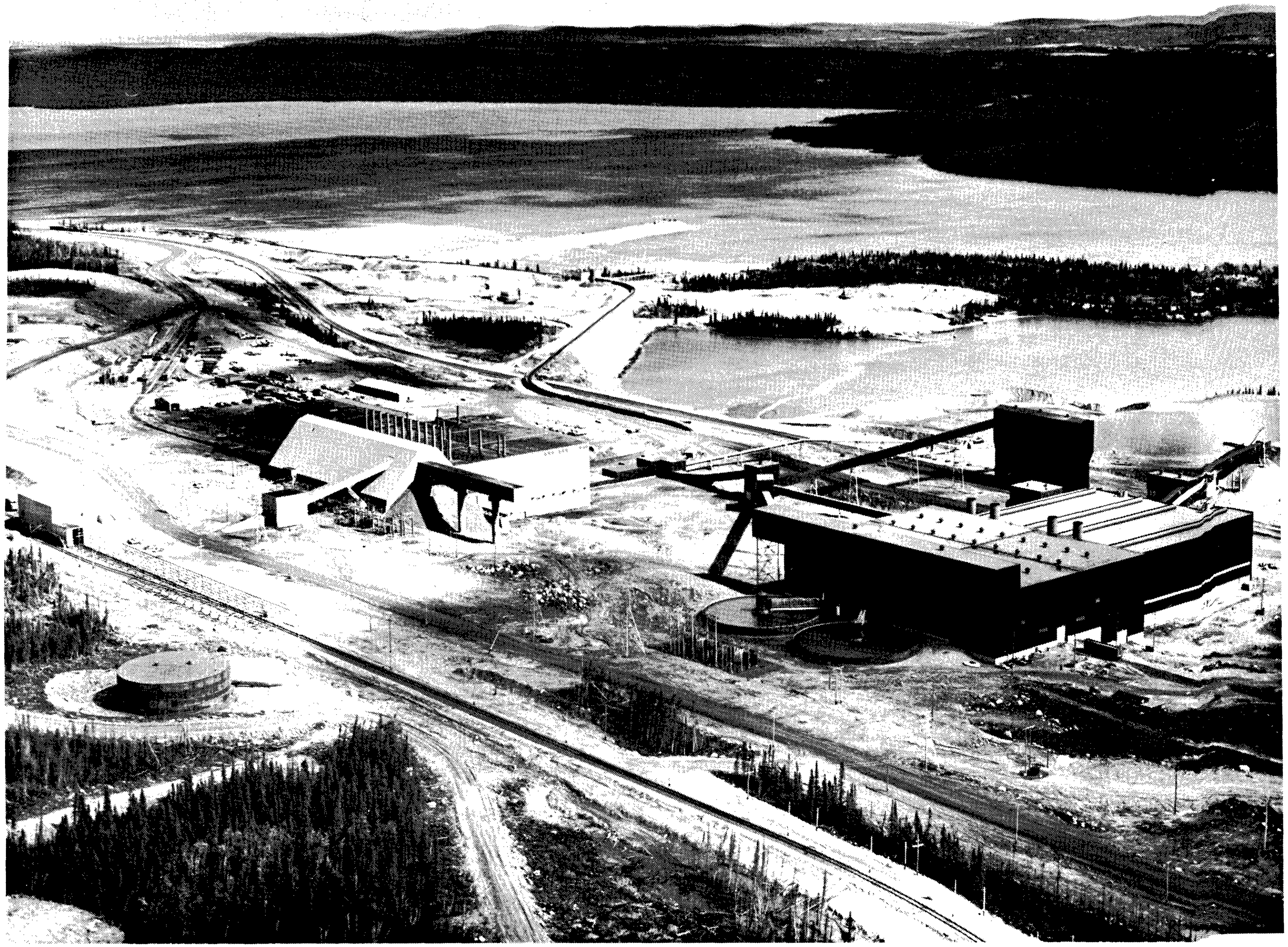


Fig. 1. Airplane view to N.E.

THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Mechanical Engineering

STUDY OF DUST EXHAUST AIR PLUMES

Mill Building, Carol Project
Iron Ore Company of Canada
(Labrador City, Newfoundland)

Bechtel and Company, Engineers
Montreal, P.Q., Canada

Final Report - Part I

R. Clay Porter
Professor of Mechanical Engineering

Glen L. Alt
Professor of Civil Engineering

Eugene A. Glysson
Associate Professor of Civil Engineering

Robert B. Harris
Associate Professor of Civil Engineering

ORA Project 06112

under contract with:

ROBERT H. SHERLOCK, CONSULTING ENGINEER
ANN ARBOR, MICHIGAN

administered through:

OFFICE OF RESEARCH ADMINISTRATION ANN ARBOR

June 1964

ABSTRACT

This report pertains to the Carol project of the Iron Ore Company of Canada, located at Labrodor City Newfoundland, Canada. The engineers for this project are Bechtel and Company; Montreal, P.Q., Canada. The report deals with a study to determine the stack height and stack gas velocity, from the iron ore concentrating mill, necessary to maintain the height of the stack gas plume, and the ground concentration of stack effluent dust within satisfactory limits.

For simplicity of presentation, and for convenient use by the client, this report is submitted in two parts.

Part I describes the problem, the wind tunnel testing program and procedures, and the test results.

Part II presents the results assembled in such form that the designing engineers may readily choose a number of combinations of stack height and stack gas exit velocity which will give satisfactory plume behavior according to the adopted criteria. These combinations may then be examined from the standpoint of operating practicability and economic limitations. An example of the use of the curves is also given. Two appendixes are included which give more detailed information as supporting discussion of some points.

PART I

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

A meeting was held in Ann Arbor on October 1, 1963, to discuss the unsatisfactory behavior of the dust and exhaust air plumes from the 23 existing stacks of the iron ore concentrating mill at Labrador City, Newfoundland, Canada. Present were Mr. A. Sobering, Assistant Manager, Iron Ore Company of Canada; Mr. A. R. MacPherson and Mr. R. A. McCaffery, both of Bechtel and Company, Montreal, Canada; Professor R. C. Porter of The University of Michigan; and Mr. R. H. Sherlock, Consulting Engineering, Ann Arbor, Michigan.

In was decided that a proposal should be prepared outlining an overall program of study to determine the stack height and the gas exist velocity necessary to keep the gas plume at a satisfactory height and to keep the ground concentration of dust at acceptable levels in several designated areas. The proposal was submitted by R. H. Sherlock in a letter dated October 4. It was accepted in a letter from A. R. MacPhaerson to R. H. Sherlock dated October 11, 1963.

In a letter dated October 11, R. H. Sherlock requested Professor Porter to submit a proposal for conducting the wind tunnel portion of the studies, including the summary of the wind tunnel data. In accordance with this request, a testing program was prepared and incorporated in a contract dated October 15, between R. H. Sherlock and The University of Michigan, with Professor Porter acting as supervisor of the project (ORA Project 06112).

For simplicity of presentation, and for convenient use by the client, this report is submitted in two parts.

PART I describes the problem, the wind tunnel testing program and procedures, and the test results.

PART II presents the results assembled in such form that the designing engineers may readily choose a number of combinations of stack height and stack gas exit velocity which will give satisfactory plume behavior according to the adopted criteria. These combinations may then be examined from the standpoint of operating practicability and economic limitations. An example of the use of the curves is also given. Two appendixes are included which give more detailed information as supporting discussion of some points.

THE PLANT AND SITE

The Carol Project of the Iron Ore Company of Canada is located at Labrador City, Newfoundland, Canada. It is situated on a spur of the Quebec North Shore and Labrador R.R. about 30 miles west of the main line and about 325 miles north of Seven Islands on the St. Lawrence River The Ore Concentrating Mill, which is served by the chimneys involved in this study, is part of a complex of buildings and other facilities to which the ore is delivered for concentration before being carried by rail to Seven Islands.

Figure 1 (Frontispiece) is a photographic view looking toward the N.E. and showing the south end of Wabush Lake in the background. The Concentrating Mill, with its present line of 12 aerofall mill exhaust stacks, appears in the left-center of the picture together with the Ore Storage Building. The large building in the right-center of the picture is the Ore Pelletizing Plant.

Figure 2 is a view looking toward the S.W., and Fig. 3 is a view looking toward the N.W.

THE TERRAIN AND CRITICAL AREAS

Figures 2 and 3 show that the terrain lying to the S.W., W., and N.W. of the plant site is quite hilly. Wabush Lake has an elevation of 1707 ft above msl, while some of the peaks shown in the figures have elevations 1100 ft higher than that. However, the ridge lying directly west of the site, and about 2000 ft away, has a maximum elevation of 2100 ft which is 400 ft higher than the lake and 300 ft higher than the average yard level (taken at elevation 1792). The ridge and the three lakes in the valley west of the ridge are included in the wind tunnel model.

Figure 4 shows the contour lines for the nearby terrain and also the location of the 8 areas to be investigated for the concentration of particulate matter in the atmosphere near the ground.

Figures 5, 6, 7, and 8 show vertical sections of the terrain. Two sets of scales are used in each figure to bring out significant features.

WIND HISTORY

The only wind records available in the area of the Carol Project are those taken at the Wabush Airport, about 4 miles S.S.E. of the mill building, for the period February, 1962, through January, 1963. The records were supplied by the

Iron Ore Company in the form of wind roses shown on three maps identified as Plan A, Plan, B, and Plan C. Figure 9 reproduces the data as given for 16 segments of the compass. The 12-month data (Plan A) is subdivided in Plans B and C into data for the spring, summer, and fall portions of the 12-month sample, as listed in Table I.

TABLE I

WIND DATA FOR 16 SEGMENTS OF COMPASS

NOMINAL DIRECTION		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
PLAN A 12 Month Sample Feb.'62 to Jan.'63	Aver. Vel.	11	9	10	13	13	11	14	11	14	8	9	8	10	9	11	10
	Max. Vel.	40	35	30	40	40	40	35	40	40	50	30	30	25	25	30	38
	%	4.6	5.5	5.6	6.6	6.5	4.9	8.3	5.7	6.6	3.7	1.7	1.2	1.7	2.5	2.5	4.8
	% Calm	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74
PLAN B Summer Months Sample June 1962 to Sept. 1962	Aver. Vel.	10	10	9	10	10	10	10	10	10	10	9	8	9	9	9	9
	Max. Vel.	18	30	20	30	25	20	24	24	35	30	16	13	20	20	15	18
	%	2.7	5.2	4.1	6.0	4.5	5.1	3.9	6.9	5.2	2.9	1.2	1.2	2.3	3.3	2.1	5.7
	% Calm	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37
PLAN C Fall, Winter, Spring Months Sample Feb62-May62 Oct62-Jan63	Aver. Vel.	11	9	11	12	13	12	14	12	16	8	9	8	10	9	11	10
	Max. Vel.	40	35	30	40	40	40	35	40	40	50	30	30	25	25	30	38
	%	5.5	5.6	6.3	6.8	7.5	4.8	10.5	5.2	7.3	4.2	1.9	1.2	1.4	2.1	2.7	4.3
	% Calm	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41

For purposes of correlation of the wind with the behavior of the stack-gas plumes at the Concentrating Mill, it is assumed that the arrow which points "north" in the wind rose coincides with the "true north" meridian; that the wind data listed in the north "petal" of the wind rose apply to winds blowing from the north and that the "calm" winds (0-3 mph) are divided equally between the 16 "petals" of the compass.

A study of the layout plans for the mill area and of the various topographic maps showed that the "nominal north" used at the mill site has a declination of about 20 degrees east from the true north meridian. Consequently, in applying the wind data to the "nominal" wind directions at the mill site, the data in Fig. 9 have been rotated in a counterclockwise direction to the next "petal" in the wind rose. For example, in Plan A (Table I) the maximum wind velocity at the site for winds blowing from the "nominal" north will be 40 mph instead of 38 mph, etc.

In his letter of December 10, 1963, Mr. Sobering stated that the wind records at the airport are based upon hourly spot readings of a U2A-type anemometer (3 cups with dial indicator). This type of instrumentation, together with the difference of terrain at the two sites, scarcely justifies the refinement of using 16 segments of the compass. The wind rose was therefore divided into 8 "petals" of 45 degrees each instead of 16 "petals" of 22.5 de-

degrees each. In Plan A this means that the average wind from the "nominal" north = 1/2 (11 + 9/2 + 10/2) = 10.25 mph; and the percent of hours of wind blowing from the "nominal" north = (4.6 + 5.5/2 + 4.8/2) = 9.75% of the hours of wind blowing from all directions, as indicated in Table II.

