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SITES FOR WIND POWER INSTALLATIONS: Wind Tunnel Simulation of the Influence of Two-Dimensional Ridges on Wind Speed and Turbulence

Annual Report: First Year

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SUMMARY

The objective of this research was to increase technical capacity to locate favorable wind system sites, reduce uncertainty in the prediction or validation of the characteristics of sites, and thus assist in the sizing and performance prediction of wind systems. The research included evaluation of low speed aerodynamics over terrain and boundary flow conditions over ridges by means of wind tunnel modeling.

Measurements have been completed over triangular and sinusoidal shape hills of wind speed, static pressure variation, turbulence intensity, wall shear, and wind deflection. Hill aspect ratios studied range from 1/2 to 1/6 with some data available at 1/20. Measurements of wind overspeed, streamline patterns, and turbulence changes over the topography are compared with results from boundary layer theory. Large overspeed effects over the hills are found for the shear layers investigated.

While the present data is still of a preliminary nature, it is found that the general inviscid flow analysis produces speedup values of the right magnitude. A detailed analysis of the effect of ridge shape on the local flow conditions will be possible when the evaluation is completed. The sharp crested ridges appear to give higher speedup ratios as long as separation does not occur on the downstream surface. As would be expected, separation is more pronounced on the sharp crested ridges. The effect of separation will vary with both the approach conditions and the Reynolds number.

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NOMENCLATURE

b	width of hill or ridge
C_p	pressure coefficient
d	diameter of static pressure hole
e	rms of fluctuating voltage output of wire
E	mean voltage output of the wires
$\overline{e_n e_y}$	time average of the product of the voltage output of the normal and the yawed wire
E_u	spectrum function of longitudinal turbulence kinetic energy
g	gravitational constant
G	transform operator
h	model height
H	height to top of grid
k	von Karman constant
L	1/4 times length of hill models
p	pressure
R	ratio of longitudinal velocities at $Z = 40$ m and $Z = 10$ m
Re	Reynolds number
Re_h	Reynolds number based on hill height
Ri	Richardson number
S	speedup ratio
ΔS	fractional speedup ratio
U,V,W*)	longitudinal, lateral and vertical mean velocities
U* *)	surface shear velocity
u,v,w	rms of turbulent velocities
$\overline{uw}$	time average of the product of the longitudinal and vertical turbulent velocities.
x,y,z	coordinates in upwind longitudinal, lateral and vertical direction

$\bar{x},\bar{z}$	transformed coordinates
z_o	roughness height
z_s	terrain height
α	exponent in power law
δ	boundary layer thickness
η	vorticity
θ	potential temperature
θ'	potential temperature deviation
ν	kinematic viscosity of air
ρ	air density
τ_w	wall shear stress
ψ	angle of yaw of the wire in the flow (page
ψ	stream function (page

*)subscript o indicates the value in the approach flow

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1.0 INTRODUCTION

Information on the general wind characteristics of a geographical region is a prerequisite for considering the utilization of wind power at a site. Climatological data gathered at area weather stations (usually located at flat open terrain near airports) will often provide information concerning wind speed, duration, return time, turbulence, etc. over a number of years. However, if the area in which wind power installations are to be made includes hilly country, an obvious desire is to choose sites on or near the top of hills or ridges, to take advantage of the faster moving stream of air which results from compression of streamlines near the summit. Thus, it is important to be able to correlate wind behavior approaching a hill and the hill topography with the character of flow over the hill.

In 1974 an extensive review of applications of fluid mechanics to wind effects on buildings, power plants, and urban areas (wind engineering) by Cermak (1974) summarized research needs for the coming decades. He concluded that one of the three major areas for investigation is to:

> "Determine the effects of local topography, trees and buildings, and atmospheric stability on wind characteristics at potential wind-power-generation sites."

Past experience with large power mills indicates that perhaps the single most important factor controlling success or failure of these systems is site selection! Incorrect placement of a site of only a few miles may drop performance to one fifth of the original expectations. The difference between the power available in an annual average wind of

10 mph versus 12.5 mph is 100 percent. Once a wind system is designed to optimally operate at a lower wind speed mechanical, aerodynamic and generating efficiencies may permit only a linear improvement at higher average annual velocities (Putnam, 1948).

Recognition of site selection importance has led to a series of monographs and papers on this subject. Unfortunately, there is only a limited amount of field and laboratory information from which the authors could draw conclusions. Indeed, because of the variability of the atmosphere and the presence of many factors which exist simultaneously, it is difficult to isolate the independent influence of topography profile, surface roughness of stability. In the 1940's and early 1950's, laboratory studies in aeronautical wind tunnels were also completed; unfortunately, the investigators found little resemblance between the field and wind tunnel results. P. C. Putnam, summing up wind investigation connected with the Grandpa's Knob aerogenerator, wrote, "...after five years of increasing familiarity with the problem of site selection, we can point to no analogy between the profiles of mountains and the profiles of airfoils by which one can predict mean wind velocities at hub height within limits which will be useful," and, again, "...we have found no criteria by which to make an economically useful quantitative prediction of the effects of topography upon wind flow." E. W. Golding seems to fully subscribe to Putnam's views, but he somewhat wistfully writes, "...it would be very convenient if it were possible to use a precise formulae relating the wind speed at a certain height over the summit of a hill of a given altitude and shape to the undisturbed wind speed at the same altitude but at a distance upwind from the hill. This would facilitate the choice of sites; one might almost choose them from close study of contoured maps, if sufficiently detailed, without being familiar with the actual localities. But no such method can be followed: it is not possible to work from the formulae" (Putnam, 1942; Golding, 1955). Early efforts to accomplish this goal were hindered by difficulties in determining the undisturbed wind at the level concerned (Petterssen, 1961), and incorrect laboratory simulation of the effects of the atmospheric surface shear layer and stratification (Putnam, 1942; Lange, 1961).

Since the Federal Wind Energy Program became active in June, 1973, a variety of research has been funded to encourage wind power as an alternative energy resource. Several laboratories have proposed utilizing meteorological wind tunnels to evaluate the characteristics of a specific site (Hewsen, 1973). A small program is underway in New Zealand to evaluate flow over escarpments (Bowen & Lindley, 1974); however, recent summaries (Cermak, 1974; Frost, 1974) support the conclusion that the wind energy site analysis proposed for continuation by this proposal is unique.

Certain advantages of benefits of laboratory simulation may be realized when similarity conditions are partially or actually satisfied between field and model. These are:

1. The problem may be studied in the three space dimensions.
2. A certain latitude is available for controlling the essential variables in the problem.
3. The inherent possibility for defining and locating particular problems which might exist on proposed weather sensitive field projects.
4. Determination of the location of sites for meteorological instruments and towers, wind power generators, etc., in the actual field for the purpose of obtaining representative observations pertinent to a particular project.

5. Obtaining relevant data that may be used in guiding field programs toward their proposed goals.

6. The reduction in time and expense of extensive field programs or studies.

Prediction of upper level flows in the undisturbed atmosphere has improved substantially in the last 25 years (Haugen, 1973). Successful modeling of atmospheric phenomena in a wind tunnel has only been accomplished in the last 15 years. The thin surface layers developed in the short aeronautical tunnels failed to reproduce even the gross character of wind profile, stratification, turbulence, and spectra required. In addition, early attempts to produce thicker shear layers with grids produced flows which were not spatially stationary. By combining the best of present understanding of the atmospheric surface layer, laboratory simulation, and numerical extrapolation procedures, Golding's speculation may become a reality. In the following sections, the report will review the conclusions of past investigations of topographical flow fields, describe the wind tunnel facility and experimental design discussed herein, and present some of the results of laboratory simulation of flow over two-dimensional ridges.

2.0 REVIEW OF PRESENT UNDERSTANDING OF WIND-POWER SITE SELECTION

In what appears to be the most recent statement concerning the art of wind-power site selection, the World Meteorological Committee led by Ben Davidson (1964) remarked that

> "...the question of the variation of wind and of exchange coefficient with height above the surface layer is not at this stage in a very satisfactory state....Still less satisfactory is the theory of wind flow in the neighborhood of obstacles. Here the conclusions of potential flow theory may be drastically modified by buoyancy forces, irregularities in slope of the obstacles and the small-scale roughness aspects of both the up and downwind slopes."

Davidson concludes that it is "almost impossible a priori to estimate the numerical value of the speedup factor if indeed such a factor exists for any particular locality." It would indeed be unfortunate if the wind-energy program abandons this area with so little actual information--the energy advantages to prediction to within even 25 percent are immense.

2.1 Field and Laboratory Evidence

Since it is desirable to be able to analyze potential site locations quickly, it is unfortunate that the quantitative effect of these important variables is not known.

One can divide the influence of the atmospheric motion on wind power into four areas:

a) Variation of wind speed over uniform terrain,

b) Local wind circulations,

c) Flow over slight or moderate relief, and

d) Flow over high mountains.

Each of these areas have received attention from past investigators. Indeed a wealth of information exists on category a, the understanding of which has recently been summarized in an AMS monograph (Haugen, 1973). However, if there is an abrupt change in roughness and heating for even flat terrain, major changes can occur as considered under category b, local wind circulations.

Local wind circulations may be driven by nonhomogeneities in roughness, temperature, or pressure. A good deal has been learned recently in the laboratory about these situations (Yamada and Meroney, 1971; Kahawita and Meroney, 1973; Cermak and SethuRaman, 1973; Huang and Nickerson, 1972; Meroney and Cermak, 1974). If a wind power site is placed near a seashore for example, the influence of the sea breeze may be significant. Similar effects may exist near an urban heat island. Saddle points, passes, or gaps offer possibilities for enhanced winds especially if they are open to a prevailing wind direction. Such local effects can greatly enhance energy potential; yet, they do not usually show up in national wind survey results.

Flow over slight or moderate relief may result in enhanced wind speeds due to wind "overshoot" or "speedup." There do exist a few field measurement programs over terrain features carried out specifically to estimate wind power potential (Putnam, 1942; Golding, 1955; Frenkiel, 1962-63; Frenkiel, 1963; Archibald, 1973; Hewson, 1973). These results are to a large degree site specific and do not cover a wide enough range of terrain types to allow more than a very limited and qualitative generalization to other situations. The combination of hill features, roughness, upstream topographies, and stabilities studied to date even appear to lead to a set of contradictory conclusions (Davidson, et al., 1964). A number of additional field and laboratory investigations of flow over topography have been completed which were not specifically oriented toward understanding for wind power site selection. The characteristics of a number of these studies together with typical results have been compiled into Table 1. These studies span some 46 years; over seven countries; and include gentle hills, cones, ridges, escarpments, and mountains. A number of the laboratory results included or were performed in parallel with field measurements.

Putnam (1948) reports meteorological measurements made over eleven peaks and ridges, four of these were modeled in aerodynamical wind tunnels. Unfortunately, the observed speedup factors are much in doubt due to difficulties in determining the undisturbed wind at peak level (Petterssen, 1961). The some 20,000 velocity measurements made over the wind tunnel models are of dubious value. Since the shear layer of the atmosphere was not preestablished, approach velocity profiles may have had power law coefficients near zero; in addition, the absence of stratification modeling may result in either too high or too low values for speedup, S. Other investigators (Field and Warden, 1963; Zrajevsky, Doroshenko and Chepik, 1968) have also failed to model approach wind profile during atmospheric simulation.

Frenkiel (1962) and Golding (1955 and 1956) published results of measurements over four hill summits. No measurements are reported on the character of the approach wind. A correlation is reported, however, between hill slope and the power law uniformity of the wind profile above the hill. It is suggested this can be a good criteria of the quality of the site for wind power once measured.

Stratification can make a major difference in the dynamic and kinematic behavior of wind flow over topography. Garrison and Cermak (1968), Kitabayshi, Orgill and Cermak, (1971), Orgill, Cermak and Grant

(1971), Meroney and Cermak (1967), and Lin and Binder (1967) consider flow over topography in the presence of stable stratification. In each case there is quantitative field evidence of similarity including the effects of stratification but poor simulation without it. Whenever the atmosphere is stable, to conserve energy the wind will want to go around the obstacle rather than over it. This should result in increased wind speeds along the edges and in gaps of hills and ridges.

High mountain ridges are potential wind power sites. It is true such sites often produce very high winds of large gustiness--yet future designs for power mills may permit use of this extremely energetic wind.

Current research at Colorado State University is examining stratified shear flow over hemispherically shaped hills (Hansen, 1975). Stratification has a strong effect on flow over and around hills. The intensity of an inversion may influence both wind velocity and direction (Putnam, 1948; Frenkiel, 1962). If inversions are frequent, a site on the hillside rather than on the hilltop may lead to larger annual average velocities. Stratified flow over mountain ridges may lead to lee waves or helm winds (Yamada and Meroney, 1971). Scorer (1951) has studied high winds in mountain gaps. Mountain ranges can lead to regions of underspeed as well as overspeed; thus the exact site is critical. Mountain range effects cannot be studied, however, without adequate simulation of stratification (or "compressibility" as described by Putnam). There is very extensive literature dealing with orographic induced waves. Since most of it deals with cloud systems and upper atmospheric character far from the surface, it is not reproduced here.

On mountaintops speedup effects as well as "speed down" effects may be observed. These effects seem to depend on the orography, slope, roughness, stability, and insolation. Thus one even sees maximum winds, not on the highest peak but at some lower level (for example, the behavior of the Hump of Mt. Washington (Putnam, 1942)) in a mountain range.

A number of field and laboratory investigations are recently available which specifically examine the influence of hill slope and profile. Plate and Lin (1965), Plate and Sheih (1965), and Chang (1965) report measurements of neutral and unstable shear flows downwind of triangular and sinusoidal ridges. Beebe and Cermak (1971) have measured flow fields over a wavy boundary where the ridges have various amplitudes and wavelengths. de Bray (1973), Freeston (1974), and Bowen and Lindley (1974) considered shear flows over upwind facing escarpments. When the upstream wind profile and stratification were simulated, close agreement appears between laboratory and field measurements.

The consensus of experience with wind site evaluation over low to medium height ridges or hills would suggest the following:

1. Ridges should be athwart the principal wind direction, but high velocities are not likely on upwind foothills.

2. Hilltops should not be too flat, slopes should extend all the way to the summit.

3. A hill on the coast as opposed to an inland hill surrounded by other hills is more likely to provide high winds (i.e., unobstructed upwind).

4. Speedup is greater over a ridge of given slope than over a conical hill of the same slope.

5. Speedup over a steep hill decreases rapidly with height.

6. The optimum hill slope is probably between 1:4 and 1:3 with 1:3.5 best (h/L between 0.5 and 0.67).

7. Topographical features in the vicinity of the hill produce the structure of the flow over it.

8. Frenkiel (1962 and 1963) ranks sites based on the uniformity of the summit and profile. He suggests ranking which has been incorporated into Table 2.0.

9. Hills with slopes greater than 1:3 should probably be avoided.

10. Vertical wind speed above a summit does not increase as much with height above ground as over level terrain.

A great deal has been learned about atmospheric flows since the early wind power siting effort. Yet despite the variety of specific studies, no effort has been made to systematically understand the separate and/or combined influence of terrain aspect ratio, insolation, roughness, and stratification. A research program primarily experimental in nature is underway, which will hopefully provide over a three-year period, a unified body of knowledge on terrain aerodynamics. Golding (1955) recognized the importance of model tests. He mentions his own attempts to model flow fields by means of an electrolytic tank. He acknowledges the limitations of such efforts but realizes that more information is needed and the model studies could "at least indicate the relative merits of widely different shapes of hills and hill groups." As noted by Smith (1974) with respect to flow over building complexes:

> "It should also be remembered that this particular problem does not need to be solved and re-solved at every site in the country. It is true that an idealized series of tests could not be expected to represent very complicated structures and terrain, but in many localities models developed to fit simple shapes would be a satisfactory guide."

The objectives and elements of this program have been previously described by Meroney (1975). It is the intent of this report to present some of the typical results and conclusions of Part 1--the influences of ridge cross sections on wind speed and turbulence. Analysts such as Hunt (1973), Jackson and Hunt (1974), Frost (1973), Taylor and Gent (1974), and Freeman (1975) are very anxious to utilize even such limited data to validate numerical and analytical models.

2.2 Analytic and Numerical Prediction Procedures

In order to organize information gathered concerning the character of flow over hills, it is important to have a framework of understanding of the phenomena to permit one to generalize and functionalize the influence of changes in the physical parameters determining the flow. Theoretical attempts to predict the velocity distribution near the hill surface have mostly used numerical solutions of various equations of motion. A few authors have presented analytic solutions of physical models where the physics and mathematics have been simplified. It is not yet clear whether it will be most cost effective to analyze each site numerically in detail or choose sites based on the less intensive generic information provided by the simple laboratory or analytic approaches. In any event, it is expected that laboratory data may be used to verify the various methodologies.

2.2.1 Classes of Mathematical Windfield Models

Numerical prospecting for a suitable site for wind power generation will require a number of wind calculations to be performed for each site to produce a site climatology. Since a complete simulation of all site characteristics which might influence the wind field--such as topography, roughness, thermal forcing, etc.--require complex and expensive-to-run numerical programs, simpler models which might substantially reduce a cost benefit ratio have been considered. Freeman (1976) has suggested three model classes--primitive equation models, simplified physics models, and objective analysis (wind fit) models.

2.2.2 Primitive Equation Models

The primitive equation model group attempt to account for all possible influences on the wind field. These models are applied by performing three-dimensional time dependent calculations including the influence of diurnally-cyclic flow with terms accounting for radiation, roughness, condensation, topography, etc. Investigators such as Freeman (1976), Anthes (1974), Orville (1968), and Fosberg (1969) have prepared models which approach the wind flow problem in this manner. At present, these codes are really not ready for general use, since they have not been generally optimized or verified.

2.2.3 Simplified Physics Models

By making restrictive assumptions, the complete Navier-Stokes equations may be simplified to obtain models which estimate wind fields under more limited circumstances. There are many different approaches, thus there are almost an unlimited set of simplified physics models. A number of these have been reviewed by Freeman (1976) and Eagan (1975). Many of these simplifications are associated with viewing the atmosphere as a series of layers. One layer approximations (known as shallow fluid or shallow water approximation) have been applied to rough heated terrain configurations. Some models were specifically developed to examine urban environments. Since these models solve for only an average layer perturbation on velocity or layer height, they lack vertical resolution. Those models which rely simply on the continuity equation for the flow field are more properly listed below as objective analysis methods.

Two layer models proposed generally consist of an incompressible inviscid outer layer which contributes a mean field pressure distribution to drive a lower boundary layer approximation. Frost, Maus, and Simpson (1974) solved the turbulent boundary layer equations with an additional transport equation for eddy viscosity. Selection of reference velocity for the irrotational layers prediction of pressure may be critical, however, to a faithful prediction of wind fields. The method cannot provide for separation or cases where strong vertical pressure gradients exist.

Solution of the Navier-Stokes equations but without the capacity to deal with separation have been submitted by Taylor and Gent (1974), Deaves (1975), and Alexander and Coles (1971). These authors generally make assumptions which limit their results to situations where $h/L >> 1.0$.

