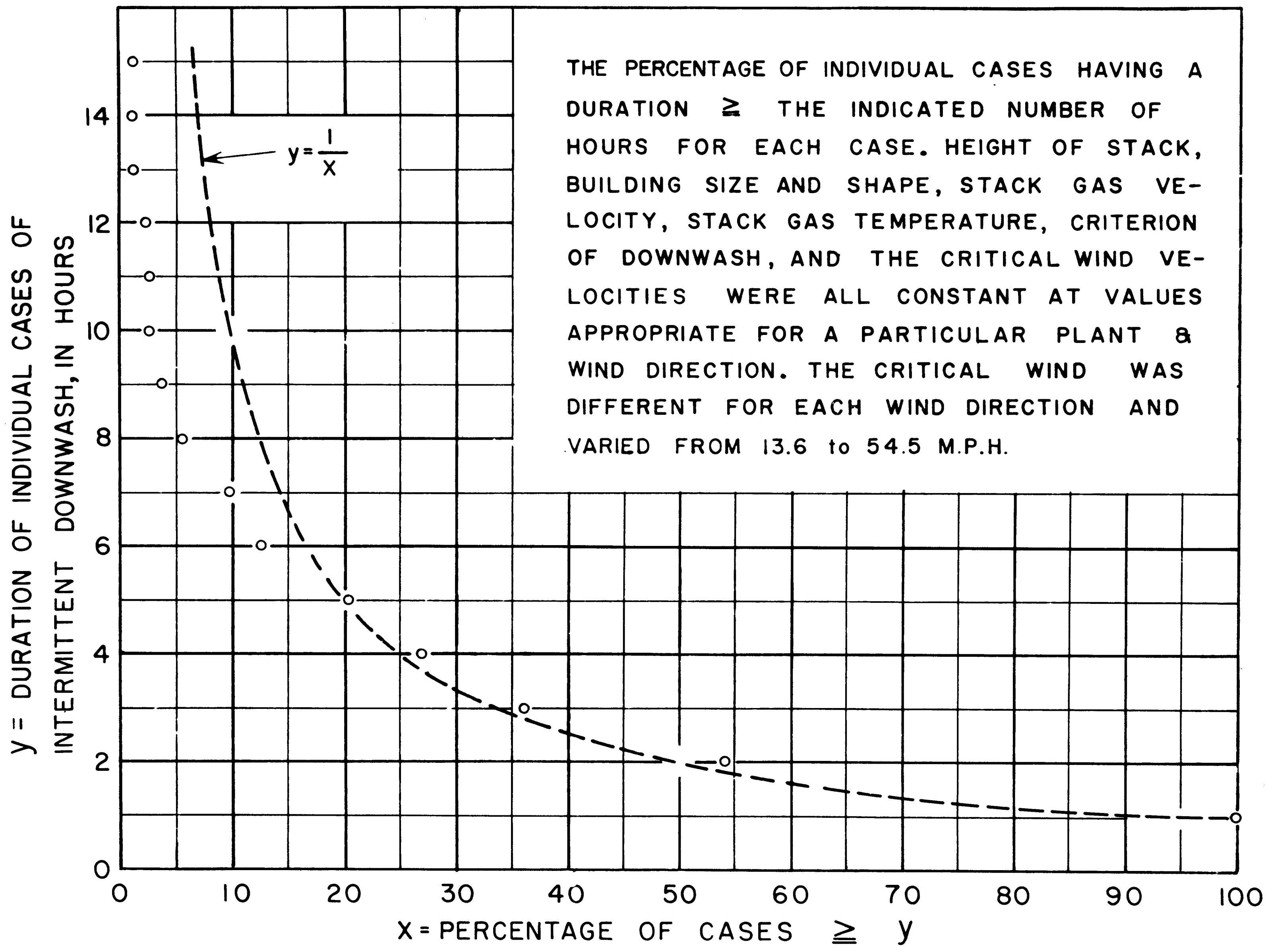
The diagrams in Part I of this report show the number of hours of intermittent downwash per year based upon the records obtained from the U. S. Weather Bureau for a sample period of several years. They give a pessimistic prediction because of the fact that they are based on hourly average velocity. For example, if 150 feet to the bottom of the plume were adopted as the criterion of downwash and if 21.8 mph were found to be the critical wind velocity necessary to maintain the plume at that height, an hour might be found when the wind was from the north with an average velocity of 21.8 mph, but in which the first half hour had a velocity of 25.8 and the second half hour a velocity of 17.8. The velocity of 25.8 would surely bring the bottom of the gas plume below the adopted criterion of 150 feet and perhaps even to the ground. But no matter how high the velocity becomes in excess of 21.8 mph, it can never do anything worse than bring the gas to the ground. However, during the second half hour, when the wind averaged 17.8 mph, the gas might be brought below 200 feet but not below 150 feet, and it would therefore most certainly not reach the ground.