TABLE II

WIND DATA FOR 8 SEGMENTS OF COMPASS

NOMINAL DIRECTION		N	NE	E	SE	S	SW	W	NW
PLAN A	Aver. Vel	10.25	10.50	12.50	12.50	11.75	8.50	9.25	10.25
	Max. Vel.	38.25	33.75	40.00	37.50	42.50	35.00	26.25	30.75
	%	9.75	11.65	12.25	13.60	11.30	4.15	3.55	6.15
	% Calm	3.47	3.48	3.48	3.48	3.48	3.47	3.47	3.47
PLAN B	Aver. Vel.	9.75	10.50	11.00	10.00	10.00	9.00	8.75	8.00
	Max. Vel.	21.00	25.00	25.00	23.00	31.00	18.75	18.25	17.00
	%	8.15	9.70	10.05	9.90	10.10	3.25	4.55	6.60
	% Calm	4.74	4.74	4.74	4.74	4.74	4.74	4.74	4.74
PLAN C	Aver. Vel.	10.25	10.75	12.50	13.00	13.00	8.50	9.25	10.25
	Max. Vel.	38.25	33.75	40.00	37.50	42.50	35.00	26.25	30.75
	%	10.45	12.50	13.30	15.60	12.00	4.60	3.05	5.90
	% Calm	2.82	2.83	2.83	2.83	2.83	2.82	2.82	2.82

Figure 4 and Table III show that there are 8 areas which are to be investigated for the concentration of particulate matter (-10μ) in the atmosphere near the ground. The wind blowing from the "nominal N.W." is used in the computations

TABLE III

AREAS TO BE INVESTIGATED FOR GROUND CONCENTRATIONS OF PARTICLES (-10μ)

Location		x		Nominal Direction	Nom. Wind	Elevation above msl	Hourly Wind Vel. Feb.'62-Jan.'63			
		Miles	Feet				Av. mph	fps	Max. mph	fps
A	Shore line	0.57	3,000	SE	NW	1750 Ft.	10.25	15	30.75	45.0
B	Yard	0.19	1,000	NE	SW	1800 Ft.	8.50	12.5	35.00	51.3
C	Labrador City	1.42	7,000	SSW	NW	"	10.25	15	30.75	45.0
D	End of Runway	2.3	12,000	SE	"	"	"	"	"	"
E	" " "	3.2	17,000	"	"	"	"	"	"	"
F	Wabush Mine	3.6	19,000	S	"	"	"	"	"	"
G	" Town	3.8	20,000	SE	"	"	"	"	"	"
H	Shore Line	0.42	2,000	E	W	1750 Ft.	9.25	13.6	26.25	39.0

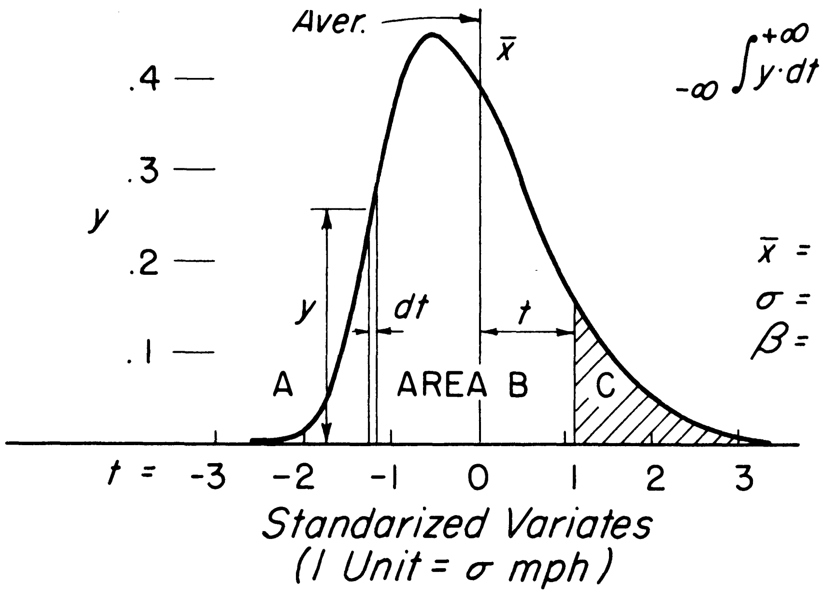
for 6 of the 8 areas; the W. and S.W. are used for the other two areas. The manner of choosing the velocities to be used in the computations for each direction will be discussed in detail for the N.W. winds only. The W. and S.W. winds will be treated in a similar manner. The controlling wind velocities will be assumed to be the wind velocity averaged over a period of one hour. There will therefore be 8760 statistical cases during the year 1962 when the data were taken. The percentage of hours assignable to each direction are shown in Table II and Fig. 9. For example, the wind blew from the N.W. for a total of 6.15% of the 1962 hours, that is, for 539 nonconsecutive hours

During the 539 hours when the wind blew from the N.W. (nominal) the average of the 539 hourly "spot readings" is assumed to give the average hourly velocity (10.25 mph). The maximum wind velocity as recorded during this time (30.75 mph) has not been used however, since there is reason to believe that the data are not homogeneous. The hourly spot readings give a fair approximation to the average hourly wind velocity since they involve many readings with a high probability of compensating errors. The maximum, however, involves only one reading and gives the velocity for perhaps less than one minute duration to compare with the readings which, when averaged, approximate one hour duration each. The ratio of maximum-to-average is 30.75 ÷ 10.25 = 3.0. This is about twice the ratio found on two previous projects, one in Chicago and one in Nova Scotia, where all velocity readings were one-hour averages taken from continuous charts.

Table IV shows the statistical analysis of five-year samples of hourly-average wind velocities at the Naval Air Station, Dartmouth, Nova Scotia, and at the Midway Airport, Chicago. It is seen that in order to exclude the highest 15% of all wind velocities, it is necessary to exclude all records above 1.57 times the average, based on Dartmouth, and 1.47 times the average, based on Chicago. This gives 16.1 and 15.05, respectively. It has been decided to ADOPT an average hourly velocity of 10.25 mph, together with a higher hourly velocity of 15 mph, in making the computations for dust concentration and for stack height. This holds for the west as well as for northwest winds.

TABLE IV

STATISTICAL ANALYSIS OF HIGHEST 15% WIND VELOCITIES
USING PEARSON TYPE III DISTRIBUTION CURVES



$$\int_{-\infty}^{+\infty} y \cdot dt = 1.0 = \text{Area } A + B + C$$

$= 100\%$ all Cases

$\bar{x}$ = Average

σ = Std. deviation

β = Coeff. of Skewness

Air Station, Dartmouth, Nova Scotia, Nov. 1951 - Oct. 1956
Av. for 5 Selected Wind Directions (N, NE, NW, SW, W)

$\bar{x} = 11.713$ mph
$\sigma = 6.426$ "
$\beta = 0.653$

Exclude upper 10% of cases
$t = +1.33$ Area A + B + C = .899973
Say 90%
= Aver. + 1.33 σ
= 1.735 x Aver.
Carol Proj. = 17.8 mph

Exclude upper 15% of cases
$t = 1.03$ A + B = .850662
Say 85%
= Aver. + 1.03 σ
= 1.57 x Aver.
Carol Proj. = 16.1 mph

Midway Airport, Chicago, 5 years
$\bar{x} = 11.70$ mph
$\sigma = 5.3$ "
$\beta = 0.43$

Exclude upper 10% $t = +1.32$
Carol Proj = 16.4 mph

Exclude upper 15% $t = +1.03$
Carol Proj = 15.1 mph

There are 6.15% of all winds blowing from NW octant.
Exclude highest 15% (> 15.1 mph)
.15 x 6.15 x 87650 = 81 non consecutive hours per year > 15.1 mph

WIND TUNNEL TESTING

The facilities and procedures used on this project have been developed over a period of about 30 years for use on about 50 similar projects. Most of these dealt with steam-electric generating stations where it had become necessary to prevent the stack-gas plumes from being brought to the ground by aerodynamic forces as the wind blew over and around the stacks and buildings. The wind-tunnel and smoke-generating equipment have recently been remodeled.

THE WIND TUNNEL

The investigation was conducted in a low-speed wind tunnel, which has a working section 8 ft wide by 5 ft 4 in. high and 26 ft 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 8 fps by controlling the fan speed. An ASHRAE standard pitot tube was used for the measurement of the wind velocity. It was located approximately above the model of the Concentrating Mill stacks, 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 1 in. at the ceiling, floor, and sides of the tunnel Even with the presence of the model, 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, the stacks, and the terrain.

SMOKE GENERATOR

The stack gas (or smoke) is produced by a specially designed smoke generator capable of producing smoke at various rates so that an adequate supply is available for all desired model stack gas velocities. The smoke is generated by evaporating oil in a vessel which was formed by welding flat ends onto a 5 in. length of standard 6 in. steel pipe. Heat is supplied to the lower end of this vessel by means of an external variable wattage electric heater under control of a selector switch. The temperature of the lower end is monitored by means of a thermocouple inserted in a horizontal hole drilled therein. Oil is supplied to the vessel by gravity feed from a slightly elevated source under control of a manually operated valve. Compressed air under manual control is forced into the vessel and sweeps the smoke out through a 1 in. pipe opening in the center of the upper end.

Smoke leaving the generator is piped to a stilling and cooling chamber equipped with appropriate liquid drains, from which it is then removed at approximately room temperature as a white fog of good photographic quality.

Leaving the stilling and cooling chamber the smoke passes through a calibrated orifice in a 1 in. pipe line enroute to the model stack. Wind tunnel air velocity is held constant at 8 fps. The desired ratio of stack gas velocity to wind velocity is obtained by varying the compressed air supply to the smoke generator, and correlating the pressure drop across the orifice as read by a water filled manometer, with the orifice calibration and the cross section area of the model stack.

THE MODEL

Figure 10 shows the completed model before it was placed in the tunnel. Since tests were to be made with the wind blowing from each of three directions (S.W., W., N.W.), and since the model was much too big to be placed in the tunnel all at one time, it was necessary to make the model in 69 pieces, each of which was built in an appropriate jig to insure proper fit when reassembled or rotated in the tunnel. The models of the buildings were made from special drawings, the information for which was obtained from 116 drawings furnished by the client.

The scale of the model (1:300) was selected to give a sufficient coverage of the terrain to insure representative test results. Contour maps of the selected area were prepared which showed the topographic features and the buildings. These maps were photographed and the resulting negatives used to make large photo-mural prints some of which were approximately 5 ft wide by 15 ft long. These murals and some prints of direct drawings were taped together to make a single map of the area having the same scale as the finished model. Upon this sheet each piece was outlined, all final features drawn, all contours examined for compliance with the chosen contour interval (6.25 ft), all contours numbered, and each piece identified as to its location in one of the finished assemblies for the tunnel. The pieces were then cut apart and used as patterns. Each individual contour line and every feature was traced onto 1/4 in. plywood sheets. After cutting around the contour lines, the resulting lifts were assembled in the jigs by gluing one upon the other. The final steps in the construction were to apply the representation of the trees, the buildings, the necessary legs, and to paint the model in appropriate colors to insure good lighting for the tunnel photographs. A photograph of a section of the completed model is shown in Fig. 15. Principal buildings and large structures were represented in accordance with available data and as illustrated in Figs. 1 to 3.

The smoke plune and a reference grid were photographed through plate-glass windows with an exposure of 2 sec. The grid is shown in Figs. 12 and 13. It served as a reference for the measurement of the height of the plume above the nominal base of the stack (elevation 1792 above msl) and the distance downwind from the reference point of the model (midpoint of the line of 12 old stacks).

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 cause annoyance to persons on the ground or damage to crops and animals.

TABLE V

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 (Fig. 11), 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, penetrating the vortex sheath so that they are brought to the ground by the turbulence behind the building. This action is termed "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 aerodynamic 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 within satisfactory limits. The effects most 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.

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 12 shows a free-flowing plume which occurs with a high stack-gas velocity in a light wind, and Fig. 13 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 a downwind 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. 13 where the "tails" appear as the hazy area on the bottom of the plume. The tails and part of the remainder of the plume are drawn down so that they sweep along the surface of the ground.