Jackson and Hunt (1975) and Jackson (1975) have prepared analytical solutions for flow of an adiabatic turbulent boundary layer on a uniformly rough surface over a two-dimensional hump with small curvature, e.g., a low hill. The theory is valid in the limit $L/z_o \to \infty$ when $h/L < 1/8\ (z_o/L)^{0.4}$ and $\delta/L >> 2k^2/\ln(\delta/z_o)$ and L and h are the characteristic length and height of the hump, z_o the roughness length of the surface and δ the thickness of the boundary layer--this implies typically 10^2m $< L < 10^4$m and $h/L < 0.05$. The analysis consists of inner and outer expansions to calculate perturbation velocities, pressures, and shear stresses. It is suggested that this analysis be used as a datum against which to compare numerical studies. Jackson (1975) has concluded that away from the ground the flow perturbation caused by a change in surface topography has exactly the same distribution as the perturbation to a uniform, inviscid flow caused by the same surface shape. This conclusion has led us to examine the value of a new model of wind flow which we shall call "super" simplified physics models in Section 2.2.5.

2.2.4 Objective Analysis Models

Objective analysis performs an interpolation of observed data in accordance with constraints imposed by the terrain and the equation of continuity. No use is made of the equations of motion or energy. These models are generally dependent on real time specification of synoptic wind fields or interpolation between real time data gathered at a number of field sites simultaneously. Three-dimensional mass consistent wind field models have been prepared by Seltari and Lantz (1974), Dickerson and Orphan (1975), Sherman (1975), Freeman (1976), and Knox, et al. (1976). Integration of the continuity equation in the vertical direction results in a shallow layer version which requires only a two-dimensional solution for an average duration from the mean wind. These somewhat simpler models have been suggested by Anderson (1971), Fosberg, et al. (1975), etc. Fast computing speed of a complex flow field is the substantial contribution of objective analysis methodologies; and if there are a number of concurrent input measurements, the resulting wind fields are quite reasonable. If there are few measurements, however, these models contain very little to define the flow. In addition, the models cannot satisfactorily treat the dynamic limitations of stratification, separation, or vorticity amplification.

2.2.5 "Super" Simplified Physics Models

Recent results by Jackson (1975) and Sacre (1975, 1974) suggest a simple cost-effective method to predict wind fields may be devised through the solution of inviscid shear flow fields by solving a Poisson equation for stream function and the vorticity transport equation. These models may adequately define the mean flow field for velocity and permit use of rapid-distortion methods as suggested by Hunt (1973) to predict the turbulence field perturbation.

Among the earliest attempts to predict wind speedup over hills, one finds the use of uniform potential flow methods of Prandtl (Putnam, 1948) and Rosenbrock (Golding, 1956). Eagan (1975) has suggested that such methods are limited to nonstratified irrotational flows. He also reviews modified potential flow models which are essentially improved objective analysis models based on mass consistency.

Thwaites (1960, p. 558) has reviewed early literature on the solution of the inviscid equations of motion for shear flow over two- and three-dimensional surface disturbances (see Lighthill (1957) and Hawthorne and Martin (1955)). The success of this approach suggests that an inviscid flow field with the appropriate approach velocity profile may satisfactorily estimate wind fields over terrain.

Sacre (1974) developed an analytical solution for stratified inviscid shear flow over modest hills. Although limited to very modest relief in near neutral conditions the results are promising indeed. They compare favorably to the computations of Jackson and Hunt (1975), Taylor and Gent (1974), and Deanes (1974) who include the influence of turbulent transport. To avoid the influence of nonlinear interactions, Sacre linearizes his equations by a perturbation approach both in his analytic effort and a subsequent numerical approach (1975) hence his results are limited to small hills of modest gradient.

2.2.6 Colorado State University "Super" Simplified Physics Numerical Model

Since laboratory evidence suggests the mean flow field over medium topography is controlled by advective momentum and thermal transport plus the shape of the approach velocity and thermal profiles, a series of two-dimensional calculations have been instituted to survey the feasibility of using a fast and economical "super" simplified physics model to evaluate wind power potential.

Using a spatial coordinate transformation, we have developed a numerical solution for steady, inviscid flow over arbitrary topography. The solution is obtained using stream function-vorticity coupled with an equation for potential temperature to handle unstable, neutral, and stable stratification as follows:

$$\nabla^2\psi = -\eta \tag{1}$$

$$\frac{\partial}{\partial x}\left(\eta \frac{\partial\psi}{\partial z}\right) - \frac{\partial}{\partial z}\left(\eta \frac{\partial\psi}{\partial x}\right) = \frac{-g}{\theta}\frac{\partial\theta'}{\partial x} \tag{2}$$

$$\frac{\partial}{\partial x}\left(\theta' \frac{\partial\psi}{\partial z}\right) - \frac{\partial}{\partial z}\left(\theta' \frac{\partial\psi}{\partial x}\right) = 0 \tag{3}$$

where $U = \frac{\partial\psi}{\partial z}$ $\quad W = -\frac{\partial\psi}{\partial x}$

and θ' is potential temperature deviation from an adiabatic atmosphere with constant θ.

The transformation (Gal-Chen and Somerville, 1975) is given by

$$\bar{x} = x, \ \bar{z} = \frac{H(z-z_s)}{(H-z_s)} \tag{4}$$

in which $z_s(x)$ is the topography height, and H is the height of the top of the grid. The transformed spatial operators are thus defined, in numerical conservative form, as

$$\frac{\partial()}{\partial x} = \frac{1}{\sqrt{G}}\left(\frac{\partial\sqrt{G}()}{\partial\bar{x}} + \frac{\partial\sqrt{G}\,G^{13}()}{\partial\bar{z}}\right) \tag{5}$$

and $$\frac{\partial()}{\partial z} = \frac{1}{\sqrt{G}}\frac{\partial()}{\partial \bar{z}} \tag{6}$$

where $\sqrt{G} = 1-z_s/H$ and $G^{13} = \frac{1}{\sqrt{G}}\left(\frac{\bar{z}}{H} = 1\right)\frac{\partial z_s}{\partial\bar{x}}$

The numerical algorithms are strictly steady state, not an asymptotic time marching technique, thus the solution is obtained very quickly. Since the equations are fully nonlinear and coupled, the only limitation is the lack of viscosity or turbulence, for which several justifications have been presented.

Initial results are very encouraging. Over 1:6 slope triangular hills speedup factors, pressure distributions, and streamline behavior are similar to laboratory measurements. Mild stability tends to decrease the speedup factor, whereas mild instability for a given approach velocity profile increases the speedup factor. This agrees with the energy analysis proposed by Lange (1961). Sacre (1974) noted a similar behavior in his numerical model and an inverse behavior in his analytic model. Since neither his analytic nor numerical model appear to account for advection of potential temperature, Sacre's results must be interpreted with caution.

3.0 RESEARCH PROGRAM

The previous remarks from Chapter 2 summarize briefly the current status of understanding for siting of wind power installations. The need for a well organized experimental and analytic study is apparent. A systematic research program (the first year of which has been completed), primarily experimental in nature, is proposed which will provide over a three-year period, a unified body of knowledge on windmill siting aerodynamics. The laboratory investigations are complemented by analytical studies of flow and turbulence over bodies of such a nature as to interpret and generalize results obtained. The acquisition of the knowledge is planned to minimize the experimental work yet permit reaching all objectives.

This proposal represents the only known planned effort to systematically study the major interactions of winds and topography. The research will produce information of immediate use in wind power site selection, architectural planning, wind loading on buildings, and environmental control.

Objectives of the proposed research are specifically:

1. To determine local flow phenomena over topography--boundary layer displacement, separation, reattachment--as affected by hill or ridge profile, upwind surface roughness, insolation, and stratification.

2. To develop knowledge of integral wind effects on topography which will lead to criteria in terms of upwind topography type and placement for the prediction of effect on speedup and gustiness.

3. To establish how the local flow environment such as gustiness and mean wind speeds are affected through the combined action of the individual effects listed above.

4. To relate the new knowledge gained through laboratory measurements and through analysis to real meteorological events and to provide a "methodology" of site selection for wind power purposes.

Two broad classes of variables are incorporated into the general research plan, a) a wide range of natural wind characteristics and, b) a range of topographical features. The program of experimental measurements and analysis will focus on the determination of how these variables affect

a) local flow characteristics over topography

b) integral wind effects over topography, and

c) local flow environment as a result of superposition of class a) phenomena

Once the details of the above are known, a well documented field site will be selected for verification of concepts.

3.1 Wind Characteristics

A wide range of natural wind characteristics can be simulated by means of the unique meteorological and environmental wind tunnels of the Fluid Dynamics and Diffusion Laboratory. Characteristics of major concern are magnitudes and spatial distribution of mean velocity, turbulence scales and turbulence spectra of winds approaching the wind power site. Verification that natural wind characteristics are simulated to a high degree of approximation by the long-test-section type wind tunnel has been reported by Cermak (1970, p. 13) and Davenport and Isyumov (1968, pp. 201-231).

The detailed structure of boundary layers formed in the long-test-section are varied by changing roughness characteristics of the lower boundary (floor), introduction of vorticity and turbulence at the test section by means of vortex generators and grids, introduction of large scale lateral motions by moving deflector vanes and introduction of hill-like surface irregularities. For all of the major topographics studied in the long-test-section wind tunnels, the wind characteristics inherent in flow over a plane rough boundary with roughness-element size scaled according to the geometric scale have been used. The following listing delineates the overall kinematic and geometric boundary conditions to be used in generating simulated natural winds for the proposed research.

1. Free-stream flow

   a) Speed: 1-30 m/sec

   b) Longitudinal pressure gradient: adjusted to zero by means of flexible ceiling

   c) Turbulence intensity: 0.1-10 percent (high levels obtainable by roughness and introduction of longitudinal vorticity by vortex generators at beginning of test section)

   d) Direction: continuously variable by rotation of model

2. Boundary-layer flow

   a) Lower boundary geometry: 27 m long by 2 m wide (meteorological tunnel) plane boundary with topography added

   b) Surface roughness upwind and surrounding topography
   Roughness elements--gravel
   Roughness heights--zero (smooth boundary reference case); 2 additional roughness heights scaled to typical total topography height H

   c) Boundary-layer thickness: 0.5 to 1.5 m at the downstream portion of the wind tunnel where the topography under study is located. These thicknesses will correspond to planetary boundary layers of 500-1,500 m when the possible scales are 1:1,000 and 1:5,000

   d) Surface temperature: isothermal flows (corresponding to an atmosphere with an adiabatic lapse rate) which is appropriate for strong winds and a stably stratified flow will be utilized

The range of wind characteristics utilized will therefore include all of the natural winds excepting those accompanying strong thunderstorm activity and tornados.

3.2 Topographical Features

Topographical features for which the wind effects have been studied in detail include two basic profile shapes, triangular and sinusoidal for the ridge section. The influence of gaps and notches of converging valley systems will be studied separately. Variations in geometry for this study are summarized in the following list.

1. Single hill and ridge cross sections
   a) triangles--slopes 1:2, 1:3, 1:4, 1:6, 1:22
   b) sinusoidal--(similar average values)
2. Typical hills with roughness added
3. Typical hills with insolation (heated sides)
4. Ridge sections with canyons on notches--depth ~ 1/4, 1/3, 1/2 height
5. Field validation model (to be selected: (perhaps from Golding, Putnam or Frenkiel sites))

Other geometries may be included as the research indicates the occurrence of significant flow behavior at intermediate values of the geometrical parameters.

This report includes results completed for ridge cross sections with and without upstream roughness.

4.0 REVIEW OF PRESENT KNOWLEDGE OF LABORATORY SIMULATION

4.1 Brief Survey of Similarity Criteria

The basic tool of laboratory simulation is similitude or similarity, defined as a relation between two mechanical (or flow) systems (often referred to as model and prototype)* such that by proportional alterations of the units of length, mass, and time, measured quantities in the one system go identically (or with a constant multiple of each other) into those in the other. In the case of flow around or over obstacles such as mountains, geometrical, kinematical, dynamical, and thermal similarity must be achieved.

Geometrical similitude exists between model and prototype if the ratios of all corresponding dimensions in model and prototype are equal. This is easily realized by using undistorted scale models of the prototype geometry. Kinematic similitude exists between model and prototype.

1. If the paths of homologous (having the same relative position) moving particles are geometrically similar, and

2. If the ratio of the velocities of homologous particles are equal.

Dynamic similitude exists between geometrically and kinematically similar systems if the ratios of all homologous forces in model and prototype are the same. Thermal similarity exists for model and prototype if the density stratification is the same.

Numerous problems arise in constructing a model of flow over hills or mountains. An important concern is friction, since, in general, it is difficult to obtain equality of Reynolds numbers in

*Prototype--actual airflow involving full scale
Model--airflow involving smaller scale than prototype but usually with geometrically similar boundaries.

model and prototype. In the atmosphere a typical value is $Re \sim 10^{10}$; in the model, $Re \sim 10^{4}$ (the difference depends primarily upon the scale one is attempting to model). Since the flow in the model may be laminar or turbulent and that in the atmosphere turbulent, adopting the terminology of Reynolds (1894), we must compare the mean motions in the model with the mean-mean motions in the atmosphere at corresponding points. The equations of motion in the model are familiar Navier-Stokes equations, while those for the atmosphere are Reynolds equations of mean-mean motion with forces produced by both molecular friction and turbulent transport of momentum (Reynolds stress terms). The forms of these two sets of equations differ fundamentally unless

1. Molecular friction and turbulent friction terms are neglected in both systems, or

2. Molecular friction is negligible compared to turbulent friction in the atmosphere and the turbulent friction is expressible in terms of mean-mean motion and has the same form as in the equations of Navier-Stokes, viz. proportional to the Laplacian of the respective velocity components.

Both viewpoints have been utilized in previous modeling work. Viewpoint (1) has been applied for aerodynamically rough flow when the drag is predominantly due to pressure forces exerted normally on the projecting roughness of the surface, and is therefore virtually independent of viscosity. Thus, when the flow is over rough sharp-edged topographical features, mean flow patterns are independent of the Reynolds number if that number exceeds a lower limit which is dependent upon the geometrical form. In such instances a value of 10^{3} for the ratio $(Re)_p/(Re)_m$ may not introduce significant error in the modeled mean-flow patterns. In such a case the viscous effects no longer dynamically govern the flow and the equation of motion reduces to Euler's equation for potential flow.

Viewpoint (2) compares the gross mean characteristics of turbulent natural flows over topographical features by a laminar laboratory flow when the scale ratio $L_p/L_m \geq 10^3$. Thus, a tunnel flow speed is selected so as to equate the Reynolds number to that applicable on the full-scale, i.e., the molecular viscosity in the model corresponds to the eddy viscosity on the full-scale.

Another basic problem concerns thermal similarity. Scorer (1953) and Corby (1954) have indicated that thermal similitude requires large temperature gradients (1° C cm^{-1}) at very low flow speeds (9 cm sec^{-1}) in the model and considered such experimental control too difficult to achieve with the conventional wind tunnels. As the result of this problem, most model experiments have been achieved at neutral stability or when the static stability is very small. However, with the recent construction of larger wind tunnels capable of environmental control, the possibility of achieving the required temperature gradients and low flow speeds are an actuality; therefore, thermal restrictions are no longer an impossible barrier (see Cermak, et al., 1966).

Not only must the various dimensionless parameters be the same for both model and prototype, but in addition, the boundary conditions must be the same. This latter requirement not only demands geometric similarity of the lower boundary, but also similarity in upstream conditions and in conditions at the upper boundary.

The upstream conditions may be matched rather precisely by setting the model at varying distances from the leading edge of the boundary layer in the wind tunnel test section. The velocity and density distributions that may be obtained in the tunnel are, however, all similar to one another. The upper boundary conditions can only be matched if the study of the prototype is restricted to the lower layers of the atmosphere, approximately one-half the height of the troposphere, primarily because the increase in stability cannot be reproduced in present wind tunnels without major modifications.

At the present time wind tunnels are capable of simulating certain aspects of atmospheric flow; several restrictions are necessary, however:

1. The prototype region is made comparatively small (~90 mi or less), so the effect of the Coriolis acceleration is negligible (i.e., convective accelerations predominate).
2. The effect of variation of hydrostatic pressure with height is negligible.
3. The effect of compressibility of the air is negligible (where prototype length L~1 km or less).
4. The effect of condensation and evaporation processes are neglected (i.e., no clouds or precipitation).
5. The unsteady state of prototype winds are neglected (i.e., the model winds are steady state).

Yet, even with these restrictive assumptions, worthwhile results have been obtained from laboratory simulation as briefly summarized in the next section. These restrictions are not critical for many, or even most, investigations of wind characteristics in the lowest troposphere.

4.2 Past Work in Laboratory Simulation

M. Abe (1941) simulated the air flow and cloud formation over Mt. Fuji using a laminar flow for a 1:50,000 model. Abe attempted to achieve greater realism by arranging for wind shear, thermal similarity and change of wind direction with height. Unfortunately Abe did not arrange these effects quantitatively to insure that strict dynamical similarity was achieved; yet, the photographed model flow was found to be in approximate agreement with some properties of the flow on site, insofar as he had deduced them from observations of the mountain clouds.

Field and Warden (1929-1930) and later Briggs (1963) used the principles of flow over rough sharp-edged topographical features in modeling flow over the Rock of Gibralter. In the model investigation no arrangements to simulate stability were made; hence, the flow obtained in the model corresponded to a full-scale case with zero static stability.

The study of Field and Warden was performed at the National Physical Laboratory of Great Britain, on a 1:5,000 scale model in a low-speed wind tunnel. This study was instigated in order to determine the types and distribution of possible disturbances before a full-scale field study was begun. It was found that wind directions and the distribution of vortices and vertical currents obtained with the model agreed closely with those occurring in nature at Gibralter. However, the actual intensity of gustiness was not in good agreement with the prototype flow.

Nemoto (1961, Parts I, II, and III) (1962, Part IV) has discussed the various aspects of similitude for several different model flows and has also derived similarity criteria for wind profiles near the ground and the intensity of turbulence. Nemoto used results from two different models to check his similarity criteria and found good agreement between model and prototype.

Halitsky, Tolciss, and Kaplin (Reports 1, 2, 3, and 4, 1962, 1963) studied the structure of the local wind field over a topographic model of Bear Mountain and surrounding terrain by means of wind tunnel measurements and evaluated the degree of correspondence between model and full-scale measurements of mean and turbulent wind properties. They were particularly interested in the region of very high turbulence in the lee of the mountain.

An interesting measurement technique to evolve out of this study was a bubble-tracking apparatus which was utilized to determine preliminary measurements of average U, V, and W flow components, standard deviations, and turbulent intensities of the air flow over the model.

4.3 A Selection of Pertinent Simulation Work at Colorado State University

Staff members of the Fluid Dynamics and Diffusion Laboratory at Colorado State University have undertaken several research projects in laboratory simulation over terrain which are briefly summarized below:

4.3.1 Study of Wind Abatement about Candlestick Ball Park, San Francisco (Cermak, et al., 1963)

A scale of 1:800 was selected for the model and tests were conducted at a wind speed of approximately 10 to 30 mph. Because the local topography, rather than thermal stability, appeared to dominate the flow pattern in the stadium and its vicinity, all tests were conducted under neutral stability conditions. The stadium was located at the base of an isolated hill which was part of a peninsula which jutted into San Francisco Bay.

In general the conclusions of this study based upon comparison with data obtained from a companion field study were that (a) the model scale study of the Candlestick Park complex yielded model flow patterns closely similar to prototype flow patterns, (b) gross Reynolds number effects were not present and the flow pattern is determined by the geometrical features inherent in the scale model, and (c) changes made in the hill or stadium geometry produced modifications in the wind patterns which would occur with a high degree of certainty in the prototype if similar geometrical changes were to be effected.