This process of refinement could be carried on indefinitely by subdividing the period of time which is used as a unit. When one hour is used as a unit, it is necessary to analyze 8,760 cases per year; if one-half hour were used as a unit, it would be necessary to analyze 17,520 cases; and if five minutes were used as a unit, it would be necessary to analyze 105,120 cases per year. Not only would this constitute an overwhelming burden of analysis, but it is doubtful whether a transient phenomenon lasting only five minutes could really give an accurate report of the true situation. There is, therefore, good reason for accepting the more pessimistic picture which is involved in using one hour as the unit of time with which to measure the duration of downwash. However, it is well to point out that an hour of downwash reported here usually indicates an hour during which there will be some periods of free flow of the plume; in other words, it will be an hour of intermittent downwash.

The reported downwash will be intermittent, not only within each hour that is reported, but also within the entire number of hours. For example, if a total of ten hours of downwash is reported, there may be one case of one hour duration, one of two, one of three, and one of four hours duration to make up the total of ten hours. It is possible to analyze the original Weather Bureau records so as to determine the duration of time for each case when the critical hourly average velocity is exceeded, that is, the duration of the occurrences when the wind is above that velocity which will bring the bottom of the plume below the height which has been accepted as the criterion of downwash.

The analysis of Weather Bureau records to obtain the duration of each case of downwash is extremely time consuming and is seldom done. Table D1 shows the results which were obtained on one project where such analysis was made. The criterion of downwash in this case was that the bottom of the plume had descended below a height of 150 feet. It will be seen from the table that there would be 185 cases of downwash from all direction amounting to 518 hours per year. This is an average duration of downwash of 2.8 hours. As already pointed out in preceding paragraphs, this is a pessimistic picture since it assumes that the downwash will be continuous during any hour when the average wind velocity is sufficiently high to bring the plume below 150 feet, as shown by the wind-tunnel test. But here again it should be remembered that during many of these hours the wind velocity may be considerably higher than the average for a fraction of the hour and considerably lower than the average for the remainder of the hour. A better way of stating the preceding data would be: during an average year there will be 185 cases of downwash, and within each average case the bottom of the plume will be intermittently brought below a level of 150 feet for a period of 2.8 hours. Table D1 shows that 46% of the cases during which intermittent downwash will occur have a duration of only one hour, that 18% have a duration of 2 hours, and that the number of cases decreases with the increase of duration.

The data in Table D1 have been plotted graphically in Fig. D1 to show the orderly relation between the time of duration and the percentage of individual cases equal to or greater than the indicated duration. The relationship is some kind of a reciprocal function whose exact form has not been determined. Instead, the reciprocal curve for $y = 1/x$ has been drawn for comparison in such a way that it passes through the point $y = 1$, $x = 100\%$.



THE PERCENTAGE OF INDIVIDUAL CASES HAVING A DURATION ≧ THE INDICATED NUMBER OF HOURS FOR EACH CASE. HEIGHT OF STACK, BUILDING SIZE AND SHAPE, STACK GAS VELOCITY, STACK GAS TEMPERATURE, CRITERION OF DOWNWASH, AND THE CRITICAL WIND VELOCITIES WERE ALL CONSTANT AT VALUES APPROPRIATE FOR A PARTICULAR PLANT & WIND DIRECTION. THE CRITICAL WIND WAS DIFFERENT FOR EACH WIND DIRECTION AND VARIED FROM 13.6 to 54.5 M.P.H.

Fig. D1.

TABLE D1

NUMBER OF CASES OF INTERMITTENT DOWNWASH OF SPECIFIED DURATION

Criterion of Downwash,
Bottom of Plume P = 150 ft

Wind Direction	Duration in Hours, Each Case															Total	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Cases	Hours
North	3	2				1										6	13
East																0	0
South	1															1	1
West																0	0
NE	20	5	3	1	2		1					1				33	72
SE	4	3							1							8	19
SW	32	14	8	6	5	2	5	2			1				1	76	222
NW	25	9	6	5	8	2	2	1	1			1			1	61	191
Total Cases	85	33	17	12	15	5	8	3	2	0	1	2	0	0	2	185	
Hours	85	66	51	48	75	30	56	24	18	0	11	24	0	0	30		518

Average Duration of Intermittent Downwash = 518/185 = 2.8 Hours