At the site of the Mill Complex of the Carol Project, the only significant hills lie to the S.W., W., and N.W. of the mill. There are no critical areas in these hills and consequently there is no interest in the behavior of the plume under the influence of winds having easterly components. Even in the case of winds from N.N.E., which will bring the plume over Labrador City, no hill effects will be acting upon the plume since it will be following parallel to the 1800- and 1900-ft topographic contour lines for the first 3000 ft, after which it will flow across the 50 ft deep ravine which drains Beverly Lake into Little Wabush Lake. No tests were run in the wind tunnel using N.N.E. winds, and in Table III winds from the N.W. were specified instead of the N.N.E. winds. This was because the N.W. winds produce the worst conditions of downwash in the first 3000 ft and because plume height will be the controlling criterion rather than ground concentration of particulate matter.

The same line of reasoning led to the substitution of N.W. winds for N. winds in Table III for studying the effects of the gas plume on the area F.

All of the other 6 critical areas are affected by either S.W., W., or N.W. winds as indicated in Table III. In every case the plume will pass over relatively flat land, or water, or both before passing over the critical area as shown in Figs. 5, 6, and 7.

GAS TEMPERATURE

In most projects the higher temperature of the stack gases in relation to that of 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 an obstacle, 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 obstacle 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.

STACK GAS EXIT VELOCITY

Early investigations on previous projects established the great value of high stack-gas exit 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 gas 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 340°F would have the same plume behavior as one operating with a gas velocity of 39.78 fps at 70°F. The accompanying wind velocity at 70°F would be 19.89 fps (13.56 mph). 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.

In the case of the Carol Project the maximum temperature of the stack gas is only 120°F and the range of ambient temperature is from +80 to -40°F. This range of temperature results in a corresponding range of air density, which in turn results in variations of the momentum of the wind for any particular wind velocity. Inasmuch as the behavior of the plume is influenced by the ratio of the momentum of the stack gases to the momentum of the wind, it is correspondingly influenced by the temperature of the wind. Figure 14 has been prepared to show the magnitude of the effect of wind temperature. It will be noticed that for any particular stack-gas velocity the effective wind is increased when the wind temperature decreases. This would mean that the plume would tend to bend downward slightly more with cold wind than with warm wind of the same velocity. Inasmuch as high winds occur principally in warm weather, the adverse effect of low temperature is not critical to the design of the stack.

TABLE VI

WIND TUNNEL TESTING PROGRAM

Stack-gas velocity = V_s^1 = 100 fps at 100°F
O.S. air temp. range = +80 to -50°F

N.W. Wind

A. Present Layout of Ore Storage and Concentration Buildings

  1. Stack Scheme 1 (tentative)
     a. Stack heights (above elev. 1792) 155.5', 300', 350', 400', 500'
     b. Velocity ratio ($V_s^1 \div V_w$) 2.0, 3, 4, 5, 6 (equiv. mom. ratios ±)

  2. Stack Scheme 3 (tentative)

     a. same
     b. same

B. With Extensions of Ore Storage and Concentration Buildings

  1. Stack Scheme 1
     a. same
     b. same

  2. Stack Scheme 2
     a. same
     b. same

  3. Stack Scheme 3

     a. same
     b. same

W. Wind (same as A and B)

S.W. Winds (same as A and B)

C. Field verification photos, west winds only for adopted height and V_s^1/V_w = ?

WIND TUNNEL TESTING PROGRAM

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 12 and 13 show two runs, one with satisfactory plume behavior and the other with the plume sweeping the ground. To complete the program, 795 such runs were required. Each set of conditions was run twice in order to provide a check on the accuracy of the work done.

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-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 10 min at the plant site, depending on the wind velocity at the site. A 2-sec 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 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.

In order to duplicate field plumes in the wind tunnel it was necessary to take into account the fact that the stack gas in the field was at 120°F, whereas that in the model was at 70°F, and thus the respective momenta were influenced by the corresponding densities. Thus to duplicate a specific field ratio of stack gas momentum to wind momentum, the stack gas velocity used in the tunnel was the field stack gas velocity multiplied by the ratio of the density of field stack gas to that of the model stack gas.

A series of runs was made for each stack location indicated in Fig. 16, with and without contemplated plant extensions, with winds from N.W., W., and S.W. Each series embraced several stack heights and stack gas velocities while the tunnel wind velocity was held constant at 8 fps, thus simulating various ratios of stack gas velocity to wind velocity in the field. Figures 17 and 18 are typical of the numerous graphs made from the tunnel data as taken from the photographs of the plume and scaled grid background. The height of the bottom of the plume and of the center line of the plume above ground level at specific distances downwind from the stack constitute the prime wind tunnel data.

WIND TUNNEL TEST RESULTS

Although the results of this study have been displayed in graphic form in Part II, Figs. 19 through 128, so that they may be read directly without any calculations whatsoever, the following explanation of the calculations leading to those results, is presented for the purpose of clarifying their bases.

Four stack gas velocities (60, 85, 100, and 120 fps) were considered with each wind velocity. The quotient of each stack gas velocity divided by one particular wind velocity (say 15 mph) multiplied by an rifice calibration constant yielded four abscissa values applicable to the numerous wind tunnel data curves similar to Figs. 17 and 18. Referring to any one particular wind tunnel data curve, such as Fig. 17, with these abscissa values, the height of the bottom of the plume and of the center line of the plume were read. This one particular wind tunnel data curve, Fig. 17, and the plume heights so obtained from it, were necessarily for a fixed set of conditions, including wind direction, stack location, stack height, plant modification status, and distance downwind from stack, all as included in the title of Fig. 17.

Repeating this procedure except using Fig. 18, which differs from Fig. 17 only in stack height, another set of plume height values were obtained. Again repeating the procedure using another such figure which differs only in stack height, a set of plume height values were obtained, etc., for each stack height, all other conditions as noted on the wind tunnel data curves being held constant.

Next, by rearranging these values of the height to the bottom of the plume into four groups, corresponding to the four stack gas velocities, a graph similar to Fig. 19 was made showing the relation between the height of the bottom of the plume and the stack height for various stack gas velocities and for the fixed set of other conditions applying to the figures used in the process.

A similar set of values of the height to the center line of the plume was obtained but instead of being graphed as such, the corresponding values of dust concentration at ground level were calculated and these values were graphed as shown in Fig. 20. The calculation of these values of dust concentration is illustrated in the following example.

Example Illustrating Use of IBM Table

Consider the following set of conditions under which it is desired to determine the concentration of dust at ground level (1792 ft).

(1) Wind from N.W. at 15 mph
(2) Stack location 1
(3) Stack height, 450 ft
(4) Stack gas velocity, 90 fps
(5) Plant with extensions
(6) Stack discharge, 800,000 cfm
(7) Dust loading at stack outlet, 0.0155 gram per cu ft
(8) Distance downwind from stack to point of concentration
question, 3000 ft

Under this set of conditions and by the procedure previously outlined, it has been determined that the height of the center line of the plume is 515 ft above ground level at 3000 ft downwind from stack. (The height of the center line of the plume was tabulated from each photographic run but was not graphed. The data are available in the files of Professor R. C. Porter's office.) Referring to Sutton's equation as presented in Appendix A of Part II and the accompanying IBM tabulation (Table X), the dust concentration, Chi, on the basis of Q = 1000 grams discharge from the stack per second, is 0.0013711 gram per cubic meter at ground level, 3000 ft downwind from this stack. In the case at hand, however, the rate of dust discharge from the stack is the product of conditions (6) and (7) or 800,000 x 0.0155 = 12,400 grams per minute, or 206.5 grams per second, instead of 1000. The concentration in question is then (206.5/1000) x (0.0013711) or 0.0002825 gram per cubic meter. Since there are 35.31 cu ft per cu m, the same concentrations may be expressed as 0.0002825/35.31 = 0.000008 gram per cu ft. Table VII (Part II) states that there are 9,998.576 x 10^6 particles per gram. On this basis, the same concentration may be expressed as 0.000008 x 9,998.576 x 10^6 = 80,000 particles per cu ft. Obviously, if the number of particles emitted per second from the stack are employed in Sutton's equation in lieu of Q, the equation will yield concentration in number of particles per cubic meter directly.

Fig. 2. Airplane view to S.W.

Fig. 3. Airplane view to N.W.

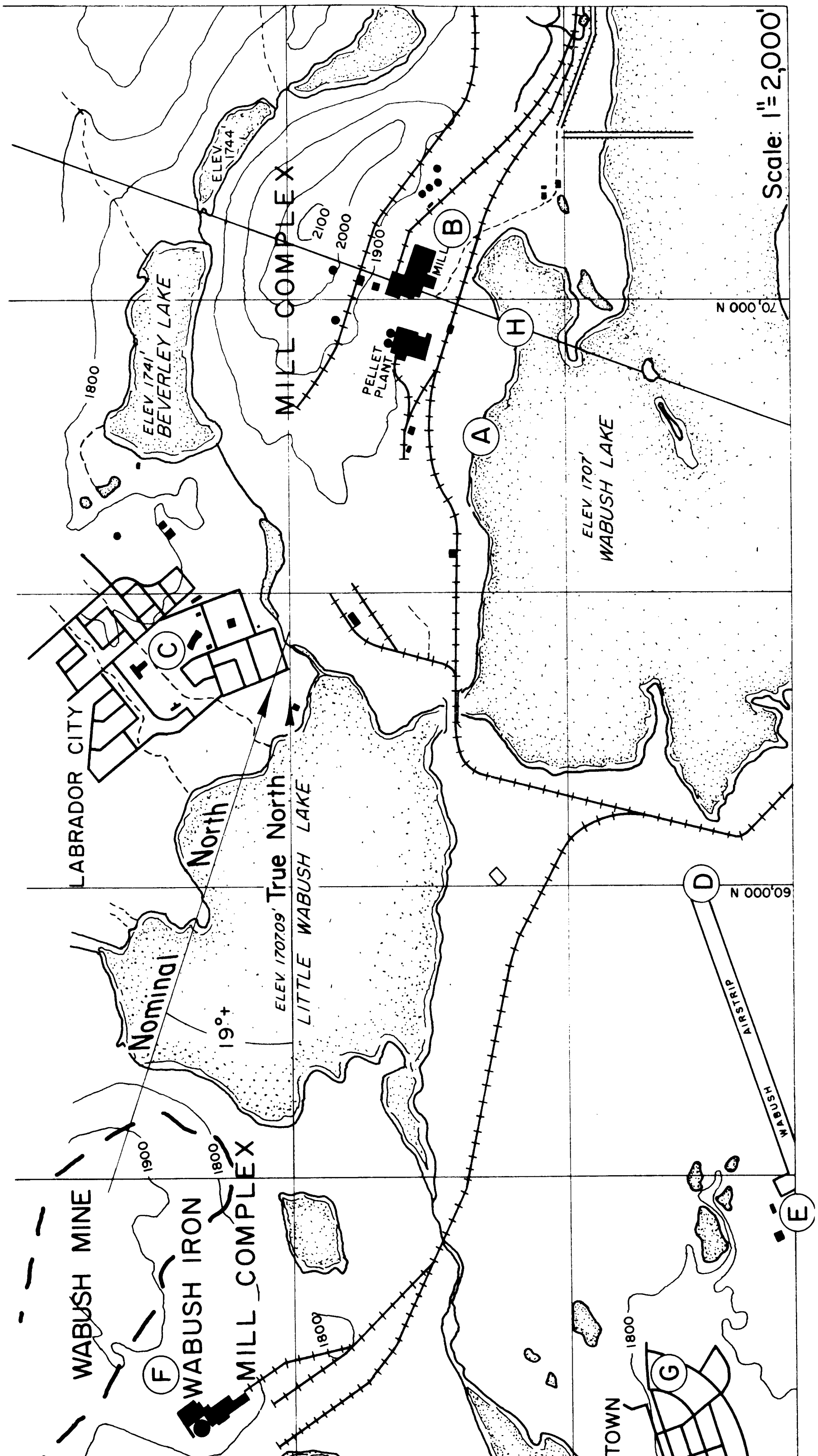


Fig. 4. Plant site and critical areas.