4.3.2 Modeling of Flow and Diffusion over San Nicolas Island (Meroney and Cermak, 1965)

A 1:6,200 scale model of San Nicolas Island was studied under conditions of inversion flow in the wind tunnel. Visualization procedures, including colored indicator paints and titanium tetrachloride smoke, were used to determine characteristic flow patterns over the island with wind orientation to the island of 315°. Diffusion of toxic rocket exhaust products were simulated by the release of controlled amounts of helium. Concentration profiles of the helium plume were measured at various distances downwind of the island model.

4.3.3 Simulation of Air Flow over Point Arguello, California (Cermak and Peterka, 1966)

A wind tunnel study of Point Arguello was motivated by the desire to estimate the diffusion characteristics of toxic gases which might be released in the vicinity of missile launch sites on the U.S. Naval Missile Facility. Accordingly, the primary purpose of this study was to determine if wind patterns observed in a wind tunnel over a 1:12,000 scale model of the Point Arguello area are representative of the prototype wind patterns which are usually stably stratified.

Since inversion flows were of primary interest, the laboratory study was confined primarily to low-speed flow (5 ft/sec) with a maximum attainable temperature difference (wind tunnel floor was 103°F cooler than the ambient air). Flow patterns for the stable stratification were well documented in the cases of flow approaching from an azimuth of 315° and from 340°. In order to minimize the apparent dissimilarity suggested by the large difference in Reynolds numbers, the ideas of Abe were applied to the model.

The agreement between model and prototype flow patterns was better than anticipated since the laboratory flow was basically laminar while the field flow was turbulent--however, both were stably stratified to approximately the same degree. Also of interest was the concentration decay rates which were essentially the same. A possible explanation for this agreement may be that in cases where the surface over which the flow occurs is irregular, i.e., composed of hills and valleys, dispersion of a passive additive to the atmosphere may be controlled primarily by strong spatial variation in convective transport by the mean motion. Especially in flows with strong stable thermal stratification is this mode of dispersion expected to be dominant.

In general, in comparing the results of the experimental work in the wind tunnel with comparable data from a field study, the authors concluded that excellent similarity existed for wind flow patterns over the Point Arguello area and the model inversion flow approaching from the northwest.

4.3.4 Modeling of Flow over San Bruno Mountain, San Francisco (Garrison and Cermak, 1968)

Extensive studies of the flow over San Bruno Mountain for a model scale of 1:6,000 have been completed. Neutral stability and thermally stable flows were investigated. Different models were utilized to show the differences in airflow patterns for different stages of excavation of San Bruno Mountain. A technique using sublimating dry ice to develop low velocity stratified gravity currents was found useful in this effort.

4.3.5 Simulation of Mountain and Heat-Island Effects on Stratified Shear Layers (Yamada and Meroney, 1971)

Two-dimensional stably stratified air flows over various nonuniform surfaces were studied. Three characteristic problems were investigated: (a) mountain lee waves, (b) heat islands (sea breezes) and (3) heated mountain phenomena. A special wind tunnel reproduced the scaled version of each geophysical flow. Results obtained agreed with field experience and a numerical simulation. The study noted an important nonlinearity of combined effects of heating and topography which suggests caution in the superposition of conventional linear models.

4.3.6 Research on Laboratory Simulation of Atmospheric Transport over Mountainous Terrain (Orgill, Cermak, Grant, 1971)

This very important study has compared detailed measurements of wind shear, direction, turbulence and transport in the wind tunnel laboratory with a carefully coordinated field program. The laboratory-field program involved three selected topographic regions. These areas are:

1) Eagle River Valley--Climax area of central Colorado (Scale 1:9,600--typical mountain barrier problem,

2) Elk Mountain area of southern Wyoming (Scale 1:9,300)--an isolated symmetric peak, and

3) The San Juan Mountain areas of southern Colorado (Scale 1:9,600 vertical, 1:14,000 horizontal)--a variegated valley channel mountain area.

Measurements were made for both neutral and stratified (barostromatic) situations. It was found that the inclusion of stratification was critical to the simulation of transport over orographic areas due to the strong blocking effects of the mountainous terrain. Figures 1, 2 and 3 display typical flow behavior both over the model and in the field situations.

4.3.7 Site Analysis of Dow Chemical Facility of Rocky Flats, Colorado (Meroney and Chaudhry, 1972).

An examination of the dispersion of potentially hazardous effluents from a plutonium processing plant was made. The terrain in this case was variegated but with only moderate relief. A scale of 1:1,000 was utilized. Model plumes exhibited acceleration over rising terrain features, and channeling and deflection due to small canyons and hills.

Other studies have been completed for various terrains and urban topography. The selection disclosed above indicates that a great deal has been learned concerning modeling terrain influences since the early wind power siting effort. Despite the variety of specific studies no effort has previously been made to systematically understand the separate and/or combined influence of terrain aspect ratio, insolation, roughness, and stratification.

5.0 EXPERIMENTAL PROGRAM

A wide range of natural wind characteristics can be simulated by means of the unique Meteorological Wind Tunnel of the Fluid Dynamics and Diffusion Laboratory which has been used for this research. Characteristics of major concern are magnitudes and spatial distribution of mean velocity, turbulence scales and turbulence spectra of winds approaching the wind power site. Verification that natural wind characteristics are simulated to a high degree of approximation by the long-test-section type wind tunnel has been reported by Cermak et al. (1966).

Measurements in wakes require considerable care, both in their acquisition and in their interpretation. In this chapter the methods used to make measurements and the techniques used in converting directly measured quantities to meaningful physical quantities are discussed. Attention is drawn to the limitations in the techniques in an attempt to prevent misinterpretation or misunderstanding of the results to be presented in the next chapter.

5.1 The Wind Tunnel Facility

The experiments were performed in the Meteorological Wind Tunnel located in the Fluid Dynamics and Diffusion Laboratory at Colorado State University. A plan view of the wind tunnel is shown in Figure 4. The tunnel is a closed circuit facility driven by a 250 hp variable-pitch, variable-speed propeller. The test section is nominally 2 m square and 27 m long fed through a 9:1 contraction ratio. The test section walls diverge 0.01 m/m and the roof is adjustable to maintain a zero pressure gradient along the test section. The mean velocity can be adjusted continuously from 0.3 to 37 m/sec. The wind speed in the test section does not deviate from that set by the speed controller by more than 1/2 percent. The tunnel is equipped with a refrigeration system to maintain the air temperature at a constant level (± 1/2°C). Though the wind tunnel is capable of simulating thermally stratified planetary boundary layers all tests reported in this report used a neutral boundary-layer stratification. The facility is described in detail by Plate and Cermak (1963).

At the entrance to the wind tunnel test section a 0.038 m high sawtooth boundary-layer trip is installed to insure prompt formation and growth of a turbulent boundary layer. A similarity profile is attained in the boundary layer within 6.1 m of the test section entrance (Zoric, 1969). All the measurements reported in this report were made with the models at or beyond 11.3 m from the start of the test section. Thus the approach-flow boundary layer has a similarity velocity profile and changed very slowly along the test section.

The boundary layer continues to thicken at successive locations along the test section. Over the smooth flat plate the thickness of the boundary layer increases in proportion to $x^{.48}$ (Zoric, 1969). However, in the region in which all measurements were made, the boundary-layer growth was linear within the ability to measure the boundary-layer thickness.

5.2 Design and Construction of Hill Models

A total of 17 hill models have been designed and constructed for the meteorological wind tunnel:

triangular-shaped hill models (width 1.83 m)
- with a height of 5.08 cm and slopes of 1/2, 1/3, 1/4, 1/6
- with a height of 15.29 cm and slopes of 1/2, 1/3, 1/4, 1/6
- with a height of 5.08 cm and a slope of 1/20

sine-shaped hill models
- with a height of 5.08 cm
- with a height-length ratio of 1/2, 1/3, 1/4, 1/6
- with a height of 15.24 cm and a height-length ratio of 1/2, 1/3, 1/4, 1/6

For each of the hills mentioned above, three types of surface instrumentations were installed. The instrumentations were static pressure holes, preston tubes, and surface hot wires. The locations of the static holes are tabulated in Table 3.

The hills were mounted in the wind tunnel with a false floor upstream. The false floor was placed 5.60 m directly downwind of the initial boundary layer trip and was 10.75 m in length, Figure 5. The false floor consisted of three sections--an approach ramp, a plywood testing base, and a trailing ramp behind the hill.

The approach ramp was that section of false floor furthest upstream. Masonite, .32 cm thick, was used to construct the ramp at an angle of .84° with the horizontal. The horizontal length of approach ramp was 1.3 m. The plywood testing base was that section of false floor positioned adjacent and flush to the approach ramp. Plywood, 1.91 cm thick, was used to maintain a horizontal surface in which designed models could be placed. The testing base covered 8.55 m in length. The trailing ramp was the final section of false floor located furthest downstream. Positioning of the ramp was flush and sloping downward from the testing base. The ramp was constructed of masonite, .32 cm thick, forming an angle of 1.21° with the horizontal. This final section of false floor was .90 m in length.

5.3 Instrumentation

The research program has been directed toward the evaluation of the viscous flow above the hill models. Detailed measurements of the static pressure distribution and the mean velocity above the hills have been completed for a number of flow conditions. Provisions for evaluation of the surface shear stress are also included on the models. Limited measures of the turbulent distributions above the hills have also been made.

5.3.1 Pressure Measurements

The hill models each contain a set of static pressure taps, as indicated in Table 3. The static holes were sharp edged, .064 cm diameter holes drilled perpendicular to the hill surface. Based on the results of Franklin and Wallace (1970) these small diameter static pressure holes will measure the static pressure with a minimum of error. Franklin and Wallace demonstrate the error in static pressure (divide by the local surface shear stress) is a function of the "Shear Reynolds Number" ($\equiv U^{*d}/\nu$); where $U^{*}(\equiv {}^{\tau}w/\rho)$ is the shear velocity, d is the static hole diameter and ν is the kinematic viscosity of air. The Shear Reynolds Number approaching the hill models is approximately 15 for a flow velocity of 15.2 m per second. For this Reynolds number the ratio of the static pressure error divided by the surface shear stress given by Franklin and Wallace is less than 0.05. The error may be somewhat larger over the upstream portion of the hills where the Shear Reynolds Number will increase.

The static pressure distribution in the boundary layers above the hills were measured with conventional, forward facing (axis aligns with the flow), cylindrical pressure probes, and also a disk probe. The cylindrical probe was a commercial type employed for pitot static design (Bryer and Pankhurst, 1971). The cylindrical probe is subject to errors due to the "pitch" angle between the air flow and the axis of the cylinder. Near the surface of the hills the air flow will vary rapidly, and thus, produce systematic errors in the static pressure measurements of a cylindrical probe. To reduce the flow direction error in static pressure measurements a disk type probe was employed (Bryer, Walshe, Garner, 1958). The disk probe employs the static pressure reading from a static tap drilled through the center of a small diameter thin disk. The measured static pressure at the disk center will be somewhat lower than the actual stream pressure, but it was found to be insensitive to pitch angles of ±30 degrees.

The cylindrical probe had a diameter of .18 cm, with an eliptical nose. The static taps were located .67 cm from the nose and 1.59 cm from the support stem. The cylindrical static probe was employed mainly for measurements well above the hill surface, where the flow direction was not influenced by the hill. The disk probe was used for measurements near the hill surface. The disk has a diameter of 62 cm which restricts the measurements near the surface.

All pressure measurements, both static and total, were made with commercial, capacitance, pressure transducers. The pressure transducers were calibrated against a laboratory standard, water manometer. For all measurements the calibration accuracy was maintained to three significant figures (differential pressure). The accuracy of individual measurements was limited due to large time dependent fluctuations of the pressure. The output of the transducers were read with special digital voltmeters with averaging circuits of 15 to 30 seconds. Even with these long averaging times, it was not possible to maintain an accuracy of three significant figures for many of the static pressure readings--particularly near the crest of the hills.

5.3.2 Velocity and Flow Direction Measurements

Mean velocity measurements above the hills were with commercial pitot- and Kiehl-total pressure probes. A pitot probe .18 cm in diameter with an eliptical nose was employed in regions where flow direction angles were small. In the region near the hill surface, where large flow angles were encountered, a small Kiehl probe, .16 cm in diameter, was employed to measure the total pressure. The Kiehl probe is insensitive to flow angles over a range of at least ±40 degrees (Winternitz, 1956). For the range of velocities measured in the present study both probes agreed with the total pressure measured by the laboratory standard pitot probe. No corrections were made to the probe reading in computing the mean velocity.

A preliminary set of mean velocity profiles were taken employing .064 cm diameter flat nosed, total pressure tubes mounted on a fixed rake. The tubes were adjusted to be approximately aligned with the flow direction at all heights. For the more detailed studies a movable carriage was employed for the surveys. The carriage spans the tunnel and contains a vertical traverse. The pressure probes were mounted on an arm 1.32 m ahead of the carriage. Both direct x-y recordings of the output of the probes traversing through the boundary layer, and direct time averaged readings of the pressures were obtained during the course of the experiments.

A limited amount of information was obtained on the flow angle over the hills with a 35 degree, cantilevered wedge probe. The wedge probe contains a static tap on the face of each side of the wedge (see for example Figure 20C of Bryer and Pankhurst, 1971). When the wedge is directly aligned with the flow the pressure at the two static taps are equal. The wedge probe was set at different heights above the hills and manually rotated to determine the null point between the two static pressure readings.

Preston tubes .07 cm in diameter were mounted on the surface of the hills to aid in the evaluation of the surface shear stress. Adequate calibrations for the tubes have not at present been completed.

5.3.3 Turbulence Measurements

Hot wire anemometers were employed to measure the turbulent velocities over the hills. Commercial, constant temperature, anemometer circuits were used to operate platinum alloy hot wires. The heat transfer from a hot wire is employed to measure both the mean and turbulent velocity components in flows (Sandborn, 1972). The present measurements employed hot wire sensing elements approximately .15 cm long and .001 cm in diameter to evaluate the turbulence. Single wires placed normal to the mean flow were used to measure the longitudinal component of the turbulent velocity, u. The turbulent velocity component, w, normal to the mean flow and perpendicular to the surface was obtained from hot wires yawed with respect to the mean flow.

The hot wire sensors were calibrated by placing them in the free stream of the wind tunnel. The electrical power required to maintain the wires at a fixed temperature (or resistance) was measured as a function of flow velocity. The flow velocity was measured directly with a pitot-static probe. The wind tunnel temperature was held constant, so only the velocity varied. Slight deviation of the air temperature produced some uncertainty in the hot wire calibrations. Since the wire resistance is held electronically constant, the hot wire power can be related to the voltage drop versus the flow velocity.

The turbulent velocities were determined from the following relations (Sandborn, 1972):

$$\text{(Wire Normal to Flow)}\quad u = \frac{dU}{dE}\quad e \tag{5.1}$$

$$\text{(Yawed Wire)}\quad \left(\frac{dE}{dU}\right)^2 u^2 + 2\left(\frac{dE}{dU}\right)\left(\frac{1}{U}\frac{dE}{d\psi}\right)\overline{uw} + \left(\frac{1}{U}\frac{dE}{d\psi}\right)^2 w^2 = e^2 \tag{5.2}$$

where $\frac{dE}{dU}$ is the local sensitivity of the hot wire output voltage drop to velocity change, and $dE/d\psi$ is the local sensitivity of the hot wire output voltage drop to a change in flow direction. The yawed wire is sensitive to two turbulent velocity components plus the correlation between the components. The correlation, $\overline{uw}$, is the Reynolds stress term and of major interest in boundary layer theory. In order to determine $\overline{uw}$ and w^2 it was necessary to operate hot wires with different sensitivities to the components. An X-probe consisting of two wires was employed for the present study. One wire was set approximately normal to the mean flow in the vertical direction, and the second wire was yawed at an angle of approximately 40 degrees to the flow. The wire normal to the flow measured directly u^2, while the product of the voltage output of the normal, e_n, and the yawed, e_y, wires give (Sandborn, 1975),

$$\overline{e_n e_y} = \left(\frac{dE}{dU}\right)_n \left(\frac{dE}{dU}\right)_y u^2 + \left(\frac{dE}{dU}\right)_n \left(\frac{1}{U}\frac{dE}{d\psi}\right)_y \overline{uw} \tag{5.3}$$

thus, the value u^2 computed directly from the normal wire output according to equation (5.1). The value $\overline{uw}$ was computed from the product according to equation (5.3), and w^2 was then determined from equation (5.2).

Preliminary evaluations of the longitudinal component u^2 were made with a set of hot wires mounted normal to the flow and parallel to the surface. A single X-probe was employed with the transversing carriage in later tests. Evaluation of the X-probe data is still being carried out.

Hot wires were also mounted on the surface of the hills to measure the fluctuations in the surface shear stress. Data from these wires have not been analyzed at the present time.

5.4 Test Conditions

The flow fields above the hills were surveyed at two free stream velocities, 9.1 meters per second and 15.2 meters per second. The wind tunnel ceiling was adjusted to produce a near zero pressure gradient along the wind tunnel test section without the hills installed. The approach turbulence level in the free stream was of the order of 0.2 percent of the mean velocity. After the initial boundary layer trip the approach flow develops over a smooth (aerodynamically) wood surface. A preliminary set of data was also recorded with a "carpet" on the upstream surface. The rough surface data is still being computed. The equivalent flat plate Reynolds numbers for the boundary layer approaching the hills for the smooth surface case are 4×10^7 and 7×10^7. The freestream velocity was monitored throughout the tests with a pitot-static probe affixed to the ceiling upstream of the hill locations.

5.5 Data Acquisition and Analysis

The initial measurements in the program employed direct analog readout of the data. The data was then punched on computer decks and evaluated in more detail. Specific parts of the data were recorded directly on both FM and digital tapes. The requirements of long time averaging, due to the large fluctuations in pressure and velocity associated with the flow over the hills, made it unfeasible to directly digitize all of the data. As noted above, long time average voltmeters were employed to measure the output of the pressure transducers. Long time average voltmeter, both d.c. and true r.m.s., were also required to evaluate the output of the hot wire anemometers.

The data analysis was directed toward mapping the complete pressure, velocity and turbulence fields above the hills. The approach has been to employ the computer to construct the maps of the quantities directly from the analog data. The program employs smoothing techniques to reduce the degree of random errors associated with the original data. The smoothing was carried out using one-dimensional "spline" functions. The smoothing was applied directly to the measured vertical profiles. An algorithm developed by Reinsch (1957) was employed to smooth the data. The formulation is as follows:

Let x_i, y_i, $(i = 0,1,2,\ldots,n)$ be given, such that $x_o<x_i<\ldots<x_n$ a smoothing function $g(x)$ is constructed such that

$$\int_{x_o}^{x_n} g''(x)^2 dx \rightarrow \text{minimized for all functions } g(x) \text{ such that} \qquad (5.4)$$

$$\sum_{i=o}^{n} \left(\frac{g(x_i) - y_i}{dy_i}\right)^2 \leq S \qquad (5.5)$$

The constant $S \geq 0$ and $dy_i > o$ $(i=o, 1,\ldots n)$ are given numbers. The function $g(x)$ is taken as a third degree polynomial. The constant S is redundant and is introduced only for convenience. The constant S allows for an implicit rescaling of the quantities dy_i, which in turn controls the extent of the smoothing. Choosing S equal to zero leads to the problem of interpolation by cubic spline functions.