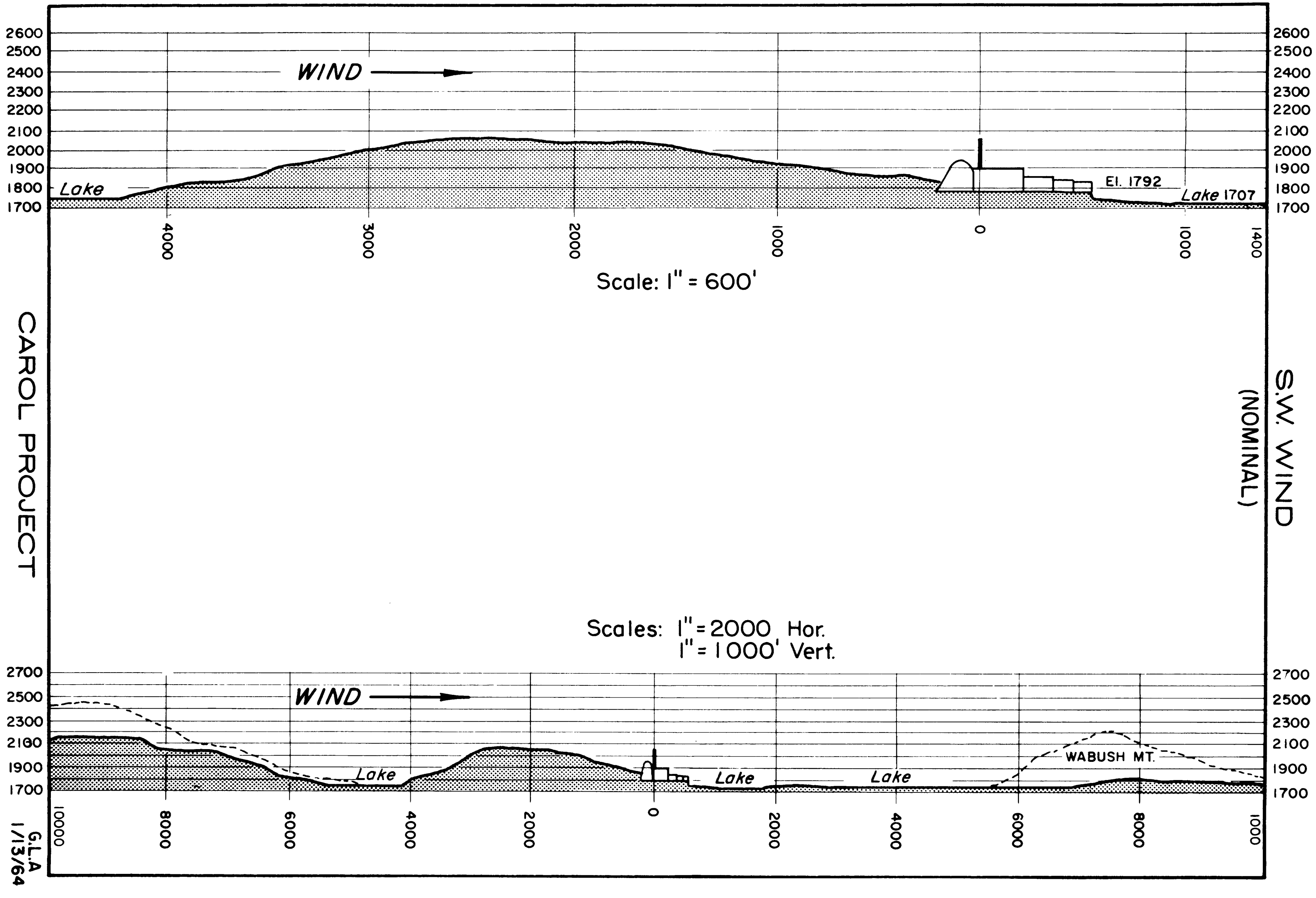


Fig. 5. Section of terrain, wind from S.W. (nominal).

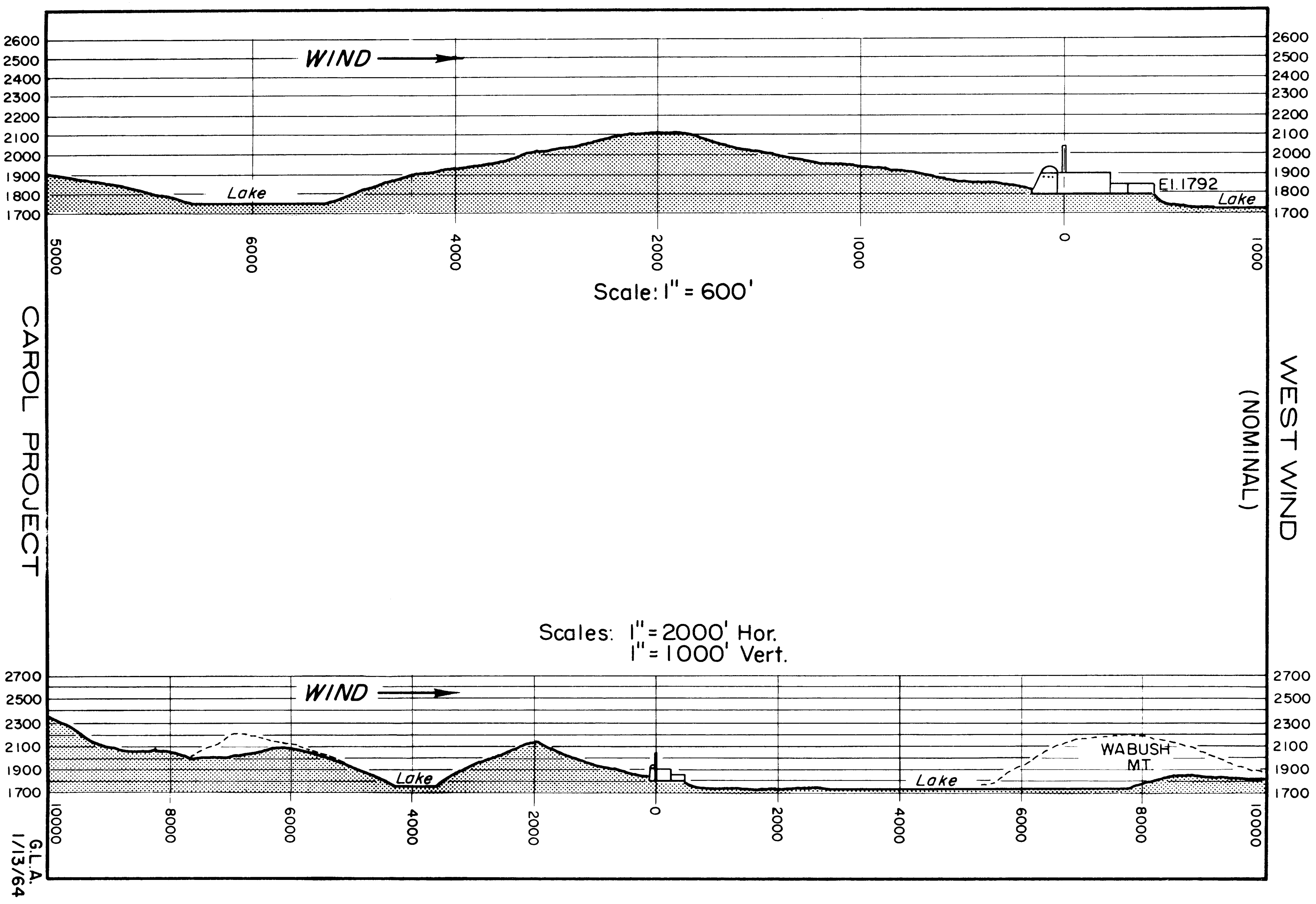


Fig. 6. Section of terrain, wind from W. (nominal).

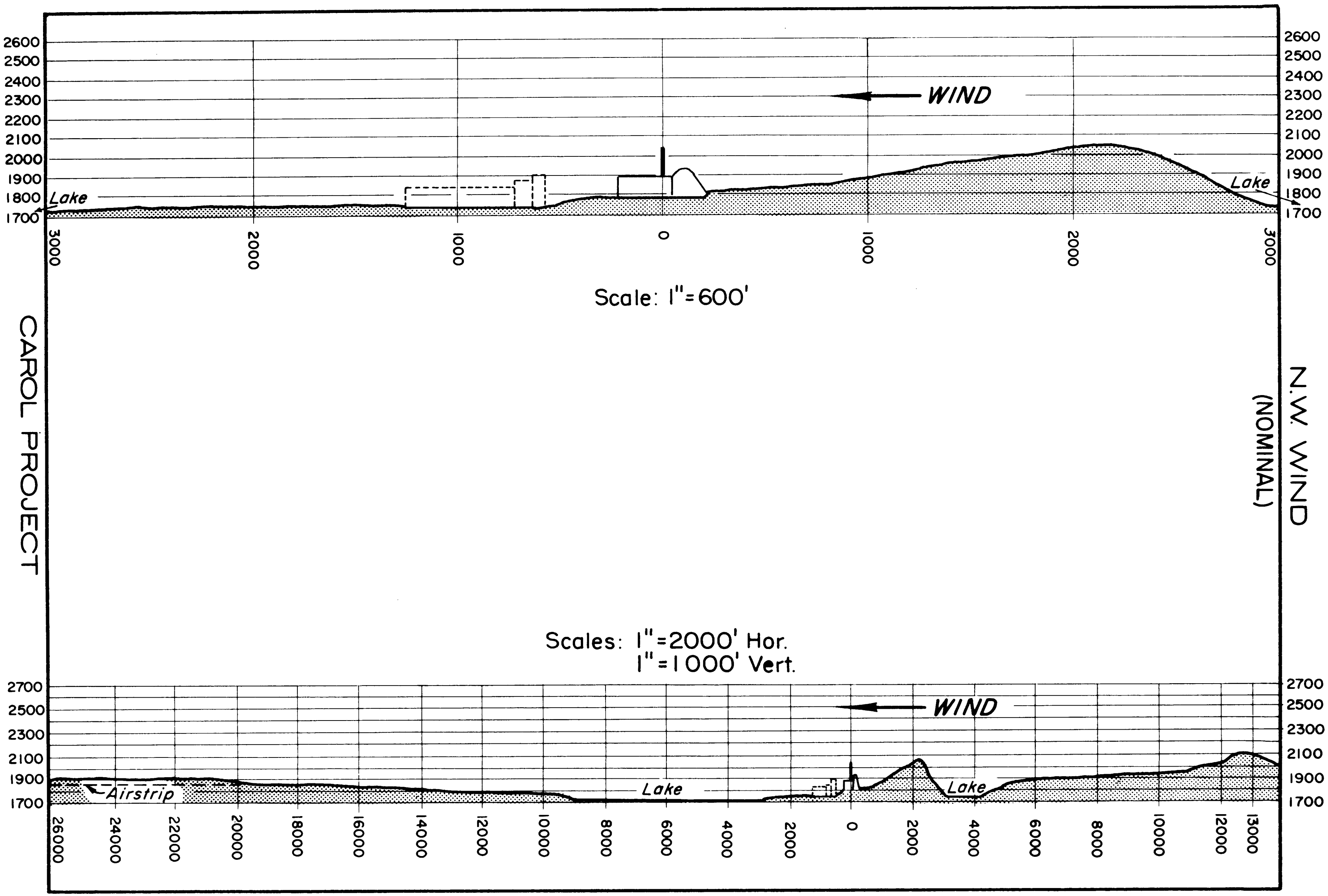


Fig. 7. Section of terrain, wind from N.W. (nominal).