Some difficulty was encountered in applying the technique. Initially the values of dy_i were set equal to 1, and S was picked such that the spline function followed the data. Improvement was obtained by adjusting the value of dy_i for bad data points. For the wake region near the crest of the hills thin layers with very large velocity gradients were encountered. These layers produce very large second derivatives with respect to y. Such large variations were not well represented by the function. The difficulty was overcome by rotating the coordinate system through an angle, θ, such that all slopes of the spline function were reduced ($<<\infty$). By taking a great number of data points in the large gradients, and employing a "stretching" transformation (such as a log-transformation) improvements in the smoothing are also possible.

The spline functions were employed both to smooth and interpolate the data, so that the complete flow field was mapped. The Appendix gives the flowchart used in the evaluation.

6.0 RESULTS

Table 4 lists the particular ridges and test conditions that have been evaluated in the wind tunnel. As noted, an extensive development of computer techniques to produce maps of the flow fields was carried out. Work is still in progress on the data, so only a small representative sample of the results are presently available. Some of the results are still subject to further cross checking for uncertainties.

The approach boundary layer characteristics for the present tests are approximately the same as those reported by Zoric (1969) and Zoric and Sandborn (1972). These large Reynolds number boundary layers display a definite similarity when the free stream velocity and the boundary layer thickness are employed as characteristic velocities and length. These boundary layers appear to closely approach the steady state atmospheric boundary layer for smooth surfaces. The turbulent characteristics of these large Reynolds number boundary layers are also found to approach the properties observed in atmospheric flows (Sandborn and Marshall, 1965; Tieleman, 1967). The turbulent energy spectrum was found to approach a similarity very quickly with distance from the surface. The similarity spectrum was nearly identical to that observed in the atmosphere, except the wind tunnel scales are smaller for the low frequencies.

6.1 Static Pressure Distributions

Figure 6 shows typical measurements of static pressure, velocity, speedup, and turbulence distribution that are currently being analyzed from the tests. From the pressure distributions, Figure 6, it is seen that the initial approach velocity slows down at or near the bottom of the ridges. The strong adverse pressure gradient can produce a local separation "bubble" in the region at the foot of the steeper ridges.

Jackson and Hunt (1975) and Jackson (1975) and the recent studies at Colorado State University (see Section 2.2.6) predict the magnitude of the perturbation pressure from inviscid flow models. The predicted values of C_p were found to agree closely with the data given in Table 1. The inviscid theories appear to give good predictions of C_p for steep ridges up to $h/L \simeq 1$. However, for these steeper ridges (see Figure 6c) separation occurs at or near the crest, and the location of maximum convergence of the streamlines--or lowest pressure occurs downstream of the crest. The static pressure distributions for a number of the hills are compared on the plot of Figure 6c.

Contour plots of the lines of constant static pressure over the ridges are shown in Figure 7. The "shallow" ridge (1:6, Figure 7a) has a near symmetrical pressure distribution, while the steeper hill (1:2, Figures 7d and 7e), has an asymmetrical distribution due to flow separation. The symmetric distributions show significant pressure changes out to a distance of $\sim L$ from the crest, while the asymmetric case shows pressure changes well beyond $\sim L$ from the crest. The smaller extent of the pressure effect demonstrates why the inviscid potential flow theories are able to predict the right order of velocity "speedup" for shallow ridges. The effect of separation for the steeper ridges produces the equivalent of a taller and wider potential flow ridge.

6.2 Mean Velocity Measurements

Mean velocity measurements were made at points spaced logarithmically in the vertical at a sequence of longitudinal positions. Data were smoothed by spline procedures which minimized average total curvature in an adjusted (rotated) coordinate system. In some cases curves were splined on logarithmic coordinates, or otherwise evaluated to improve overall consistency. The fractional speedup factor, ΔS, suggested by Jackson and Hunt (1974) is plotted in Figure 6 together with typical mean velocity profiles.

It would appear that the fractional speedup factor may be an appropriate measure of speedup for low slope hills (< 1:10) since it does not vary with height quite as much as the speedup factor S. Unfortunately, for steeper hills both speedup factor S and fractional speedup factor ΔS vary markedly with height. Except for a very small region near the surface where a low level jet seems to appear, the gradient of velocity with height is nearly zero in all cases studied. The results confirm the criteria preferred by Frenkiel (1962). The variation of S or ΔS with height may thus not be significant since a single value of S or ΔS at a reference height defines velocity over a finite depth for a near optimum hill. Separation generally reduces peak velocity, increases turbulence, and reduces negative pressure values at the summit.

For measurements over the 1:2-sine models of equivalent h/L values, the wide flat top resulted in much reduced values of S and ΔS. This agrees with field experience which recommends against flat topped peaks as prospective wind power sites.

Figure 8 shows computer contour plots of the velocity over the 1:4 ridges. The speedup is somewhat greater for the triangular shape than for the sinusoidal shape. Thus, the sharp crested hill may offer an advantage in maximum power production. The sinusoidal hill has a region near the crest where the velocity distribution remains nearly constant, independent of the X-distance. The higher Reynolds number flow produces a near symmetrical distribution about both the triangular and sinusoidal shapes. At the lower Reynolds number the triangular shape shows a marked effect of separation on the downstream side.

Figure 9 shows a preliminary set of data for the velocity and speedup ratio obtained using the "carpet" upstream roughness. A problem exists in the proper technique of matching the start of the hills with the roughness. Thus, the present results are still of questionable value. The carpet increases the approach roughness height by approximately a factor of 1000.

6.3 Turbulence Measurements

Profiles of longitudinal turbulence scaled against local velocity are shown in Figure 6 for the 1:6 and 1:4 slope triangular hills. The upstream profile exhibits a flat plate boundary layer shape with a maximum at the wall surface. As the fluid slows in the forward stagnation region, turbulence production near the wall decreases and the maximum appears to move outward. Near the summit the velocity gradient is large only near the surface, thus only preexisting turbulent energy is convected over the ridge at most heights. Since longitudinal velocity on a given streamline has increased, local turbulent intensity decreases by almost one-half near the surface up to $z \simeq 2h$. This picture of turbulent energy rapidly convected through a flow convergence and divergence for moderate hills supports the contention by Hunt (1973) that turbulent diffusion from the surface region should be small, and turbulent character may be influenced by the rapid distortion of vortex lines as fluid is convected over an abrupt bluff body.

As noted, the analysis of turbulent measurements is still underway. The turbulent shear stress and vertical turbulent velocity components, as well as the longitudinal component, should be available in the near future. Data from the hot wire anemometers have in some cases been digitized directly. Figure 10 shows preliminary longitudinal turbulence spectra and autocorrelations that have been evaluated direct from the digital data. The case shown is for the carpet roughness. The speedup over the ridge does not appear to produce any marked changes in the spectral content of the turbulence, which is in keeping with the concepts noted above, Hunt (1973).

REFERENCES

Abe, Masanao (1941), "Mountain Clouds, Their Forms and Connected Air Currents, Part II," Bull. Centr. Met. Obs., Japan 7 (3).

Alexander, A. J. and Coles, C. F. (1971), "A Theoretical Study of Wind Flow over Hills," 3rd Int. Congress on Wind Loads on Buildings and Structures, Tokyo.

Anderson, G. E. (1971), "Mesoscale Influences of Wind Field," J. of Applied Meteorology, Vol. 10, pp. 377-386.

Anthes, R. A. and Warner, T. T. (1974), "Prediction of Mesoscale Flows over Complex Terrain," U.S. Army Electronics Command Report ECOM-5532, March.

Archibald, P. B. (1973), "An Analysis of the Winds of Site 300 as a Source of Power," UCLR-51469, Lawrence Livermore Laboratories, University of California, Livermore, California.

Beebe, P. S. and Cermak, J. E. (1972), "Turbulent Flow over a Wavy Boundary," Project THEMIS TR No. 16, Fluid Dynamics and Diffusion Laboratory, Colorado State University, Fort Collins, Colorado (CER71-72SB-JEC44).

Beryland, M. E., Genikhovich, E. G., and Kurenbin, O. L. (1968). "The Influence of Relief on the Dispersion of Pollution from a Source," Trudy Glavnaya Geofizicheskoya Observatoriya, No. 234, p. 28, (Translation in Scientific Periodicals Library, Cambridge).

Bowen, A. J. and Lindley, D. (1974), "Measurements of the Mean Wind Flow over Various Escarpment Shapes," 5th Australian Conference on Hydraulics and Fluid Mechanics, Christchurch, New Zealand, December 9-13, 9 p.

Briggs, J. (1963), "Airflow around a Model of the Rock of Gibralter," Meteorological Office Scientific Paper No. 18, p. 20.

Bryer, D. W. and Pankhurst, R. C. (1971), Pressure-Probe Methods for Determining Wind Speed and Flow Direction, Her Majesty's Stationery Office, London.

Bryer, D. W., Walshe, D. E., and Garner, H. C. (1958), "Pressure Probes Selected for Three-Dimensional Flow Measurement," Rep. Memor. Aero. Res. Coun., London, No. 3037.

Cermak, J. E. (1970), Proceedings, Symposium on Wind Effects on High-Rise Buildings, Northwestern University, Evanston, Illinois, March 23.

Cermak, J. E. (1975), "Applications of Fluid Mechanics to Wind Engineering," 1974 Freeman Scholar Lecture, ASME Journal of Fluids Engineering, Vol. 97, Series 1, No. 1, March, Colorado State University, Fort Collins, Colorado (CEP74-75JEC7).

REFERENCES (continued)

Cermak, J. E., Malhotra, R. C., and Plate, E. J. (1963), "Investigation of the Candlestick Park Wind Problem," Vol. II: Wind-Tunnel Model Study, Fluid Dynamics and Diffusion Laboratory, Colorado State University, Fort Collins, Colorado (CER63JEC-RCM-EJP27).

Cermak, J. E., et al. (1966), "Simulation of Atmospheric Motion by Wind-Tunnel Flows," Technical Report for DA-AMC-28-043-G20 Fluid Dynamics and Diffusion Laboratory, Colorado State University, Fort Collins, Colorado (CER66JEC-VAS-ESP-GJB-HC-RNM-SI17).

Cermak, J. E. and Peterka, J. (1966), "Simulation of Wind Fields over Point Arguello, California, by Wind-Tunnel Flow over a Topographic Model," Colorado State University, Fort Collins, Colorado (CER65JEC-JAP64).

Cermak, J. E. and SethuRaman, S. (1973), "Stratified Shear Flows over a Simulated Three-Dimensional Urban Heat Island," Project THEMIS Technical Report No. 23, Colorado State University, Fort Collins, Colorado (CER73-74SS-JEC4, AD-767-063).

Chang, S. C. (1966), "Velocity Distributions in the Separated Flow behind a Wedge-Shaped Model Hill," Colorado State University, Fort Collins, Colorado, 101 p. (CER65SCC66).

Chang, S. C. (1966), "Velocity Distributions in the Separated Flow behind a Wedge-Shaped Model Hill," Technical Report, Grant DA-AMC-28-043-G20, March, Colorado State University, Fort Collins, Colorado (CER65SCC66).

Corby, G. A. (1954), "The Airflow over Mountains--A Review of the State of Current Knowledge," Quart. J. of the Royal Meteorological Society, Vol. 80, No. 346, pp. 491-521.

Davenport, A. G. and Isyumov, N. (1968), Proceedings, International Research Seminar on Wind Effects on Buildings and Structures, Ottawa Canada, September 11-15, 1967, Vols. I and II, University of Toronto Press.

Davidson, Ben (1964), "Sites for Wind-Power Installations," World Meteorological Organization, Technical Note No. 63, WMO-No. 156, TP 76.

Davidson, Ben, Gerbier, N., Papagionakis, S. O. and Rijkvort, P. G. (1964), "Sites for Wind-Power Installations," W.M.O. Technical Note 63.

de Bray, B. G. (1973), "Atmospheric Shear Flows over Ramps and Escarpments," Industrial Aerodynamics Abstracts, 5, September-October, 4 p.

Deaves, D. M. (1973), "A Theoretical Study of Three-Dimensional Effects on Wind Flow over Hills," M. Sc. Thesis, Loughborough University of Technology, United Kingdom.

REFERENCES (continued)

Deaves, D. M. (1975), "Wind over Hills--A Numerical Approach," Environmental Sciences Research Unit, Cranfield Institute of Technology, United Kingdom, May, 30 p.

Dickerson, M. H. and Orphon, R. C. (1975), "Atmospheric Release Advisory Capability (ARAC) Development and Plans for Implementation," Lawrence Livermore Laboratory, Rept. UCRL-51839.

Eagan, B. A. (1975), "Turbulent Diffusion in Complex Terrain," Ch. 4 of Lectures on Air Pollution and Environmental Impact Analysis, American Meteor. Society, pp. 112-135.

Eliseev, V. S. (1973), "Stereo Photogrammetric Investigation of the Air Flow in the Boundary Layer of the Atmosphere above a Hill," Air Pollution and Atmospheric Diffusion, ed. M. E. Beryland, pp. 95-108, John Wiley & Sons.

Field, J. H. and Warden, R. (1929-30), "A Survey of Air Currents in the Bay of Gibralter," Geophysical Memoirs, No. 59.

Field, J. H. and Warden, R. (R and M 1963), "A Survey of Air Currents in the Bay of Gibralter, 1929-1930," Geophysics Memoirs, No. 59, Published by Her Majesty's Stationery Office.

Fosberg, M. A. (1969), "Airflow over a Heated Coastal Mountain," J. of Applied Meteor., Vol. 8, pp. 436-442.

Fosberg, M. A., Marlatt, W. E. and Krupnak, L. (1976), "Estimation of Airflow Patterns over Complex Terrain," U.S. Forest Service Research Paper, RM 162, 16 p.

Franklin, R. E. and Wallace, J. M. (1970), "Absolute Measurements of Static-Hole Error Using Flush Transducers," Jour. Fluid Mech., Vol. 42, Pt. 1, pp. 33-48.

Freeman, B. E. (1975), "A New Wind Energy Site Selection Methodology," Quarter Report, March 17, 1975 - June 16, 1975, Science Applications, La Jolla, California, SAI75-621-LJ, 57 p.

Freeman, B. E. (1976), "Discussion of the Role of Meteorological Modeling in Selecting Wind Energy Sites," Science Applications, Inc., La Jolla, California, 23 p.

Freeston, D. H. (1974), "Atmospheric Shear Flows over Ramps and Escarpments," 5th Australian Conference on Hydraulics and Fluid Mechanics, Christchurch, New Zealand, December 9-13, 8 p.

Frenkiel, J. (1962-1963), "Wind Profiles over Hills (In Relation to Wind Power Utilization)," 88, pp. 156-169, 89, pp. 281-283.

REFERENCES (continued)

Frenkiel, J. (1963), "Gusts over Hills (In Relation to Wind-Power Utilization)," Quarterly Journal of the Royal Meteorological Society, 89, pp. 281-283.

Frost, W. (1973), "Review of Data and Prediction Techniques for Wind Profiles around Man-Made Surface Obstructions," AGARD Conference Proceedings #140, Flight in Turbulence, Woburm Abbey, United Kingdom, pp. 4-1 to 4-18.

Frost, W. (1974), "Wind Fields over Terrain Irregularities," in "Initial Wind Energy Data Assessment Study," NSF-RA-N-75-020 (1975), pp. 80-106.

Frost, W., Maus, J. R., and Simpson, W. R. (1973), "A Boundary Layer Approach to the Analysis of Atmospheric Motion over a Surface Obstruction," NASA CR-2182, 141 p.

Gal-Chen, T. and Somerville, R. C. J. (1975), "On the Use of a Co-Ordinate Transformation for the Solution of the Navier-Stokes Equations," J. Computational Physics, Vol. 17, pp. 209-228.

Garrison, J. A. and Cermak, J. E. (1968), "San Bruno Mountain Wind Investigation--A Wind-Tunnel Model Study," Colorado State University, Fort Collins, Colorado (CER67-68JEC-JAG58).

Golding, E. W. (1955), The Generation of Electricity by Wind Power, Philosophical Library, New York, 318 p.

Golding, E. W. (1956), "The Economic Utilization of Wind Energy in Arid Areas," Wind and Solar Energy, New Delhi Symposium, UNESCO, pp. 90-95.

Golding, E. W. (1961), "Studies of Wind Behavior and Investigation of Suitable Sites for Wind Driven Plants," Proceedings of UN Conference on New Sources of Energy, Rome, Vol. 7, pp. 3-8, 15-17.

Halitsky, L., Tolciss, J., and Kaplan, E. L. (1962), "Wind Tunnel Study of Turbulence in the Bear Mountain Wake," Quarterly Progress Reports No. 1, 2, 3, and 4, Contract No. DA 36-039 SC-89081, Department of Meteorology and Oceanography, New York University.

Hansen, C. and Cermak, J. E. (1975), "Vortex-Containing Wakes of Surface Obstacles," Project THEMIS TR No. 29, December, Colorado State University, Fort Collins, Colorado (CER75-76HCH-JEC16).

Haugen, Duane A., ed., (1973), Workshop on Micrometeorology, American Meteorological Society, Boston, Mass., 392 p.

Hawthorne, W. R. and Martin, M. E. (1955), "The Effect of Density Gradient and Shear on the Flow over a Hemisphere," Proc. Royal Soc. A, Vol. 232, pp. 184-195.

REFERENCES (continued)

Hewson, E. Wendell, et al. (1973), "Wind Power Potential in Selected Areas of Oregon," Oregon State University (PUD73-1).

Hsi, G., Binder, G. J., and Cermak, J. E. (1968), "Topographic Influences on Wind near Green River, Utah," Technical Report, Grant DA-AMC-28-043-65-G20, for Atmospheric Science Laboratory, White Sands Missile Range, Colorado State University, Fort Collins, Colorado (CER67-68GH-GJB-JEC54).

Huang, C. and Nickerson, E. C. (1972), "Numerical Simulation of Wind, Temperature, Shear Stress and Turbulent Energy over Non-Homogeneous Terrain," Colorado State University, Fort Collins, Colorado, 276 p. (CER71-72CH-ECN23).

Hunt, J. C. R. (1973), "Turbulent Flow around Two-Dimensional Bluff Bodies," J. Fluid Mechanics, 61, Part 4, pp. 625-706.

Jackson, P. S. (1975), "A Theory for Flow over Escarpments," Ministry of Works and Development, New Zealand, 8 p.

Jackson, P. S. and Hunt, J. C. R. (1975), "Turbulent Wind Flow over a Low Hill," Quarterly Journal of the Royal Meteorological Society, 101, pp. 292-955.

Kahawita, R. A. and Meroney, R. N. (1973), "The Stability of Parallel, Quasi-Parallel, and Stationary Flows," Colorado State University, Fort Collins, Colorado, 162 p. (CER73-74RK-RNM12).

Kitabayshi, K. K., Orgill, M. M., and Cermak, J. E. (1971), "Laboratory Simulation of Air Flow in Atmospheric Transport-Dispersion over Elk Mountain, Wyoming," Technical Report prepared under Atmospheric Water Resources Research, Bureau of Reclamation, Contract No. 14-06-D-6455 and 14-06-6842, Colorado State University, Fort Collins, Colorado (CER70-71KKK-MMO-JEC65).

Knox, J. B., Hardy, D. M., Sherman, C. A., and Sullivan, T. J. (1976), "Status Report: Lawrence Livermore Laboratory Wind Energy Studies," Lawrence Livermore Report UCIP-17157-1, 18 p.

Lange, K. O. (1961), "Some Aspects of Site Selection for Wind Power Plants on Mountainous Terrain," Proceedings of the UN Conference on New Sources of Energy Resources, 7, W/28, pp. 125-128, August 21-31.

Lighthill, M. J. (1957), "The Fundamental Solution for Small Steady Three-Dimensional Disturbances to a Two-Dimensional Parallel Shear Flow," J. Fluid Mechanics, Vol. 3, pp. 113-144.

Lin, J. T. and Binder, G. J. (1967), "Simulation of Mountain Lee Waves in a Wind Tunnel," Technical Report, Grant No. DA-AMC-28-043-65-G20, Colorado State University, Fort Collins, Colorado (CER67-68JTL-GJB24, AD-664-172).

REFERENCES (continued)

Meroney, R. N. (1975), "Sites for Wind Power Installations," Proceedings Second U.S. National Conference on Wind Engineering Research, June 22-25, 1975, Fort Collins, Colorado, pp. V-19-1 to 3.

Meroney, R. N. and Cermak, J. E. (1965), "Wind-Tunnel Modeling for Flow and Diffusion over San Nicolas Island," Progress Reports for 4th and 5th Quarters, Contract No. 123 (61756) 50192A (PMR), Colorado State University, Fort Collins, Colorado.

Meroney, R. N. and Cermak, J. E. (1967), "Wind-Tunnel Modeling of Flow and Diffusion over San Nicolas Island, California," 97 pp., Colorado State University, Fort Collins, Colorado (CER66-67RNM-JEC44).

Meroney, R. N., Cermak, J. E., Garrison, J. A., Yang, B. T., and Nayak, S. (1974), "Wind Tunnel Study of Stack Gas Dispersal at the Avon Lake Power Plant," Prepared under contract to Commonwealth Associates, Inc., April, Colorado State University, Fort Collins, Colorado (CER73-74RNM-JEC-BTY-SKN35).

Meroney, R. N. and Chaudhry, F. H. (1972), "Wind Tunnel Site Analysis of Dow Chemical Facility at Rocky Flats, Colorado," Colorado State University, Fort Collins, Colorado (CER71-72RNM-FC45).

Nemoto, S. (1961 and 1962), "Similarity between Natural Wind in the Atmosphere and Model Wind in a Wind Tunnel," Papers in Meteorology and Geophysics, Tokyo:
Vol. 12, No. 1, pp. 30-52,
Vol. 12, No. 2, pp. 117-128,
Vol. 12, No. 2, pp. 129-154,
Vol. 13, No. 2, pp. 171-195 (1962).

Orgill, M. M., Cermak, J. E., and Grant, L. O. (1971), "Laboratory Simulation and Field Estimates of Atmospheric Transport-Dispersion over Mountainous Terrain," Technical Report, Colorado State University, Fort Collins, Colorado (CER70-71MMO-JEC-LOG40).

Orville, H. D. (1968), "Ambient Wind Effects on the Initiation of Cumulus Clouds over Mountains," J. Atmos. Sci., Vol. 25, pp. 385-403.

Peterka, J. A. and Cermak, J. E. (1966), "Simulation of Wind Fields over Point Arguello, California, by Wind Tunnel Flow over a Topographical Model," Contract N123(61756)34361A(PMR), Colorado State University, Fort Collins, Colorado (CER65JAP-JEC64, AD-643-689).

Petterssen, Sverre (1961), "Some Aspects of Wind Profiles," New Sources of Energy, Proceedings of the United Nations Conference in Rome, Vol. 7 (W/26), pp. 133-136.

Plate, E. J. and Lin, C. W. (1965), "The Velocity Field Downstream from a Two-Dimensional Model Hill--Part 2," Colorado State University, Fort Collins, Colorado (CER65EJP-CWL41).

REFERENCES (continued)

Plate, E. J. and Sheih, C. M. (1965), "Diffusion from a Continuous Point Source into the Boundary Layer Downstream from a Model Hill," Colorado State University, Fort Collins, Colorado (CER65EJP-CMS60).

Putnam, Palmer Cosslett (1948), Power from the Wind, 224 p., Van Nostrand Reinhold Company, New York.

Reinsch, H. R. (1967), "Smoothing by Spline Functions," Numerische Mathematik, Vol. 10, pp. 177-183.

Sacre, C. (1974), "Theoretical Estimation of the Properties of Airflow over a 2-Dimensional Hill," Centre Scientifique et Technique du Batement, Nantes, France, 30 p.

Sacre, C. (1975), "Numerical Method for near Calculation of the Excess Velocity of the Wind on a Hill," Centre Scientifique et Technique du Batement, Nantes, France, 26 p.

Sandborn, V. A. and Marshall, R. D. (1965), "Local Isotropy in Wind Tunnel Turbulence," Colorado State University, Fort Collins, Colorado (CER65VAS-RDM71).

Sandborn, V. A. (1972), "Resistance Temperature Transducers," Meteorology Press, Fort Collins, Colorado.

Sandborn, V. A. (1975), "Laboratory Instrumentation in Turbulence Measurements," Fundamentals and Applications of Turbulence, Eds. W. Frost and T. H. Moulden (Short course at University of Tennessee Space Inst., April, 1975, to be published in book form).

Scorer, R. S. (1952), "Mountain-Gap Winds; a Study of Surface Wind at Gibralter," Quarterly Journal of the Royal Meteorological Society, Imperial College, London, Vol. 78, pp. 53-61.

Scorer, R. S. (1953), "Theory of Airflow over Mountains II--The Flow over a Ridge," Quarterly Journal of the Royal Meteorological Society, Vol. 79, pp. 70-83.

Seltari, A. and Lantz, R. B. (1974), "A Turbulent Flow Model for Use in Numerical Evaluation of Air Quality," Journal of Canadian Petroleum Industry, October-December, Montreal.

Sherman, C. A. (1975), "A Mass-Consistent Model for Wind Fields over Complex Terrain," Lawrence Livermore Laboratory, Report UCRL-76171, Rev. 1.

Smith, Maynard E. (1974), "Deficiencies in Data and Analyses for Environmental Impact Statements," Presented at the 67th Annual Meeting of the Air Pollution Control Association, Denver, Colorado (74-126).

REFERENCES (continued)

Taylor, P. A. and Gent, P. R. (1974), "A Model of Atmospheric Boundary-Layer Flow above an Isolated Two-Dimensional 'Hill,' an Example of Flow above 'Gentle Topography,'" Boundary-Layer Meteorology, 7, pp. 349-362.

Thwaites, B. (1960), Incompressible Aerodynamics, Clarenoon Press, Oxford, 636 p.

Tieleman, H. W. (1967), "Viscous Region of Turbulent Boundary Layer," Ph.D. Dissertation, Colorado State University, Fort Collins, Colorado (CER67-68HWT21).

Winternitz, F. A. L. (1956), "Simple Shielded Total Pressure Probes," Aircraft Eng., Vol. 28, p. 273.

Yamada, Tetsuji and Meroney, Robert N. (1971), "Numerical and Wind Tunnel Simulation of Response of Stratified Shear Layers to Nonhomogeneous Surface Features," Project THEMIS TR No. 9, Fluid Dynamics and Diffusion Laboratory, Colorado State University, Fort Collins, Colorado (CER70-71TY-RNM62).

Zoric, D. L. (1969), "Approach of Turbulent Boundary Layer to Similarity," Colorado State University, Fort Collins, Colorado (CER68-69DLZ9).

Zoric, D. and Sandborn, V. A. (1972), "Similarity of Large Reynolds Number Boundary Layers," Boundary-Layer Meteorology, Vol. 2, No. 3, pp. 326-333.

Zrajevsky, I. M., Doroshenko, V. N., and Chepik, N. G. (1968), "Investigation of the Effect of Various Types of Relief on the Characteristics of an Airstream in a Wind Tunnel," Trudi Glavnaya Geofizicheskoya Observatoriya, No. 207 (In Russian).

Table 1. Experimental Data of Flow over Hills, Ridges, and Escarpments. (Part 1)

AUTHOR	METHOD	SHAPE RAMP OR HILL	$\frac{h}{L}$	STABILITY	α	$\frac{z_o}{h}$	$\frac{U_o^*}{U_o(L)}$	MEASUREMENTS REPORTED						$-C_{p_{max}}$	ΔS	S
								p	U	u	τ_w	w	$E_u(k)$			
[L]Field & Warden (1929-1930)	wind tunnel	Gibraltar	-1.10	N	~0	--	--			x		x		--	--	--
	field		-1.10	N						x		x		--	--	--
[L]Putnam (1948) (Petterssen, 1961)	field	Pond	1.27	--	.3	.05	--		x					--	--	0.84
		Glastenberg	--	--	.3	--	--		x					--	--	1.04
		Mt. Washington	.61	--	.3	.05	--		x					--	--	1.47
	wind tunnel	Pond	1.27	N	~0				x					--	--	1.29
		Glastenberg	--	N	~0				x					--	--	1.44
		Mt. Washington	.61	N	~0				x					--	--	1.30
Golding (1955)	field	Costa, Orkney U.K.	0.3-0.6	--	--	--	--		x					--	--	--
		Vestra Fiold, U.K.	0.2	--	--	--	--		x					--	--	--
Frenkiel (1961)	field	Hreiba Ridge, Israel	0.25	N,S	0.15	$1.4x10^{-4}$	--		x	x				--	--	--
		Givat Hamere Hill, Israel	-0.57	N,S	0.15	$9x10^{-5}$	--		x	x				--	--	--
[L]Halitsky et al. (1962-1963)	wind tunnel	Bear Mtn., NY	-0.46	N	--	--	--		x	x	x			--	--	--
Chang (1966)			1.0	N	.15		.036	x	x	x	x			.33	.27	1.0
Plate & Lin (1965)	wind tunnel		1.0	US*	.19	$1.5x10^{-4}$	.033		x		x			--	.24	1.15
			2.0	N	.15		.036	x	x	x	x			.33	.35	1.1
			0.5	N	.15		.036	x	x	x	x			.33	.35	1.0
		 $\frac{1}{2}$ sine	0.8	N	.15	$1.5x10^{-4}$	.035	x	x	x	x		x	.55	.76	1.38
				US**	.19		.032		x		x			--	--	--
[L]Cermak & Peterka (1966)	wind tunnel	Pt. Arguello, CA	0.11	N	0.25	--	--		x					--	--	--
			0.11	$S^{\Delta\Delta}$	0.25	--	--		x					--	>3.0	1.25
[L]Meroney & Cermak (1967)	wind tunnel	San Nicolas Is., CA	0.12	N	0.14	$1.2x10^{-2}$	.032		x	x		x		--	--	--
			0.12	$S^{\Delta\Delta}$	0.20	--	--		x					--	--	--
Lin & Binder (1967)	wind tunnel		0.67	S					x					--	--	1.2
		 f($\frac{x}{L}$)	1.33	S		Lee Waves			x					--	--	2.6
Garrison & Cermak (1968)	wind tunnel	San Bruno Mtn., CA	-0.43	S	0.16	$2.5x10^{-3}$	.125		x					--	0.5	1.07
[L]Hsi et al. (1968)	wind tunnel	Green River, UT	-.09	N	0.14	$2x10^{-4}$	--		x					--	--	1.14
[L]Beryland et al. (1968)	field		0.1	N	--	--	--		x					--	0.25	--
Zrajevsky, Doroshenko & Chepik (1968)	wind tunnel	"	"	N	~0	--	--		x					--	0.1	1.1
[L]Kitabayashi et al. (1971)	wind tunnel	Elk Mtn., WY	0.35	N	0.21	$7x10^{-3}$	0.149		x	x				--	0.37	1.04
				S***	0.32	--	--		x						0,29	1.29

Table 1. Experimental Data of Flow over Hills, Ridges, and Escarpments. (Part 2)

AUTHOR	METHOD	SHAPE RAMP OR HILL	$\frac{h}{L}$	STABILITY	α	$\frac{z_o}{h}$	$\frac{U_o^*}{U_o(L)}$	MEASUREMENTS REPORTED p	U	u	τ_w	w	$E_u(k)$	$-C_{p_{max}}$	ΔS	S
Eliseev (1971)	field	Razdan Valley, USSR	0.61	N	--				x					--	0.35	--
$^{\Delta}$Orgill & Cermak (1971)	wind tunnel	Climax, CO	.10	N	0.25	$3.0\text{x}10^{-4}$	--	x	x	x	x	x		--	1.86	1.18
			.10	S$^{\Delta\Delta\Delta}$					x					--	0.67	1.00
			.10	N	0.57	--	--		x	x		x		--	1.20	0.75
de Bray (1973)	wind tunnel	20°	0.72	N	0.14	--	--		x					--	0.41	1.13
		sine	0.5	N	0.14	--	--		x					--	0.34	1.07
		source	--	N	0.14	--	--		x					--	0.30	1.04
				N	0.11	--	--									
Freeston (1974)	wind tunnel	20°	0.72	N	0.14	--	--	x	x					0.40	0.38	1.10
		40°	1.67	N	0.14	--	--	x	x					0.90	0.45	1.16
		60°	3.46	N	0.14	--	--	x	x					1.00	0.18	0.94
		sine	0.5	N	0.14	--	--	x	x					0.50	0.34	1.07
		source	--	N	0.14	--	--	x	x					0.40	0.30	1.04
$^{\Delta}$Bowen & Lindley (1974)	field	26°	0.98	N	0.1	$5\text{x}10^{-5}$	0.102		x					--	0.39	1.06
	New Zealand		∞	US	0.45	$1\text{x}10^{-2}$	--		x					--	1.13	1.16
	wind tunnel	26°	0.98	N	0.18	$4\text{x}10^{-3}$	0.160		x					--	0.40	1.12
			∞	N	0.18	$5.3\text{x}10^{-3}$	0.160		x					--	0.47	1.10
Watanabe, Nakase, &* Fukutomi (1975)	wind tunnel		1.0	N	0.15	--	--	x	x	x	x			0.80	2.00	1.40
Meroney et al. (1976)	wind tunnel		1.0	N	0.14	$9\text{x}10^{-5}$	.032	x	x	x	x	x	x	0.25	0.71	1.07
			0.67	N	0.14	"	"	x	x	x				.26	0.79	1.15
			0.50	N	0.14	"	"	x	x	x				0.93	1.41	1.53
			0.33	N	0.14	"	"	x	x	x	x	x	x	0.77	1.11	1.35
			0.10	N	0.14	"	"	x	x	x	x	x	x	0.15	.40	0.90

$$C_{p_{max}} = \frac{\Delta p}{\frac{1}{2}\rho\, u_o(\delta)^2}\ ,\ \Delta S = u(\bar{z})/u_o(\bar{z})\ ,\ S = \frac{u(\bar{z})}{u_o(\bar{z}+hf/L)}$$

$^{*}Ri_{\delta h} = -.016$

$^{**}Ri_{4h} = -.019$

$^{***}Ri_{\delta} = 1.70$

$^{\Delta}$Field comparisons available

$^{\Delta\Delta}Ri_{\delta} = 0.30$

$^{\Delta\Delta\Delta}Ri_{h} = 6.0$

* note $h/\delta \sim 2.0$

Table 2. Site Classification as Suggested by Frenkiel (1962).

QUALITY	$R = u_{40m}/u_{10m}$	α	SLOPE	h/L
Optimum	R < 1.05	0.0	1:3.5	0.57
Very Good	1.05 < R < 1.10	0.07	1:6 smooth regular	0.35
Good	1.1 < R < 1.15	0.1	1:10	0.20
Fair	1.15 < R < 1.21	0.14	1:20 smooth 1:6 regular	0.10
Avoid	1.21 < R	>0.14	>1:20 <1:2	< .05 >1.0

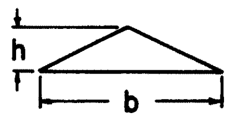
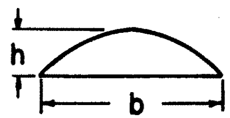
HILL SHAPE	HEIGHT-LENGTH RATIO		LOCATION OF STATIC PRESSURE TAPS ALONG SURFACE OF HILL (Dimensions in Centimeters)
 TRIANGULAR-SHAPED	h = 2 in. b = 8 in.	1/2	1.91 – 2.54 – 1.27 – 1.27 – 1.27 – 1.27 | CREST | 0.64 – 0.64 – 0.64 – 0.64 – 0.64 – 1.27 – 1.27 – 1.27 – 1.27
	h = 2 in. b = 12 in.	1/3	2.54 – 2.54 – 2.54 – 2.54 – 2.54 | CREST | 0.64 – 0.64 – 0.64 – 1.27 – 1.27 – 1.27 – 1.27 – 1.27 – 2.54 – 2.54
	h = 2 in. b = 16 in.	1/4	2.54 – 2.54 – 2.54 – 2.54 – 2.54 – 1.27 – 1.27 | CREST | 1.27 – 1.27 – 1.27 – 1.27 – 2.54 – 2.54 – 2.54 – 2.54
	h = 2 in. b = 24 in.	1/6	5.08 – 5.08 – 5.08 – 2.54 – 2.54 | CREST | 1.27 – 1.27 – 2.54 – 2.54 – 2.54 – 2.54 – 2.54 – 2.54 – 2.54 – 2.54
 SINE SHAPED	h = 2 in. b = 8 in.	1/2	1.91 – 2.54 – 1.27 – 1.27 – 1.27 – 1.27 | CREST | 0.64 – 0.64 – 0.64 – 0.64 – 0.64 – 1.27 – 1.27 – 1.27 – 1.27
	h = 2 in. b = 12 in.	1/3	2.54 – 2.54 – 2.54 – 2.54 – 2.54 | CREST | 0.64 – 0.64 – 0.64 – 1.27 – 1.27 – 1.27 – 1.27 – 1.27 – 2.54 – 2.54
	h = 2 in. b = 16 in.	1/4	2.54 – 2.54 – 2.54 – 2.54 – 2.54 – 1.27 – 1.27 | CREST | 1.27 – 1.27 – 1.27 – 1.27 – 2.54 – 2.54 – 2.54 – 2.54
	h = 2 in. b = 24 in.	1/6	5.08 – 5.08 – 5.08 – 2.54 – 2.54 | CREST | 1.27 – 1.27 – 2.54 – 2.54 – 2.54 – 2.54 – 2.54 – 2.54 – 2.54 – 2.54

Table 3. Location of Static Pressure Instrumentation on the Hill Models.

Table 4. Test: Two-Dimensional Ridges.

The following table depicts the tests which have been completed:

SHAPE	SLOPE*	$\frac{h}{L}$	h (cm)	U_o(10h) (m/sec)	Re_h	$\frac{z_o}{h}$	$\frac{\delta}{h}$	U_o^*/U_o(10h)
Triangular	1:2	1.0	5.08	9.14	30,000	$1.5x10^{-4}$	10.5	.032
Triangular	1:2	1.0	5.08	15.24	50,000	$9.0x10^{-5}$	3.5	.032
Triangular	1:3	.67	5.08	9.14	30,000	$1.5x10^{-4}$	10.5	.032
Triangular	1:3	.67	5.08	15.24	50,000	$9.0x10^{-5}$	3.5	.032
Triangular	1:4	.50	5.08	9.14	30,000	$1.5x10^{-4}$	10.5	.032
Triangular	1:4	.50	5.08	15.24	50,000	$9.0x10^{-5}$	3.5	.032
Triangular	1:6	.33	5.08	9.14	30,000	$1.5x10^{-4}$	10.5	.032
Triangular	1:6	.33	5.08	15.24	50,000	$9.0x10^{-5}$	3.5	.032
Triangular	1:20	.10	5.08	9.14	30,000	$1.5x10^{-4}$	10.5	.032
Triangular	1:20	.10	5.08	15.24	50,000	$9.0x10^{-5}$	3.5	.032
Sinusoidal	1:3	.67	5.08	9.14	30,000	$1.5x10^{-4}$	10.5	.032
Sinusoidal	1:3	.67	5.08	15.24	50,000	$9.0x10^{-5}$	3.5	.032
Sinusoidal	1:4	.50	5.08	9.14	30,000	$1.5x10^{-4}$	10.5	.032
Sinusoidal	1:4	.50	5.08	15.24	50,000	$9.0x10^{-5}$	3.5	.032
Sinusoidal	1:6	.33	5.08	9.14	30,000	$1.5x10^{-4}$	10.5	.032
Sinusoidal	1:6	.33	5.08	15.24	50,000	$9.0x10^{-5}$	3.5	.032
Triangular	1:4	.50	5.08	9.14	30,000	$5.0x10^{-3}$	10.5	--

*For sinusoidal hill slope equals hill height to half width ratio.