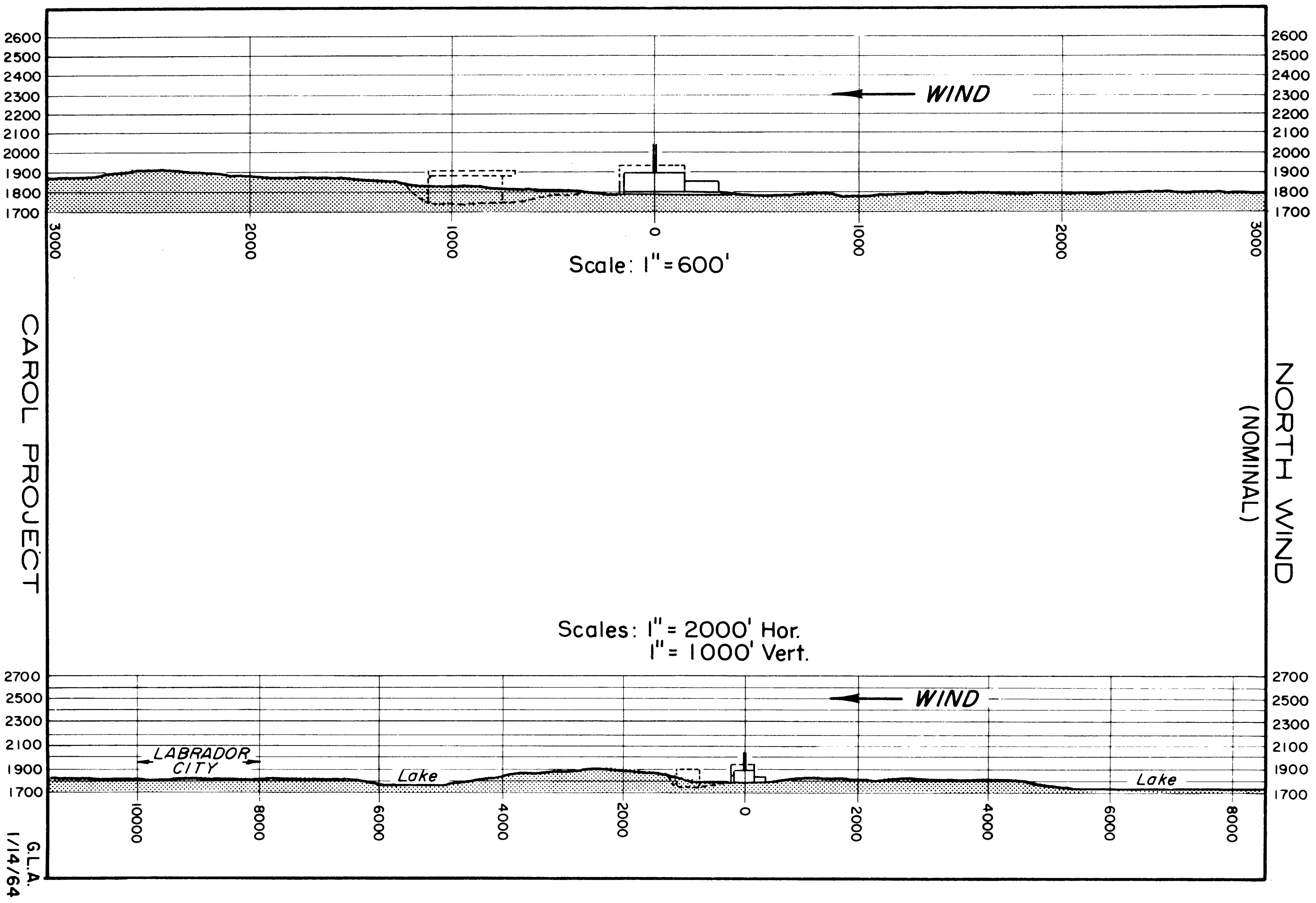


Fig. 8. Section of terrain, wind from N. (nominal).

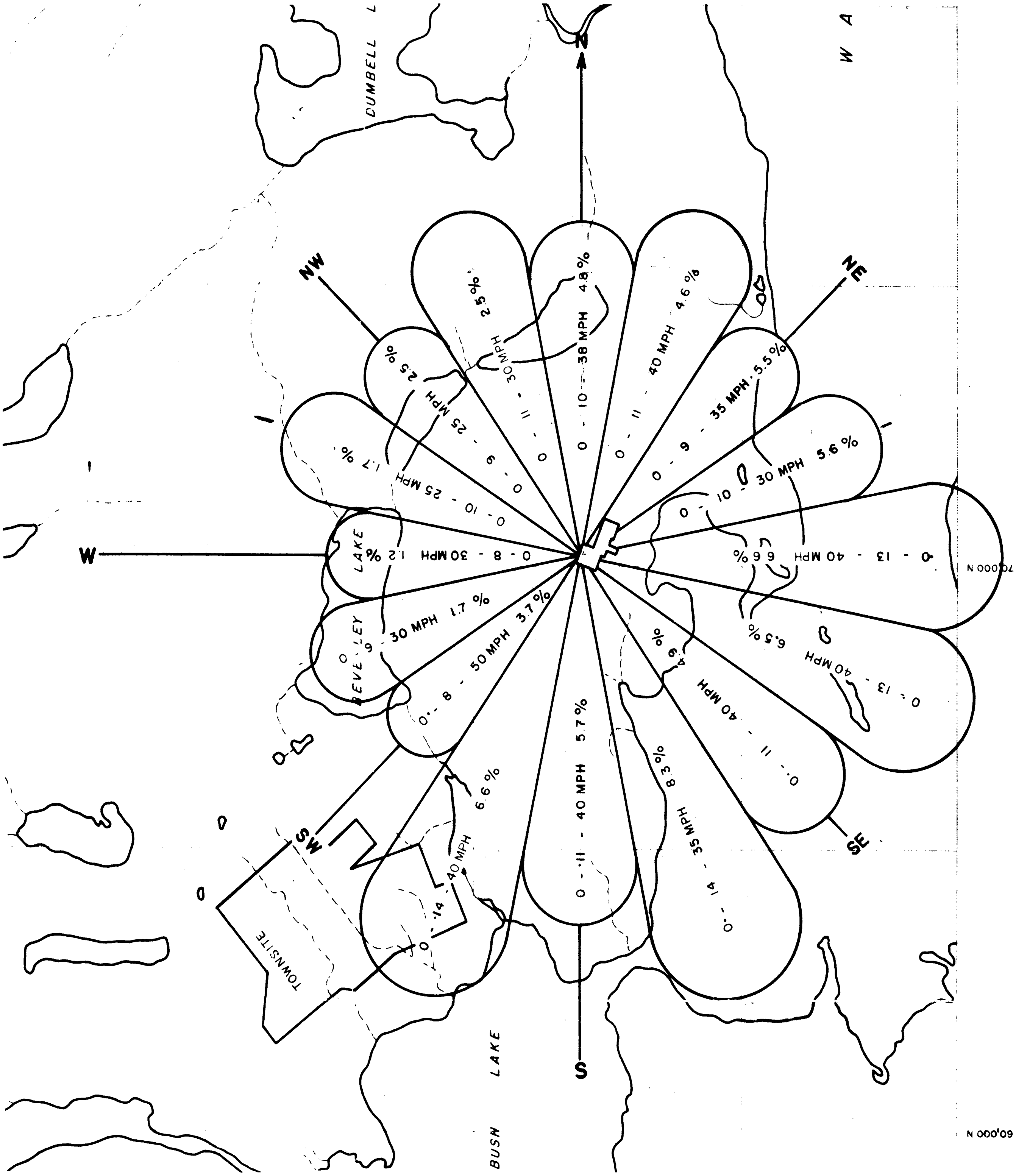


Fig. 9. Wind roses. Plan A.

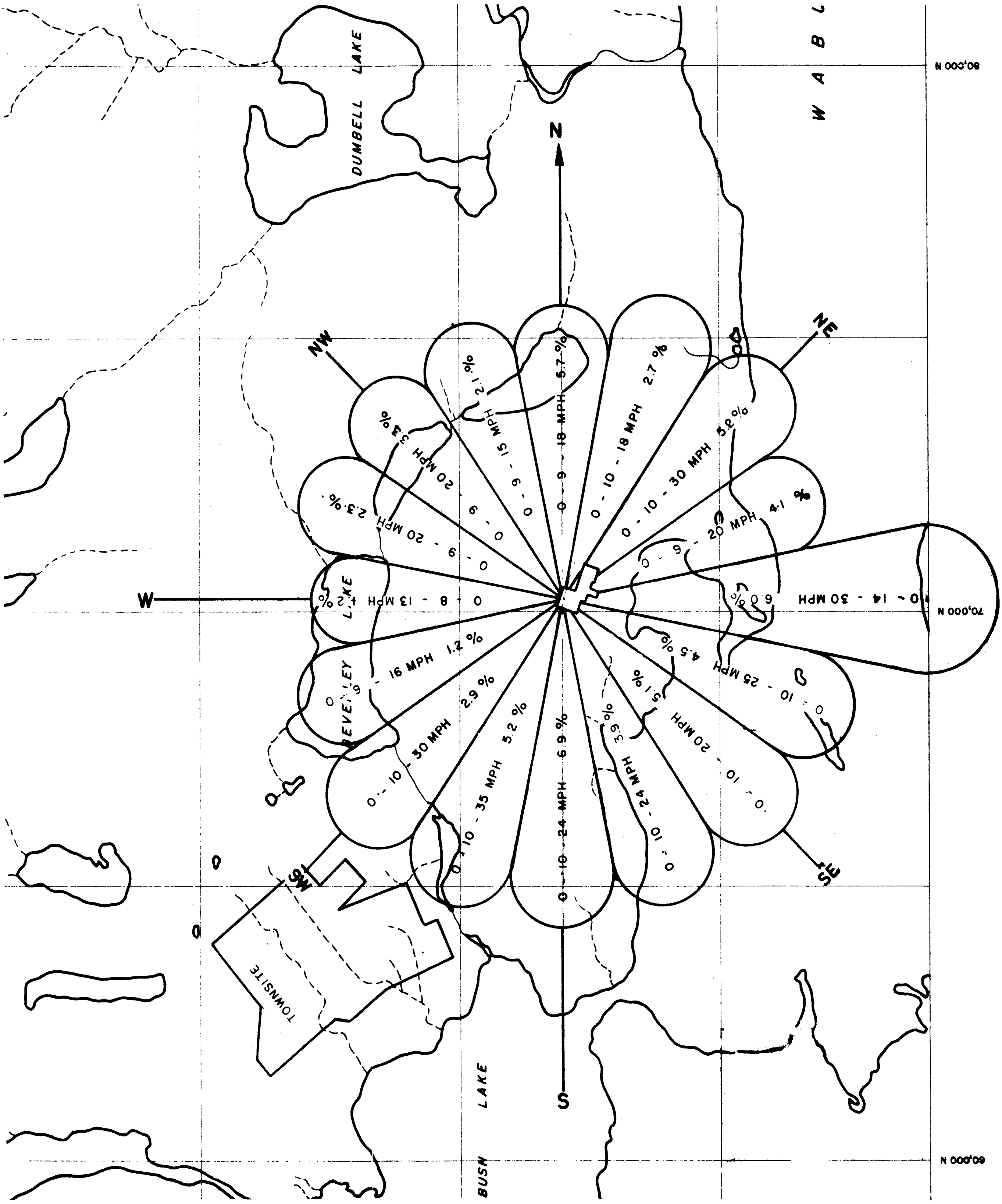


Fig. 9. (Continued). Plan B.