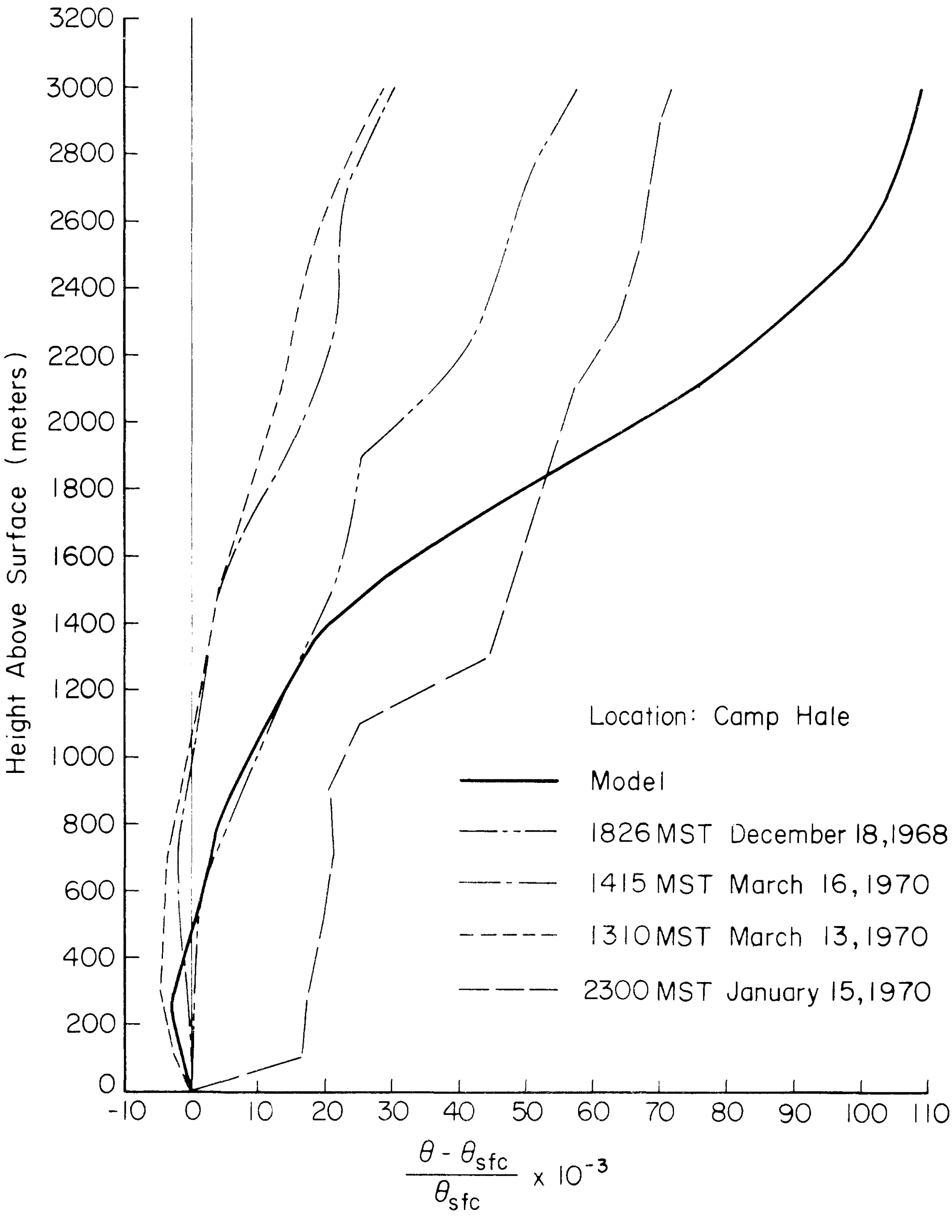


Figure 1. Comparison of selected field potential temperature vertical profiles with a barostromatic model temperature profile (Orgill, Cermak, Grant, 1971: Final Report).

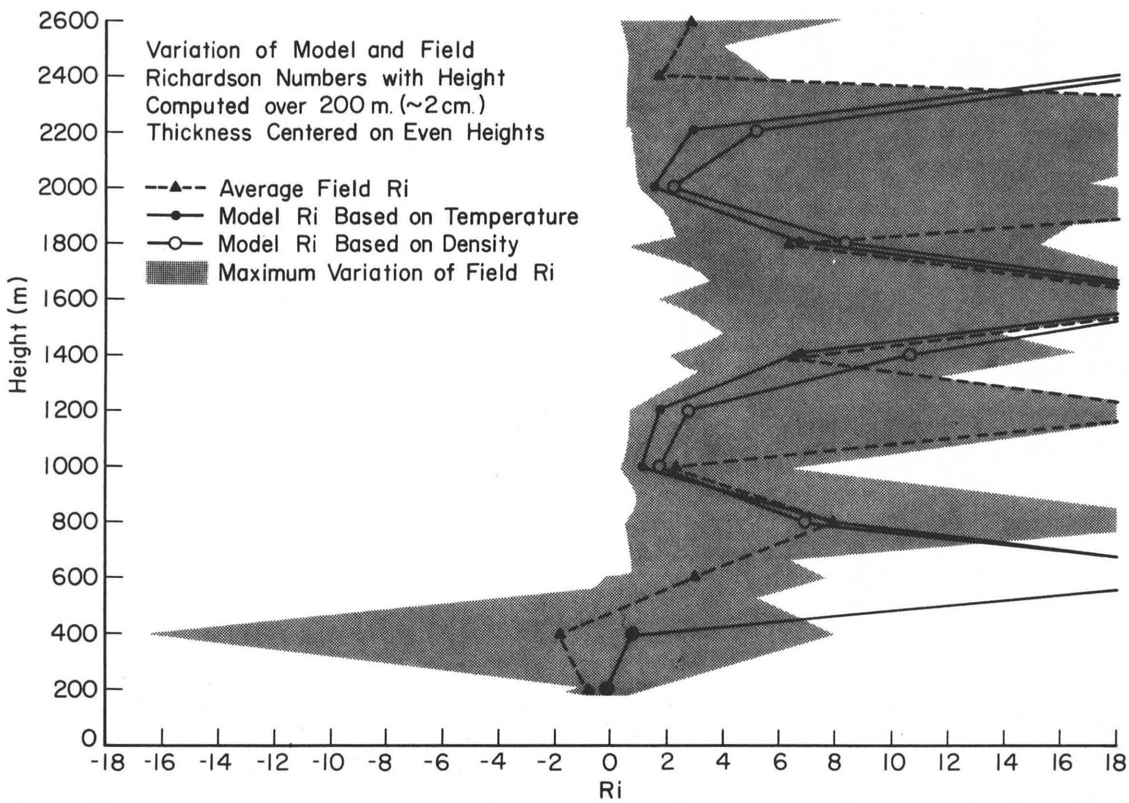


Figure 2. Comparison of field and model bulk Richardson Numbers at the Camp Hale location (Orgill, Cermak, Grant, 1971: Final Report).

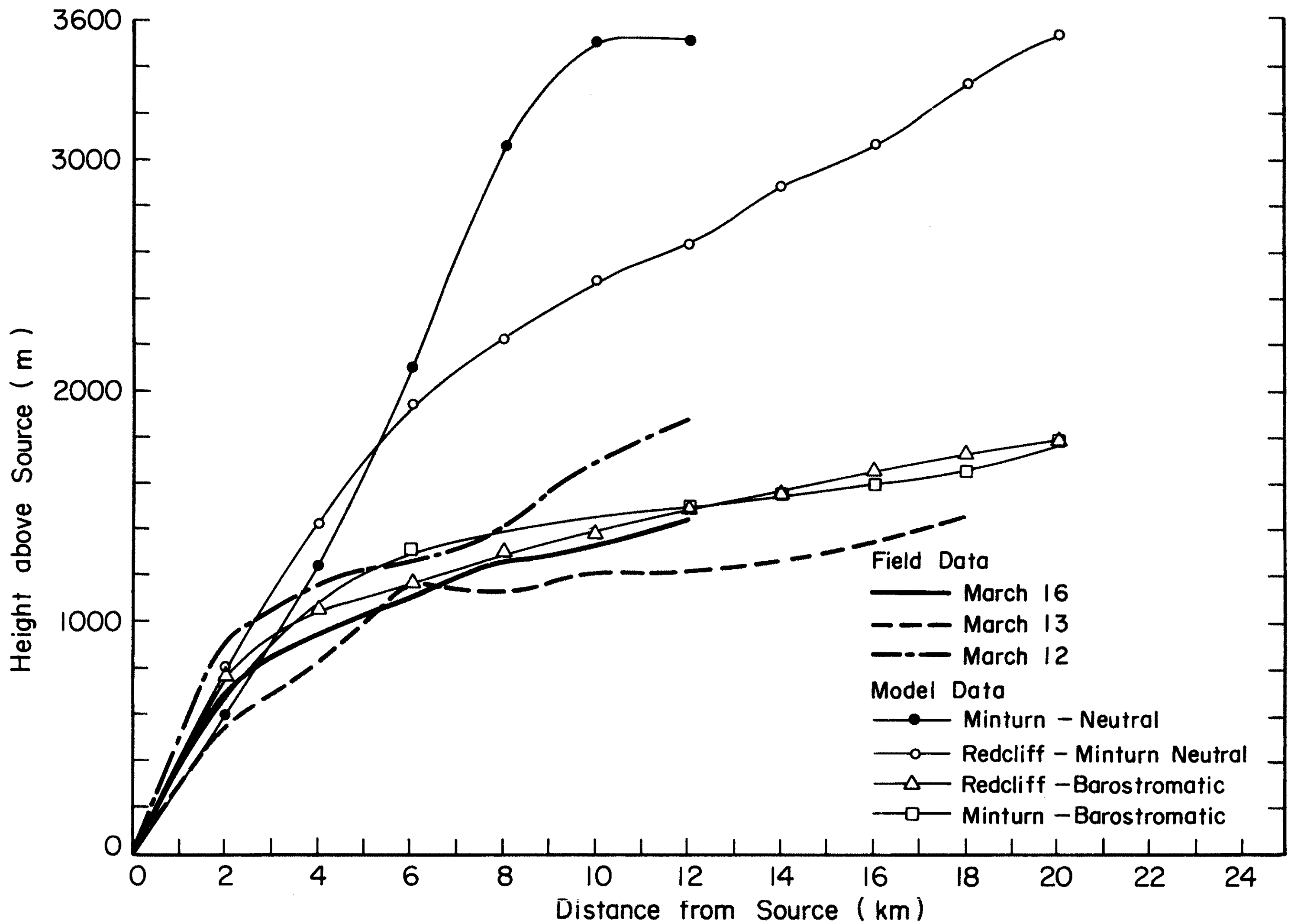


Figure 3. Comparison between the vertical rise of model and field tracer plumes (Orgill, Cermak, Grant, 1971: Final Report).