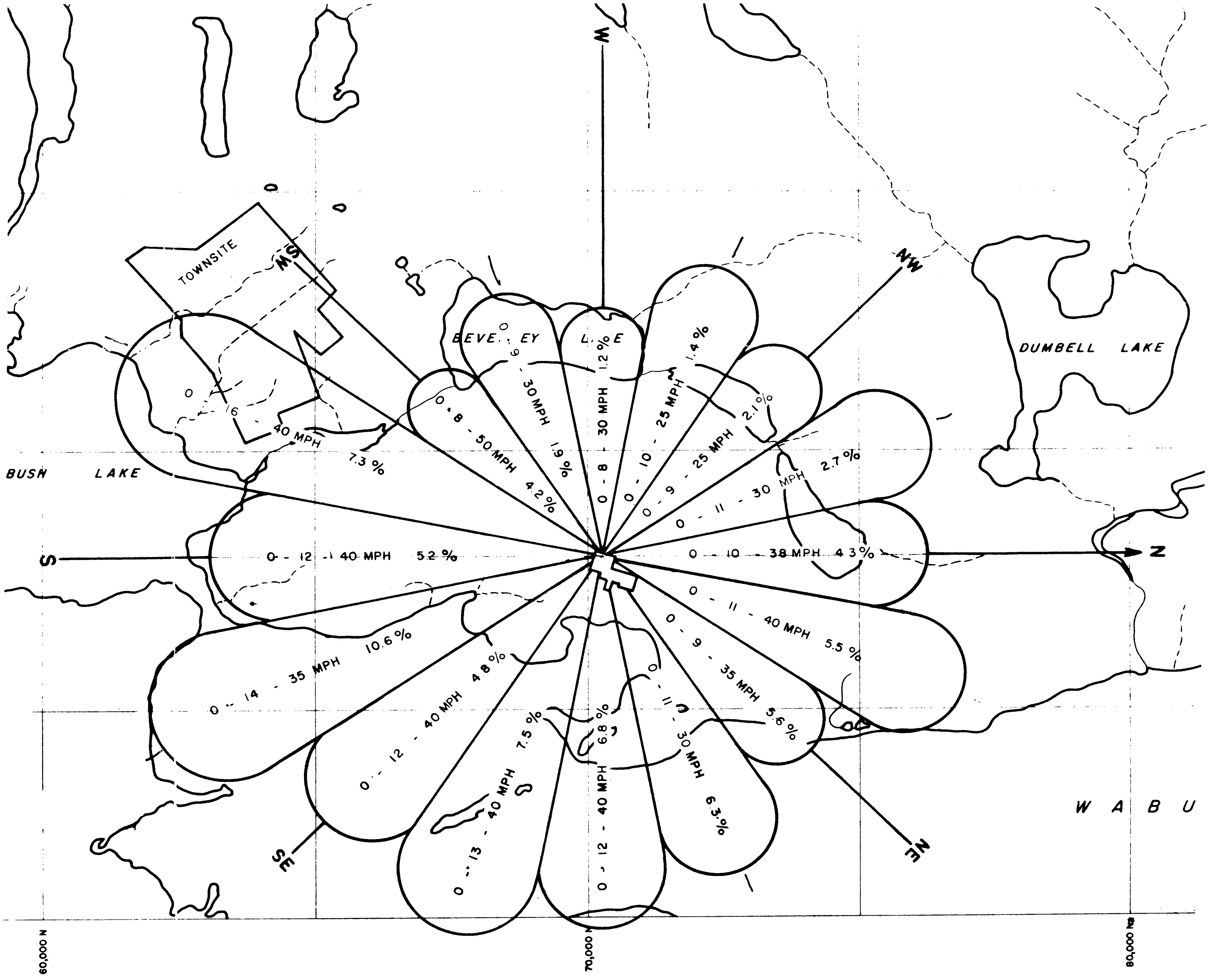
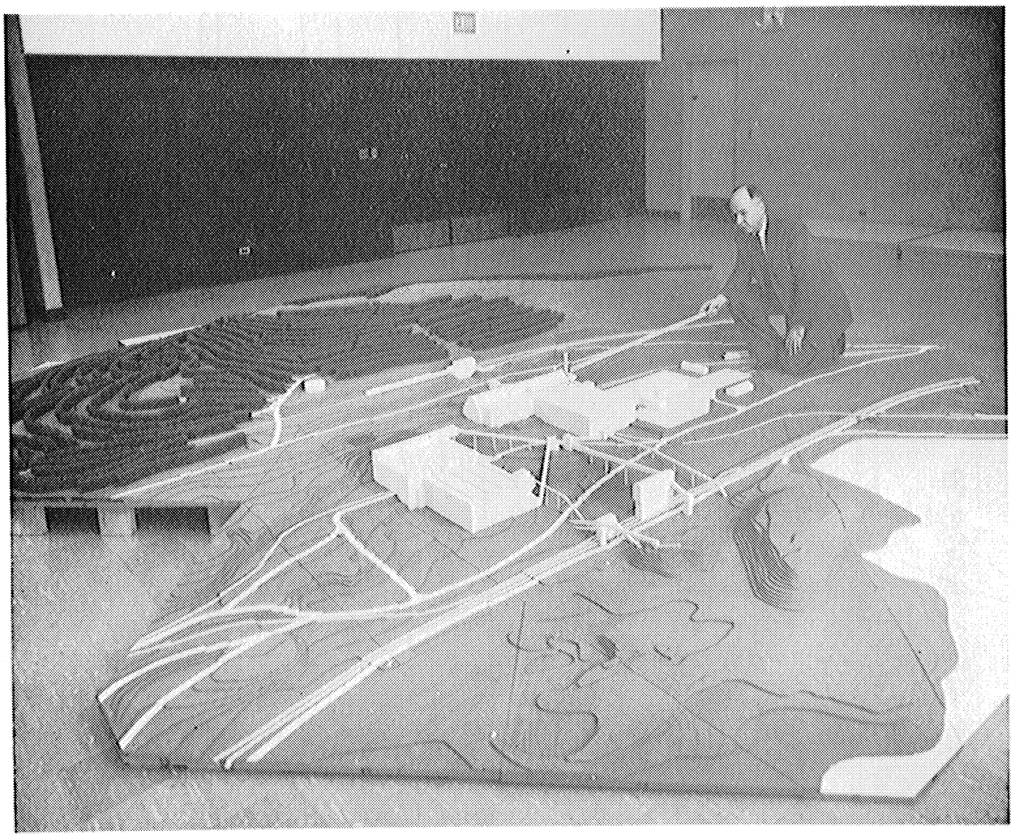


Fig. 9. (Concluded). Plan C.



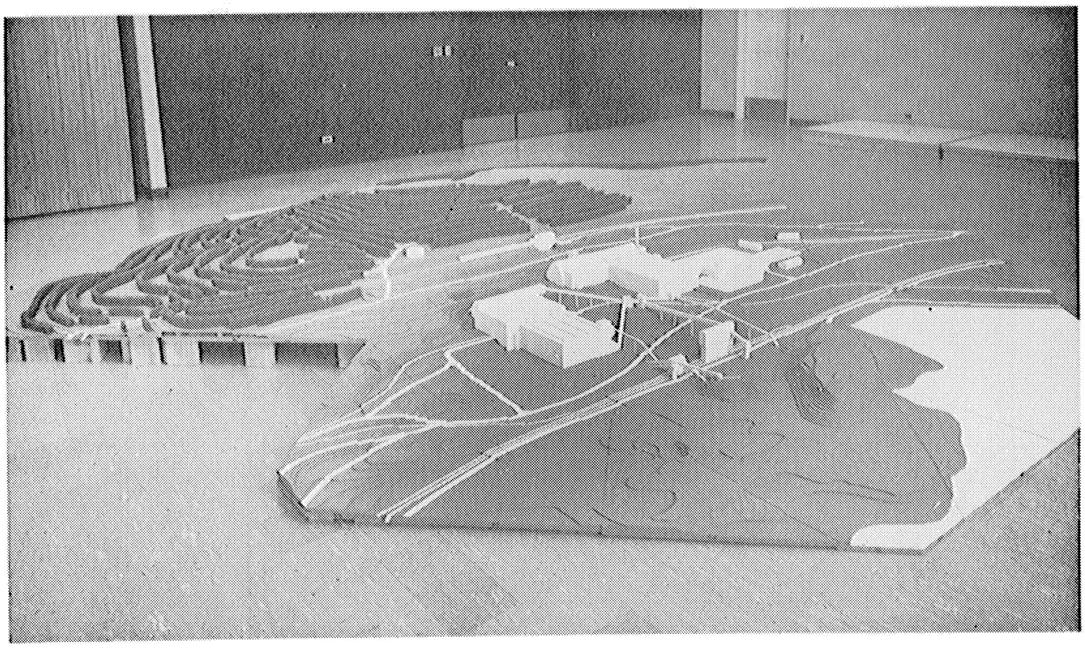
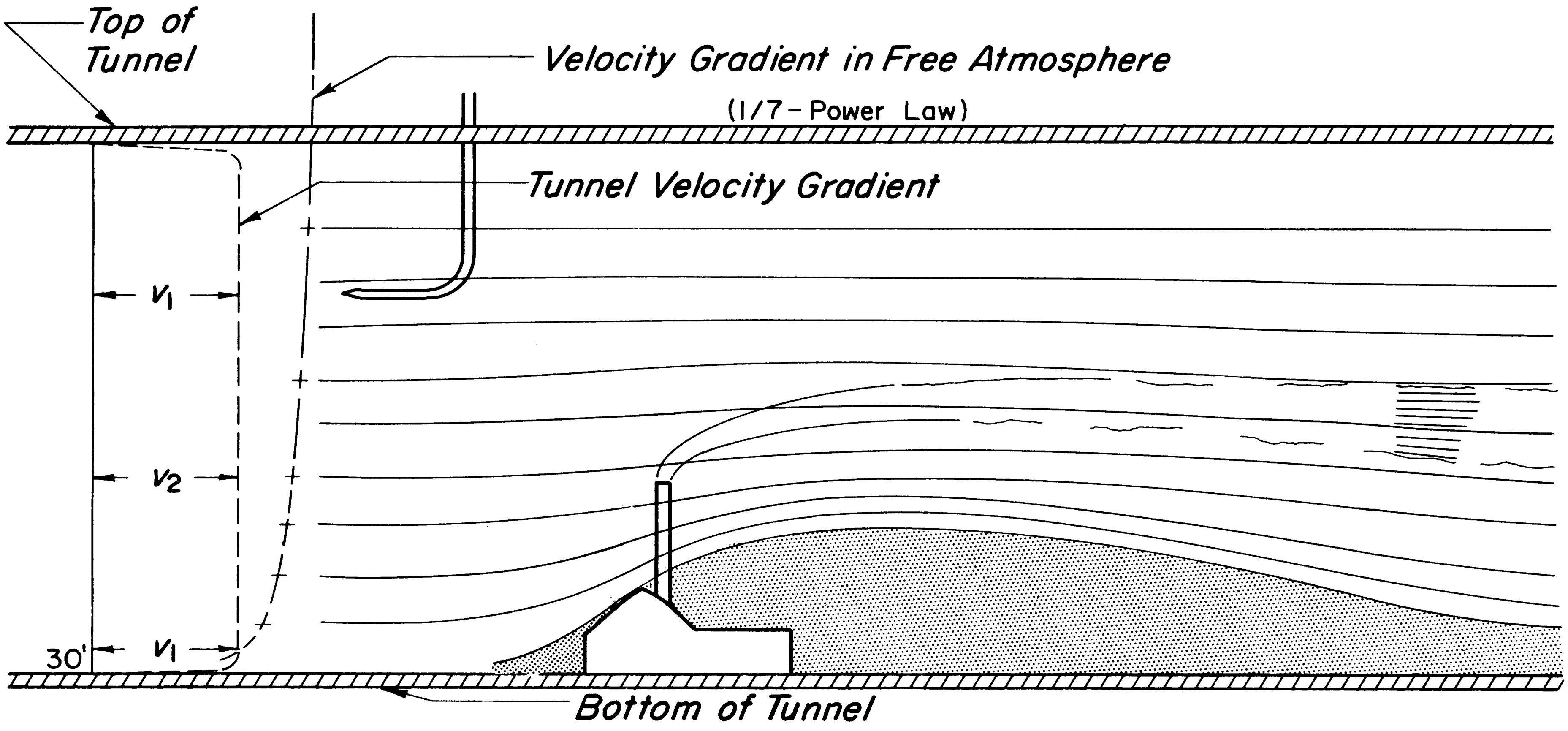


Fig. 10. Photograph of assembled model.



STREAMLINES AND VELOCITY PROFILES IN WIND TUNNEL

Fig. 11. Streamlines and velocity profiles.

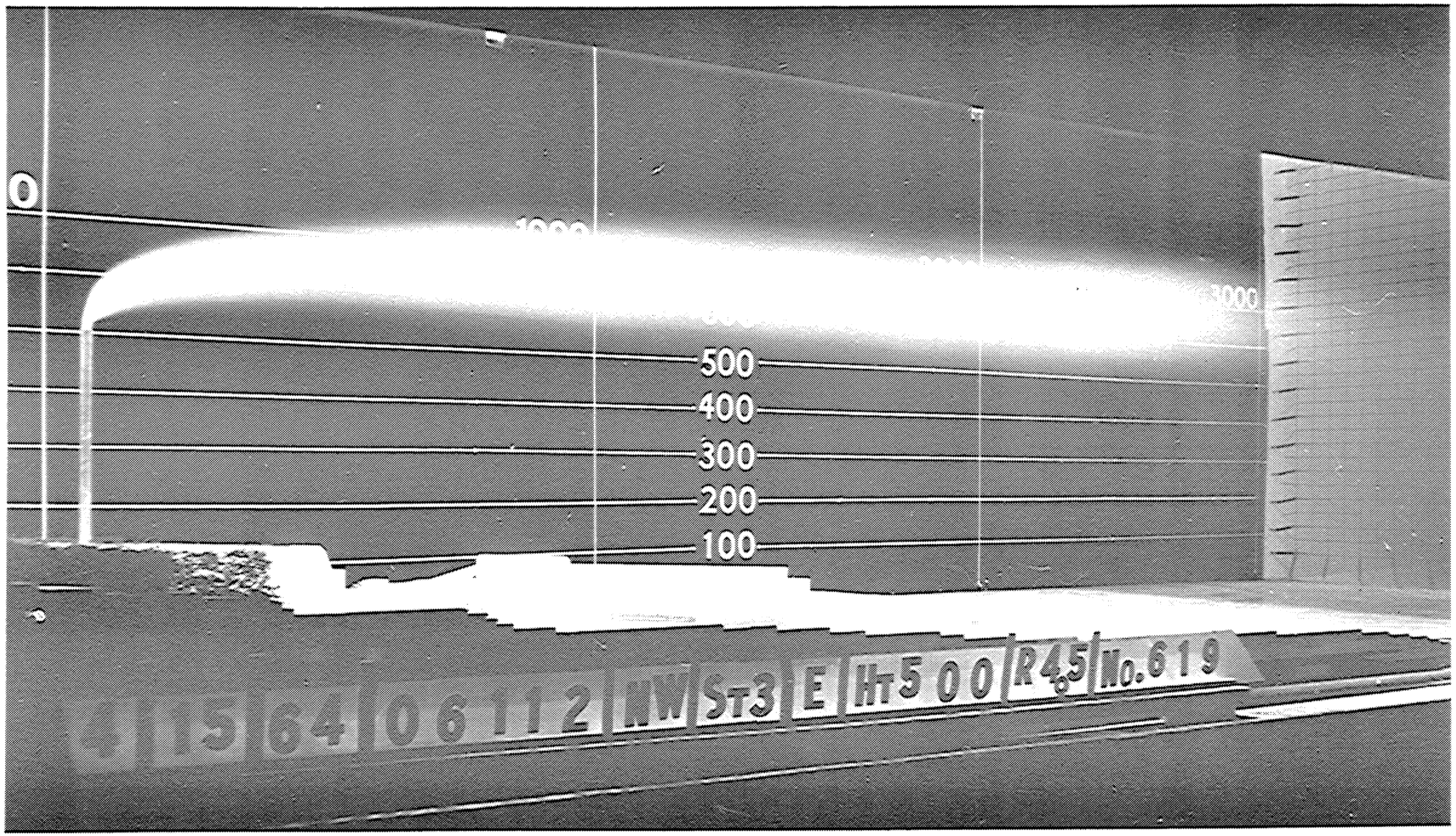


Fig. 12. Free-flowing plume in tunnel.