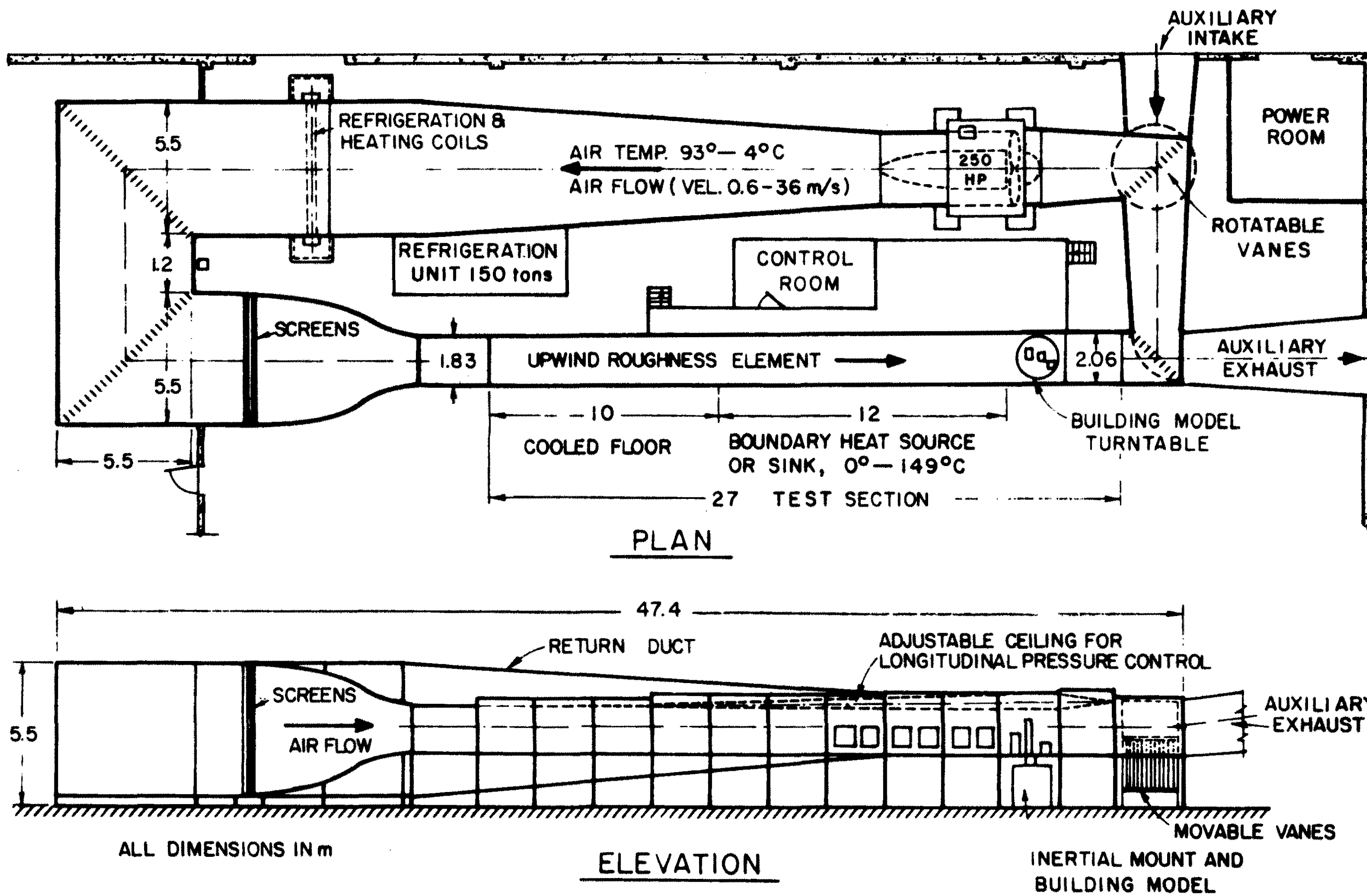


Figure 4. METEOROLOGICAL WIND TUNNEL (Completed in 1963)
FLUID DYNAMICS & DIFFUSION LABORATORY
COLORADO STATE UNIVERSITY

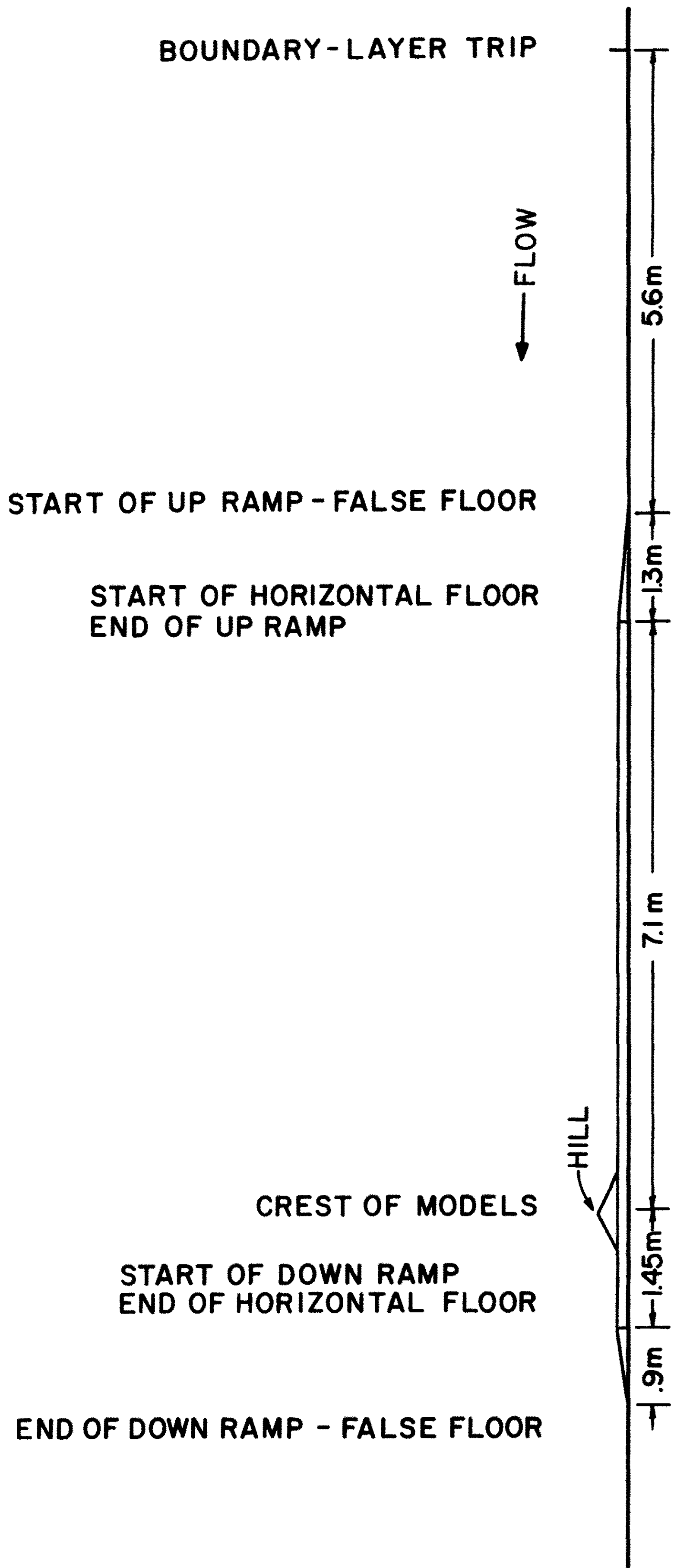
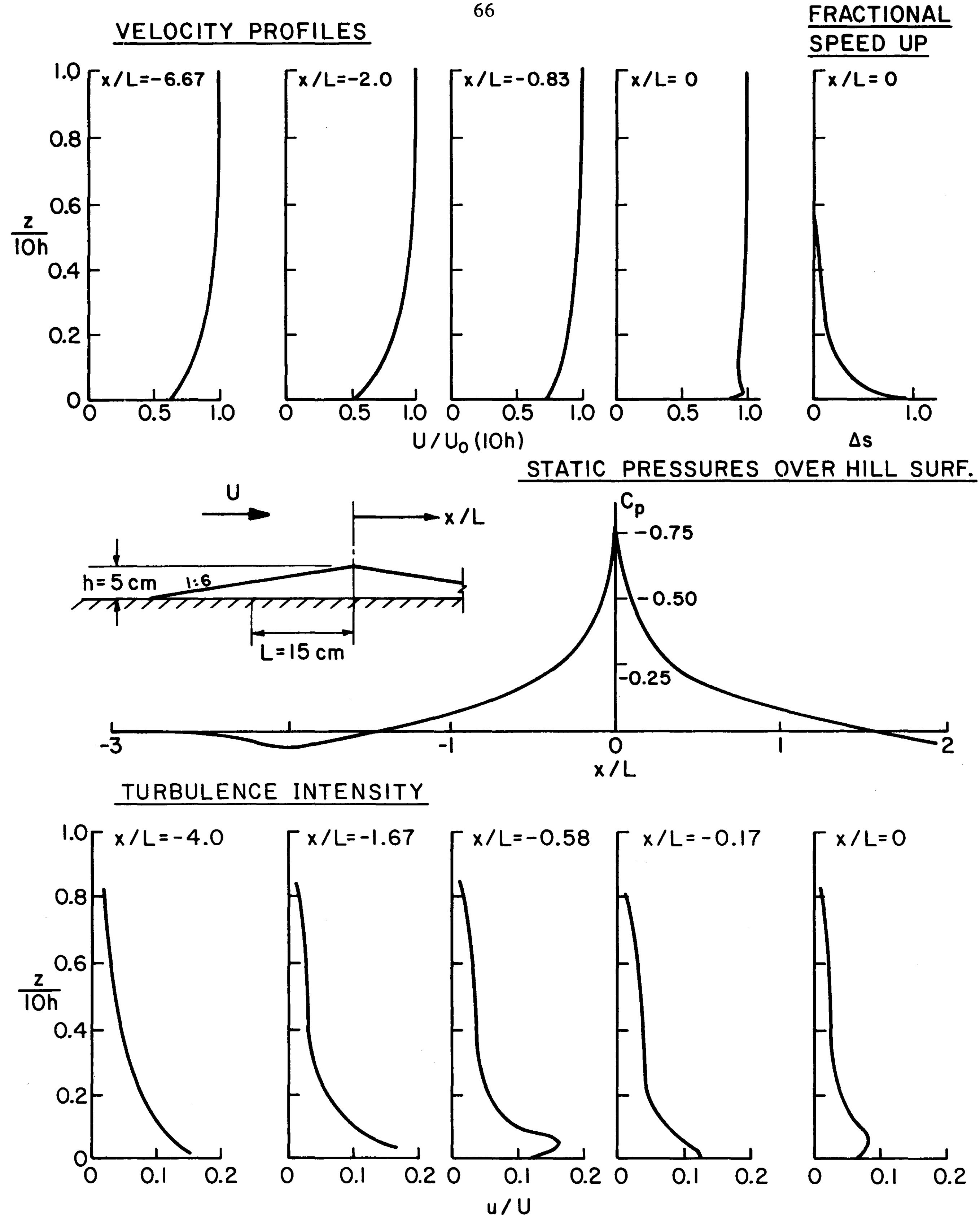
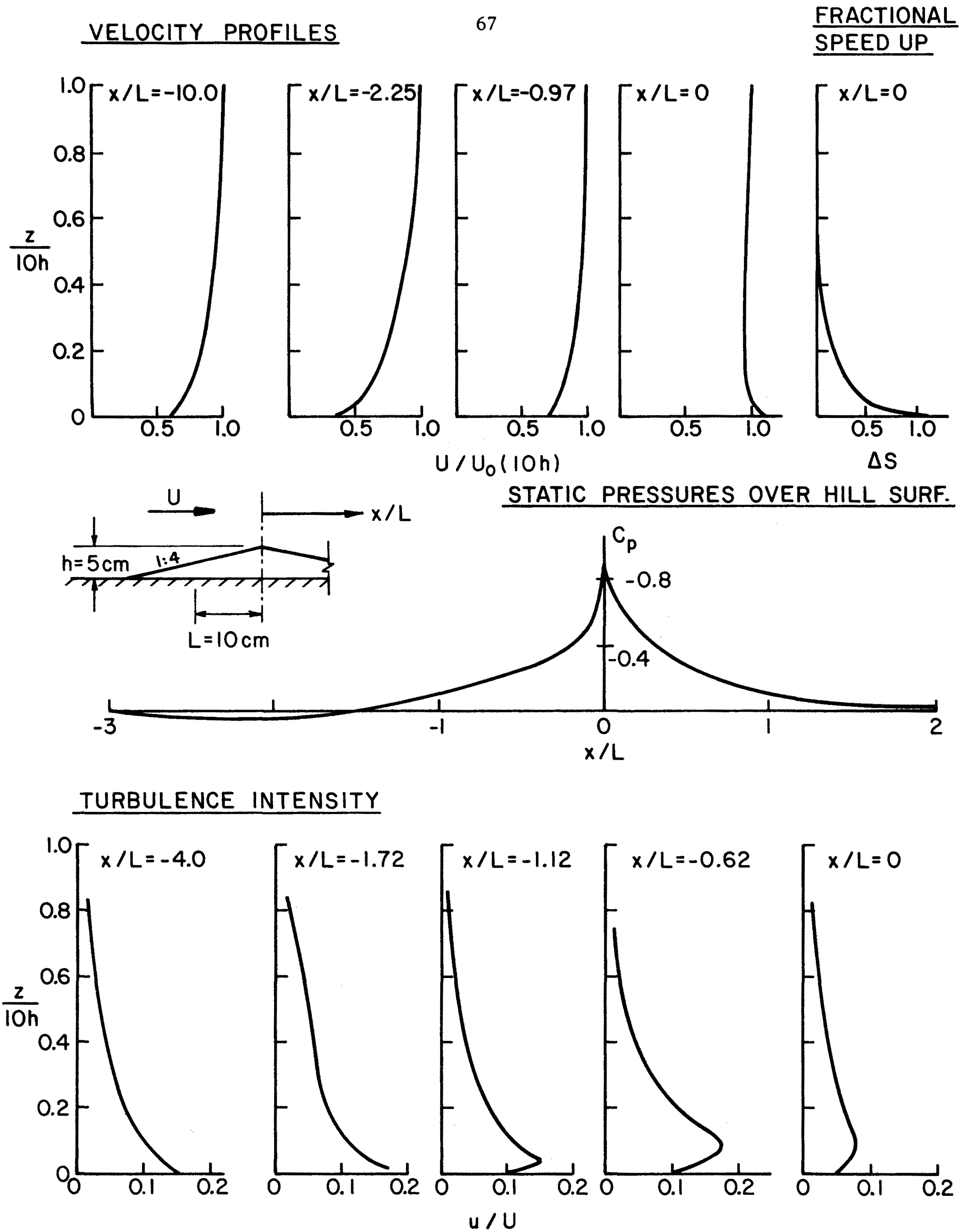


Figure 5. Model installation in the wind tunnel.



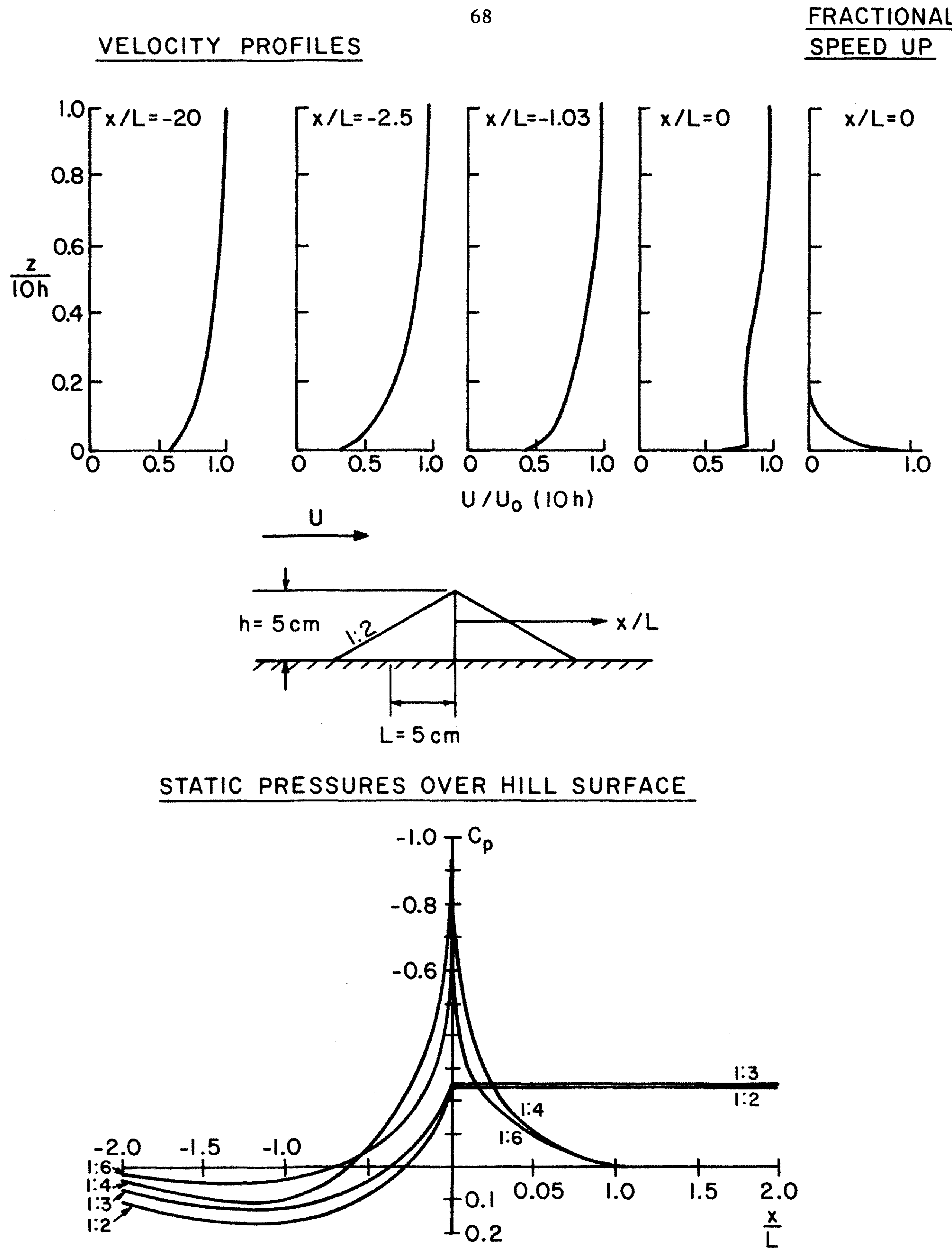
1:6 Model, $U_o(10h)$ = 15.24 m/sec

Figure 6a. Velocity, static pressure and turbulence measurements over the triangular ridges.



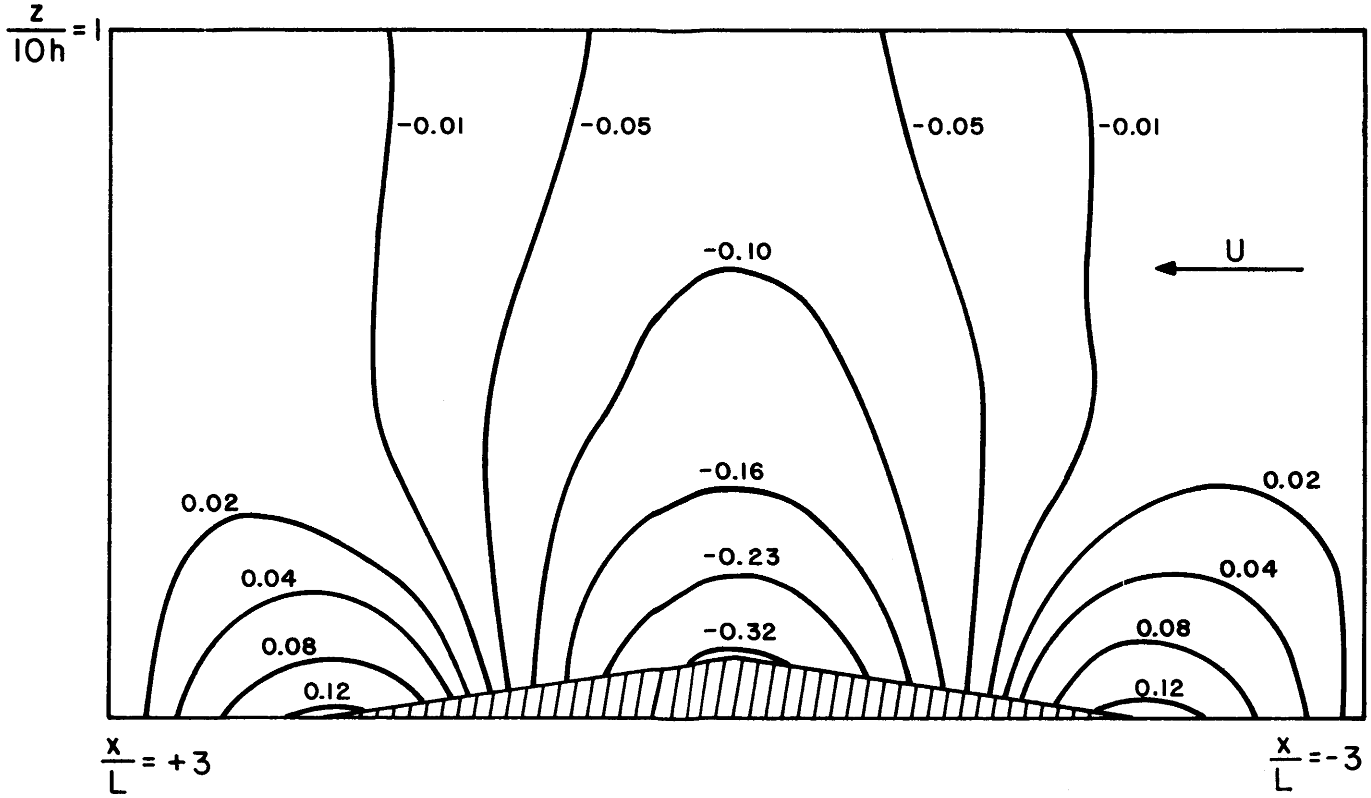
1:4 Model, $U_o(10h)$ = 15.24 m/sec

Figure 6b. Velocity, static pressure and turbulence measurements over the triangular ridges.



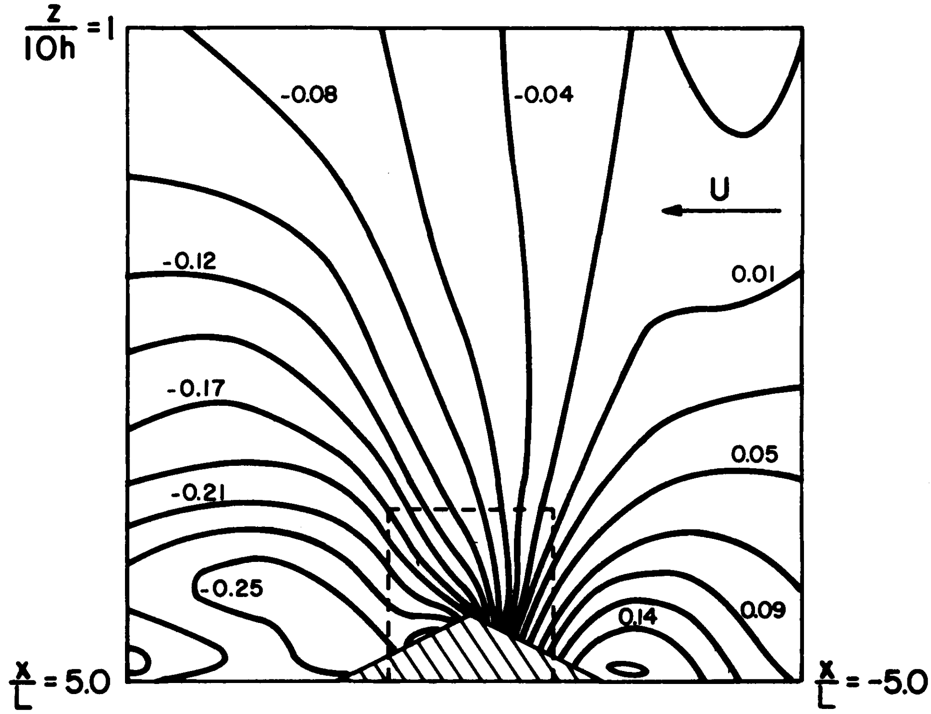
1:2 Model, $U_o(10h)$ = 15.24 m/sec

Figure 6c. Velocity, static pressure and turbulence measurements over the triangular ridges.

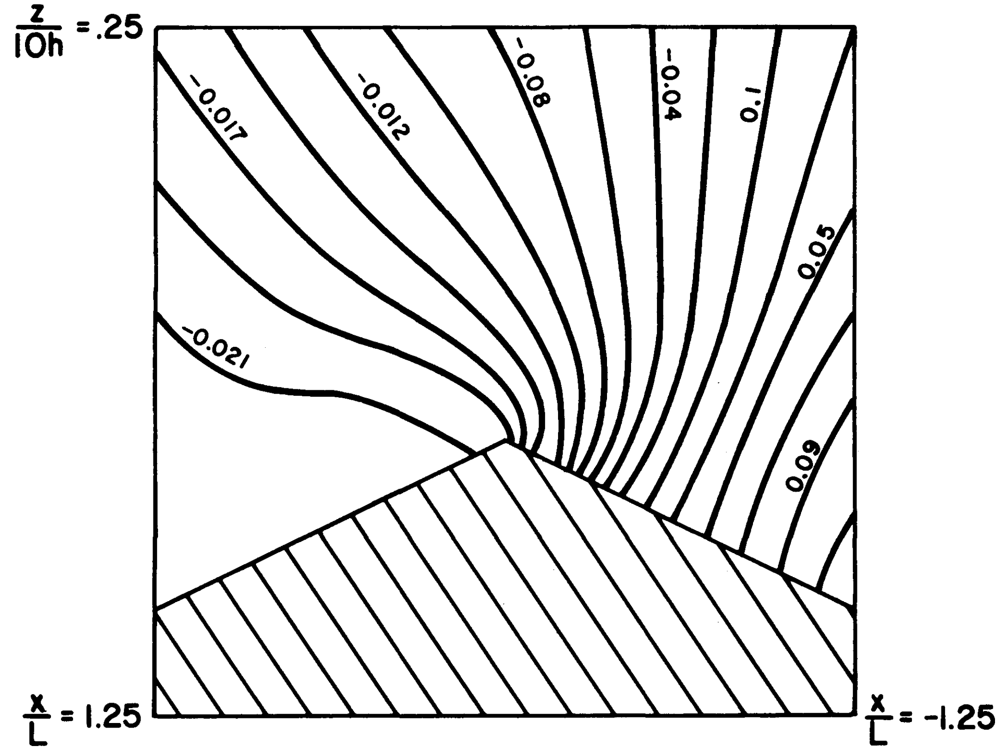


1:6 Model, $U_o(10h)$ = 15.24 m/sec

Figure 7a. Static pressure contours (in C_p).