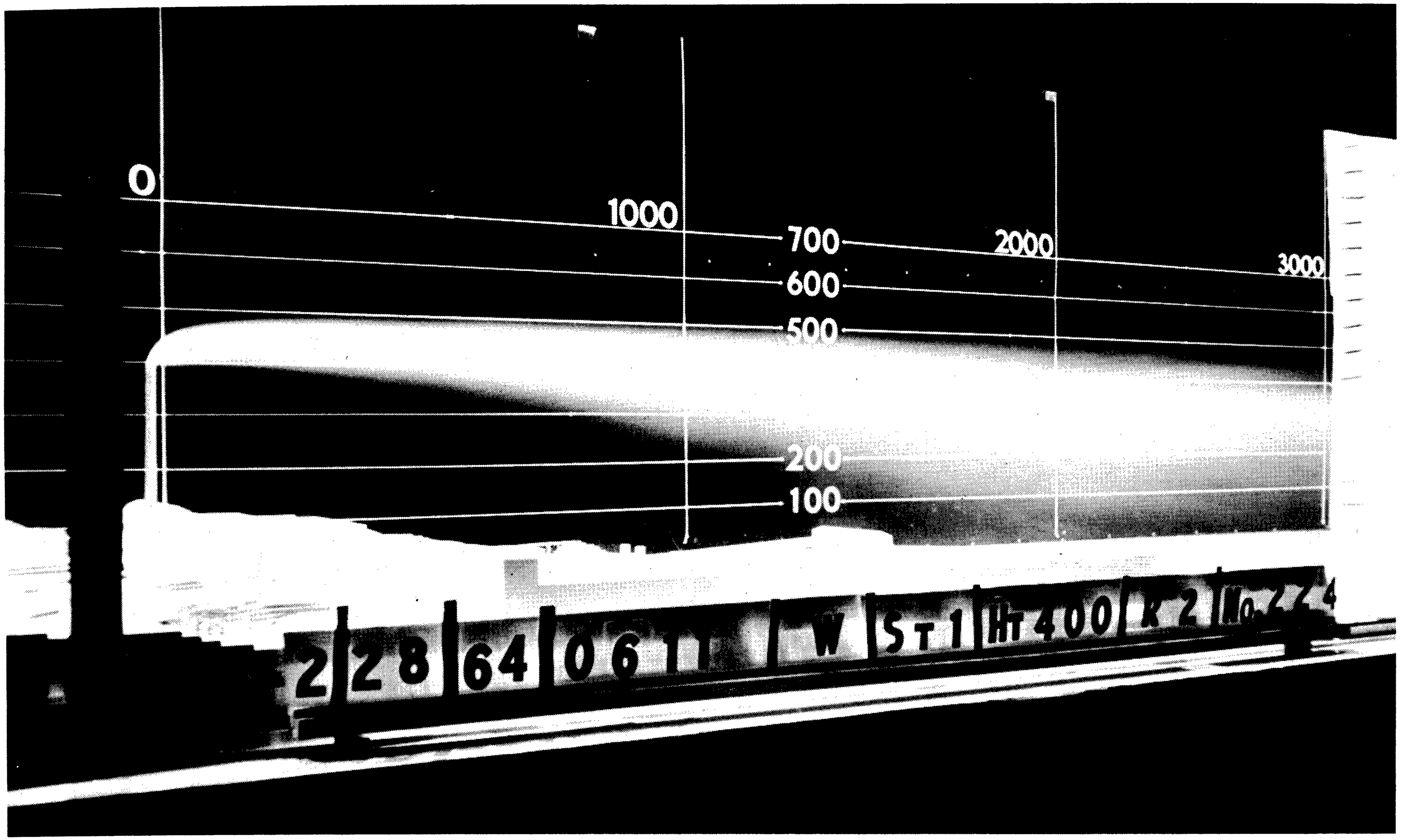


Fig. 13. Entrapped plume in tunnel (downwash).

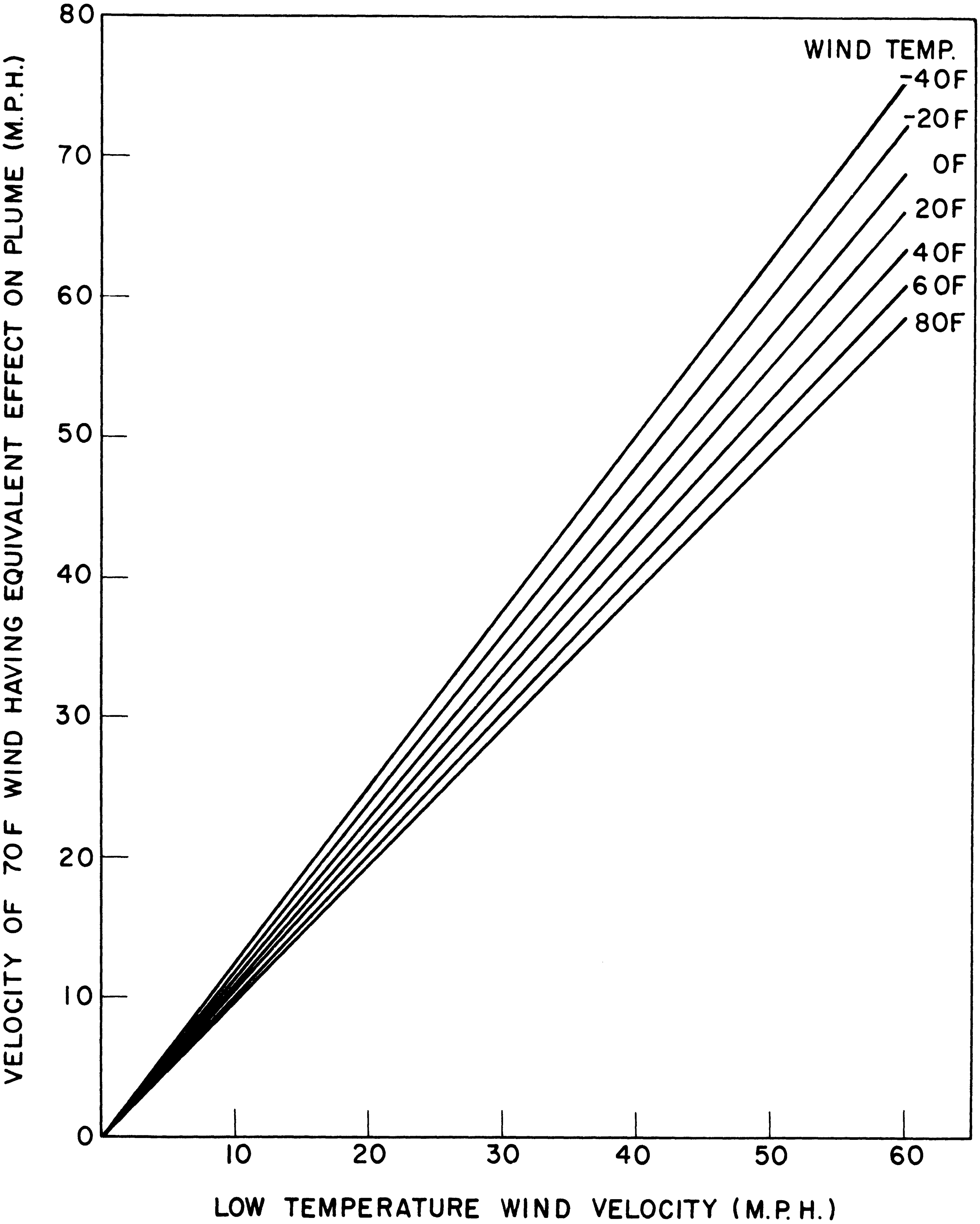


Fig. 14. Wind temperature effects.

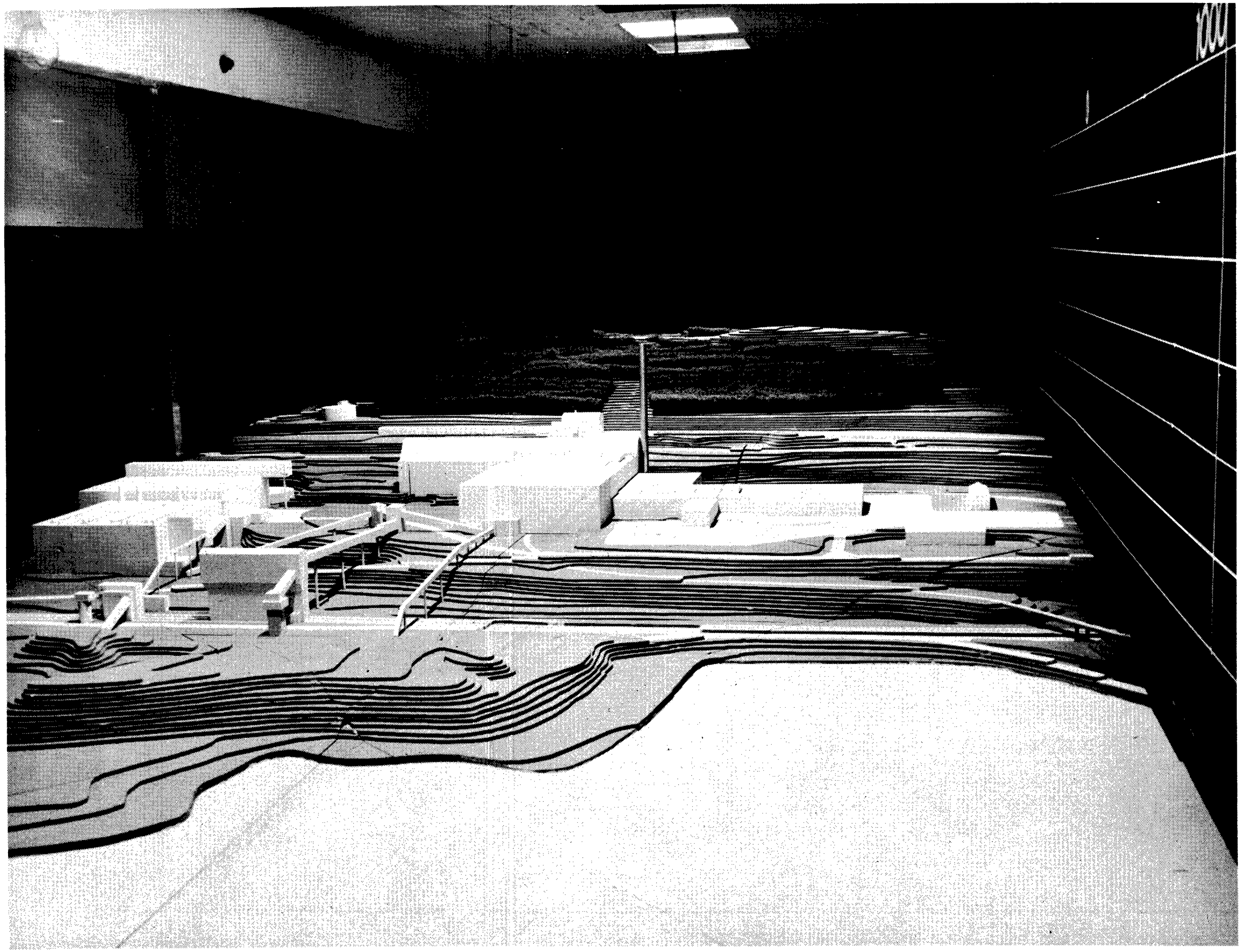


Fig. 15. Model in the tunnel.

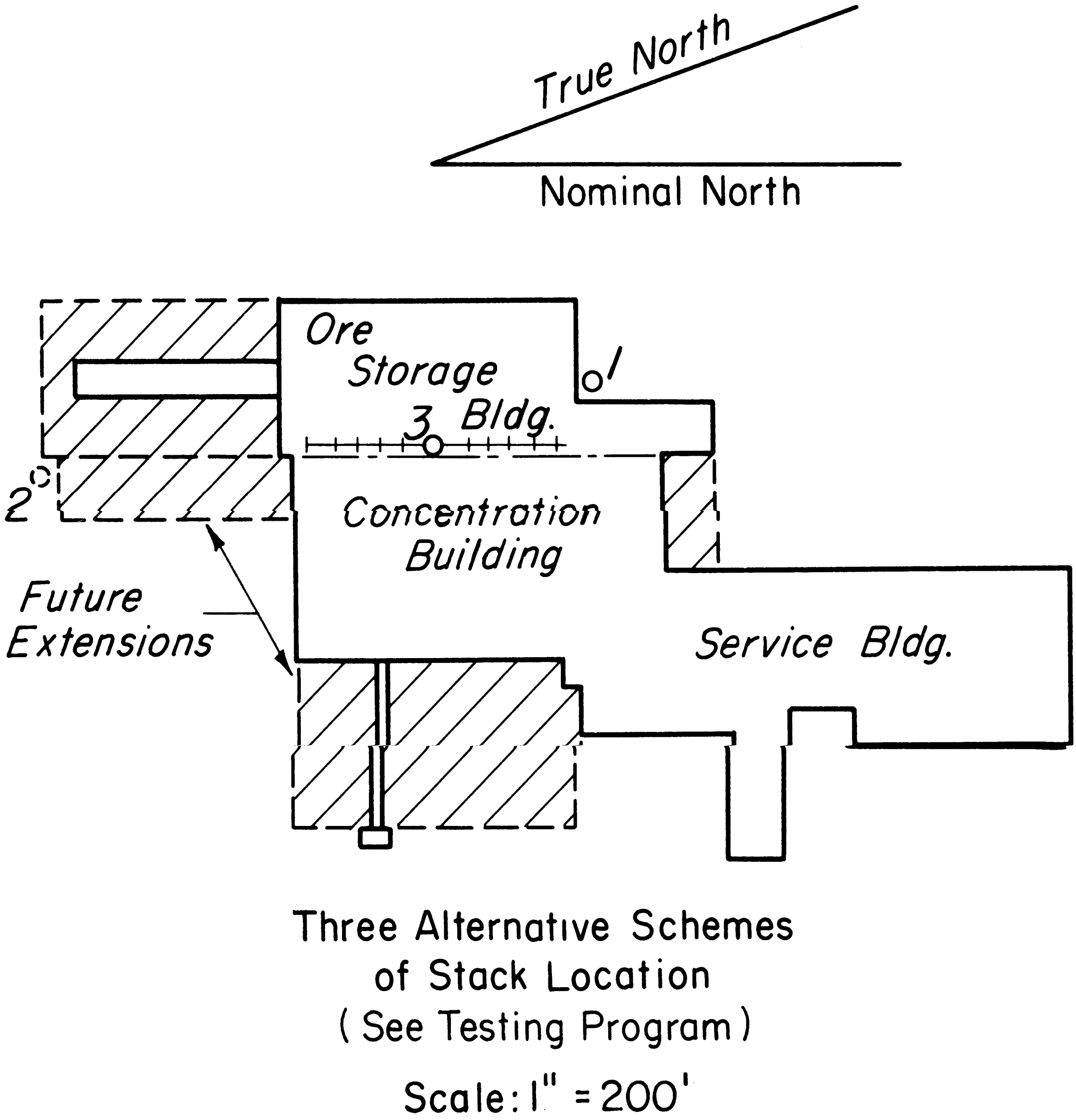
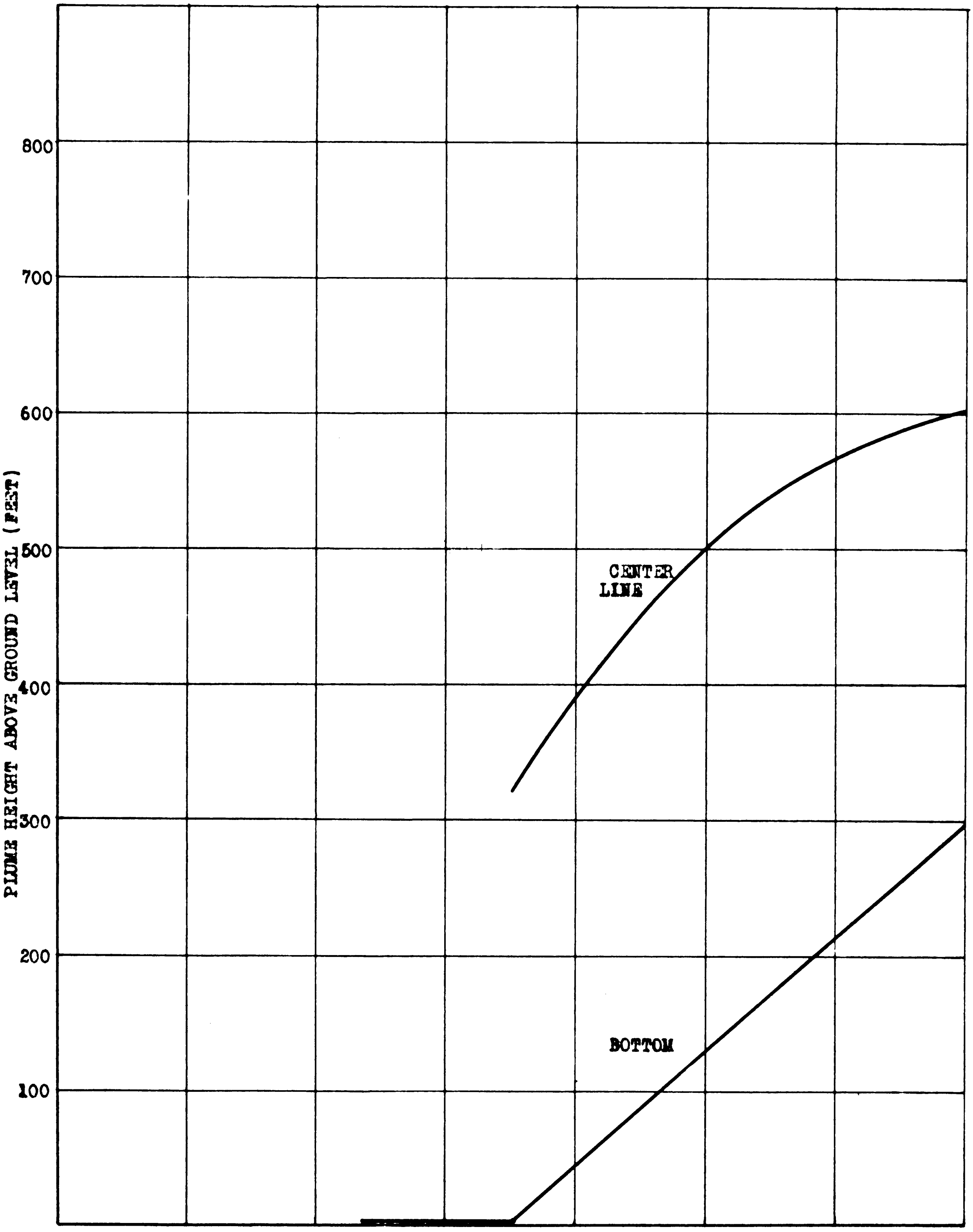


Fig. 16. Three alternative schemes of stack location.



WIND FROM NORTH-WEST
STACK LOCATION I.

STACK HEIGHT 350 FEET
PLANT WITHOUT EXTENSIONS

PLUME HEIGHT ABOVE GROUND LEVEL,
3,000 FEET DOWNWIND FROM STACK.

Fig. 17. Graph of wind tunnel data.

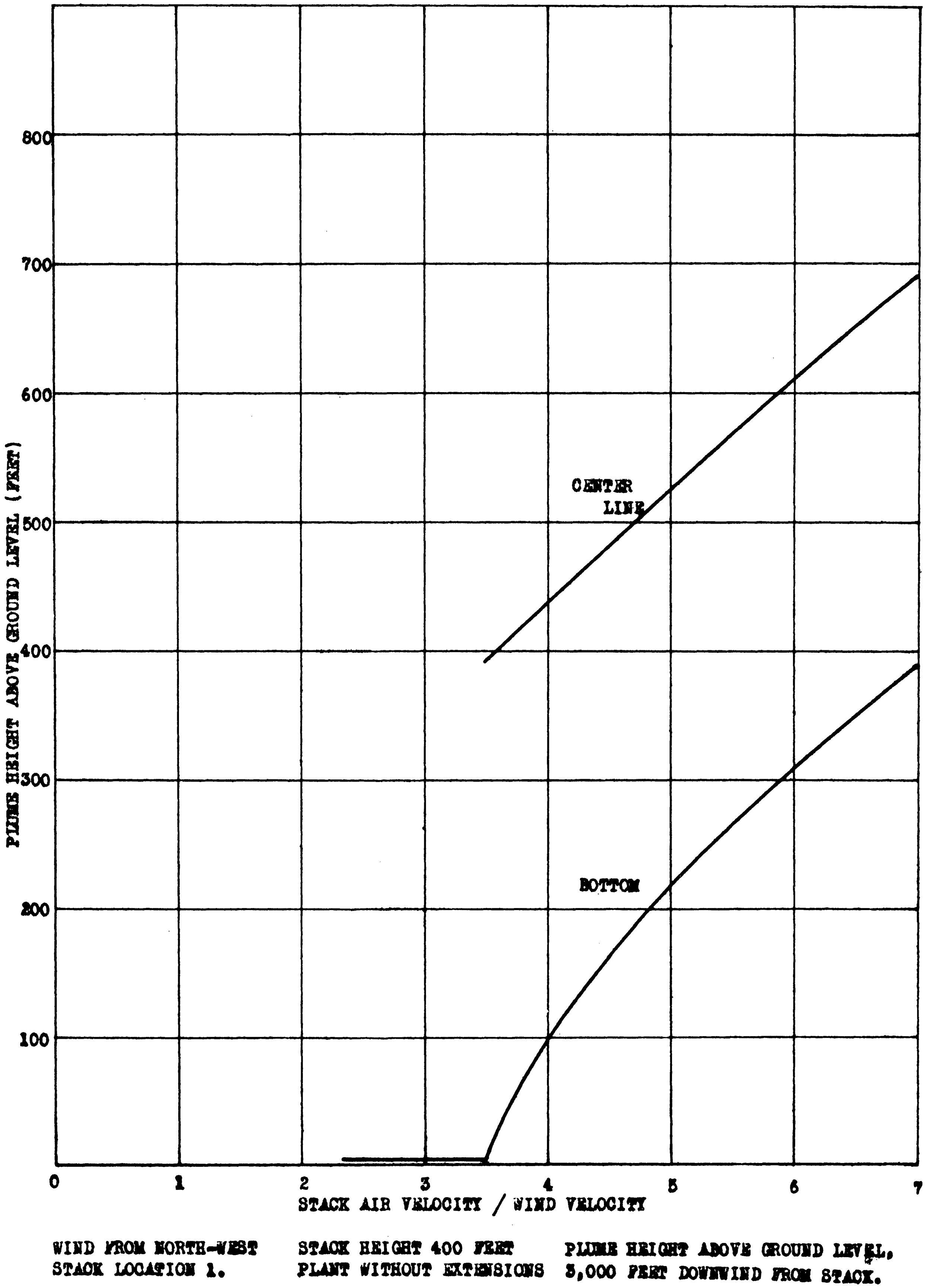


Fig. 18. Graph of wind tunnel data.