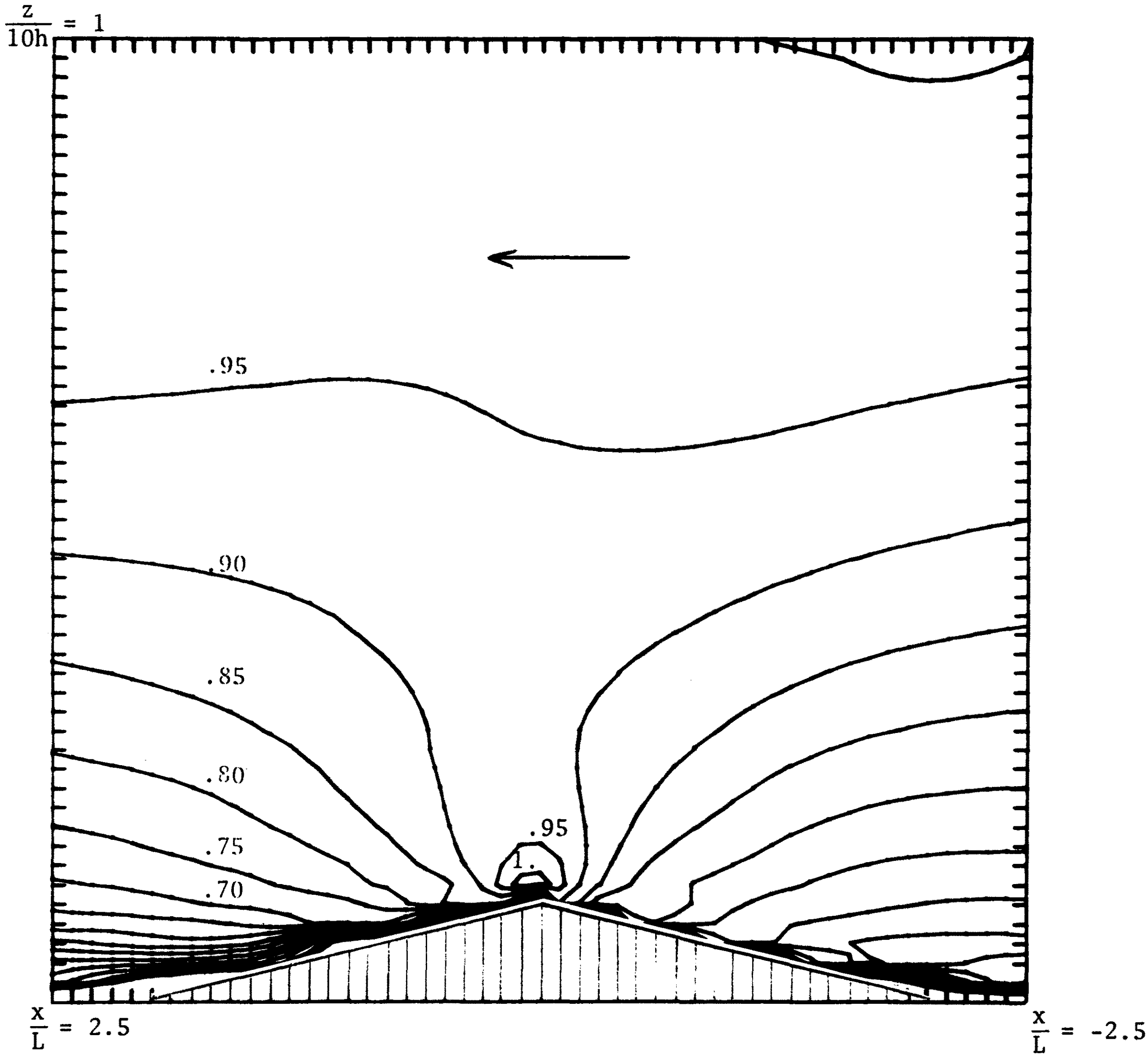


7b) 1:2 Model, $U_o(10h)$ = 15.24 m/sec



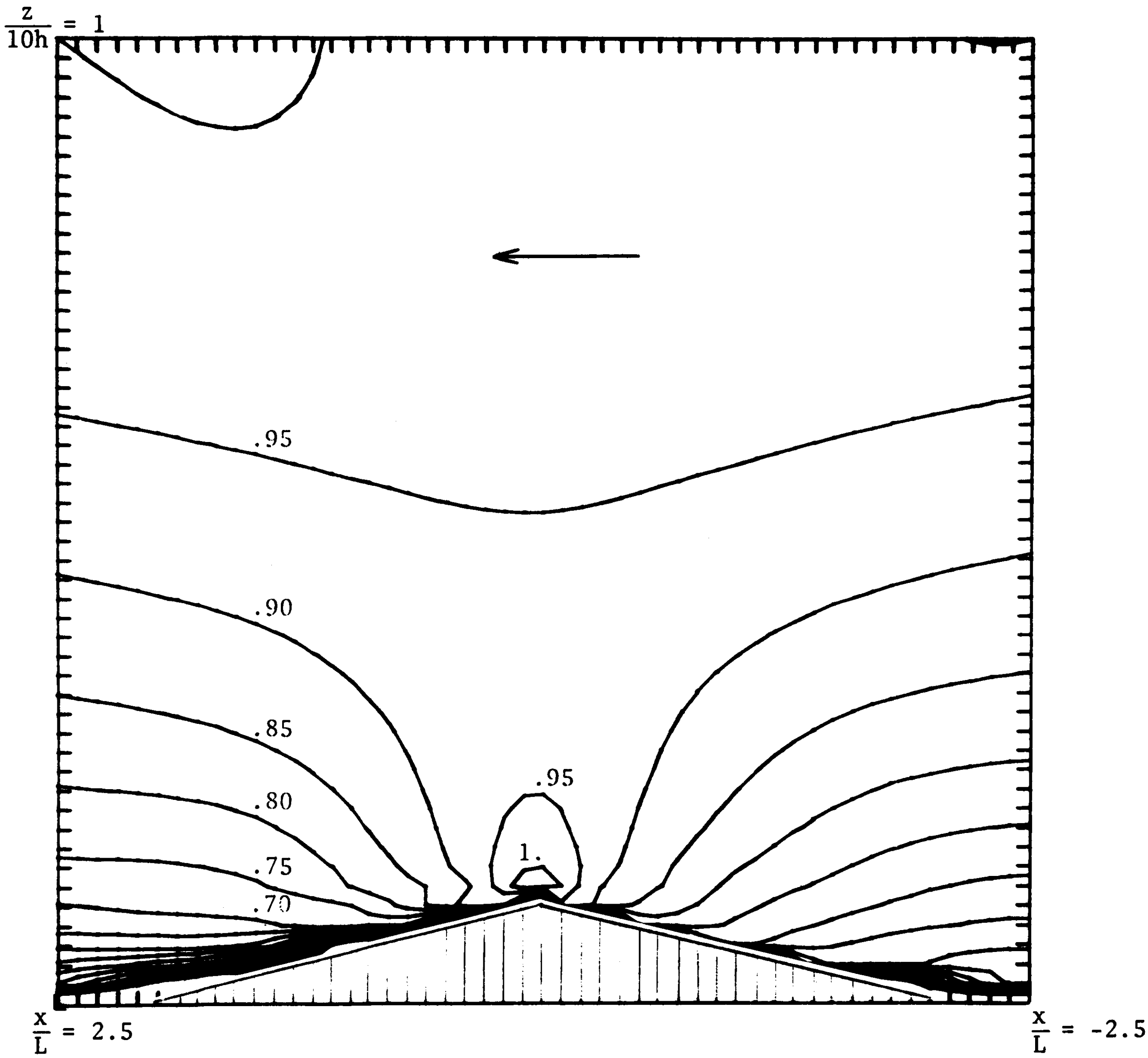
1:2 Model, $U_o(10h)$ = 15.24 m/sec

Figure 7c. Static pressure contours (in C_p).



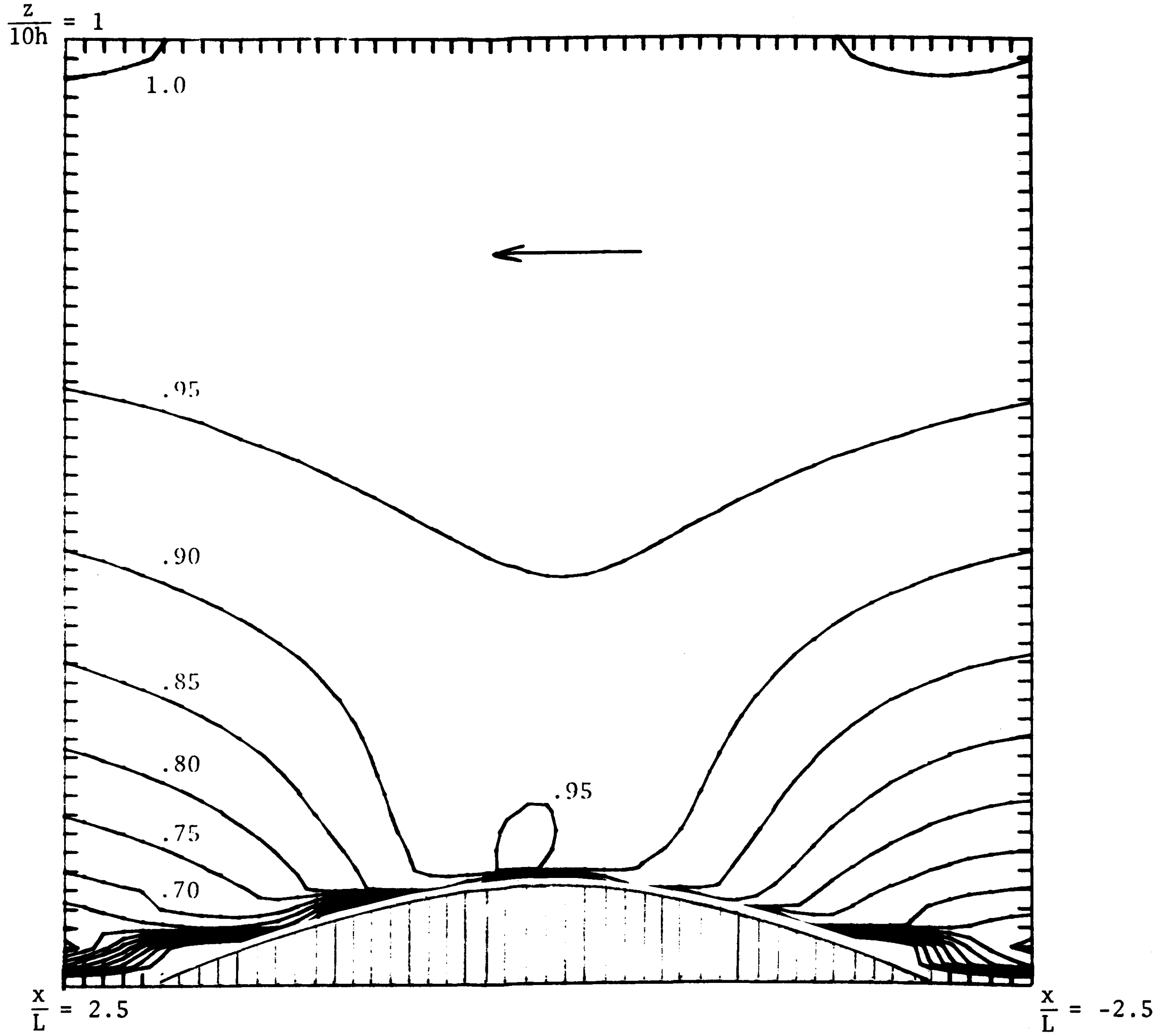
Triangular hill model, 1:4, $U_o(10h)$ = 9.14 m/sec

Figure 8a. Velocity contours (nondimensionalized w.r.t. $U_o(10h)$).



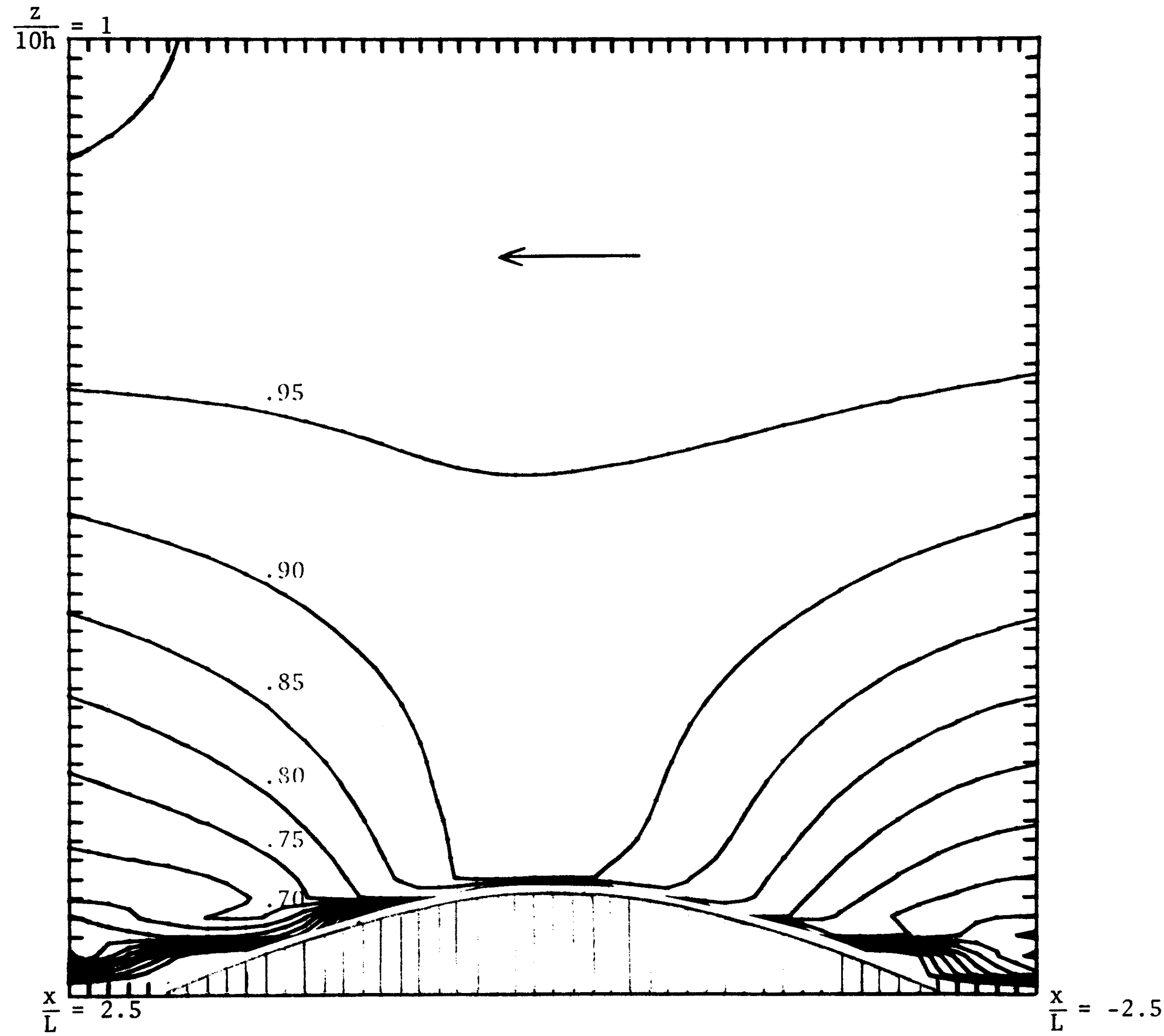
Triangular hill model, 1:4, $U_o(10h)$ = 15.24 m/sec

Figure 8b. Velocity contours (nondimensionalized w.r.t. $U_o(10h)$).



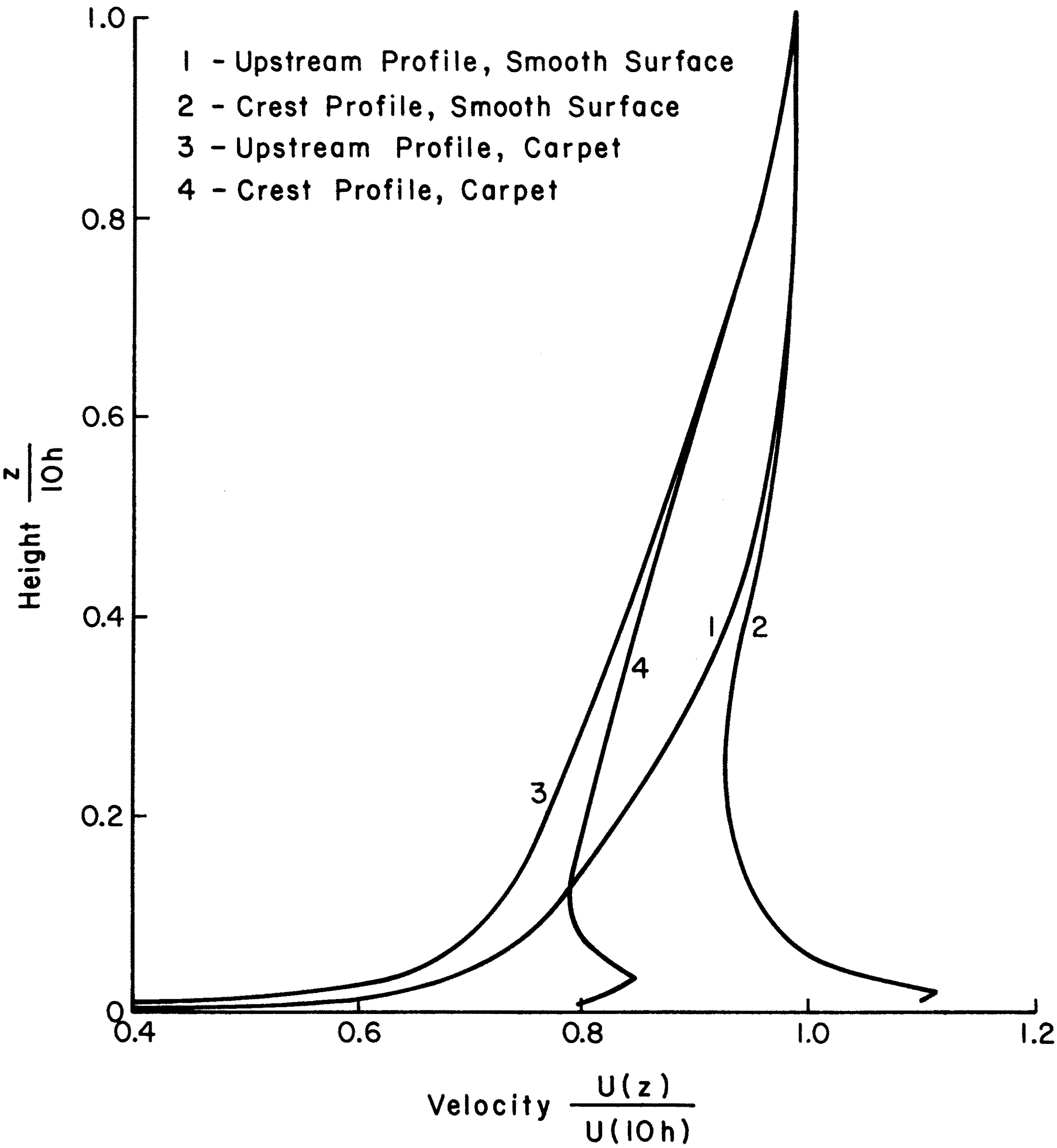
Sinusoidal hill model, 1:4, $U_o(10h)$ = 15.24 m/sec

Figure 8c. Velocity contours (nondimensionalized w.r.t. $U_o(10h)$).



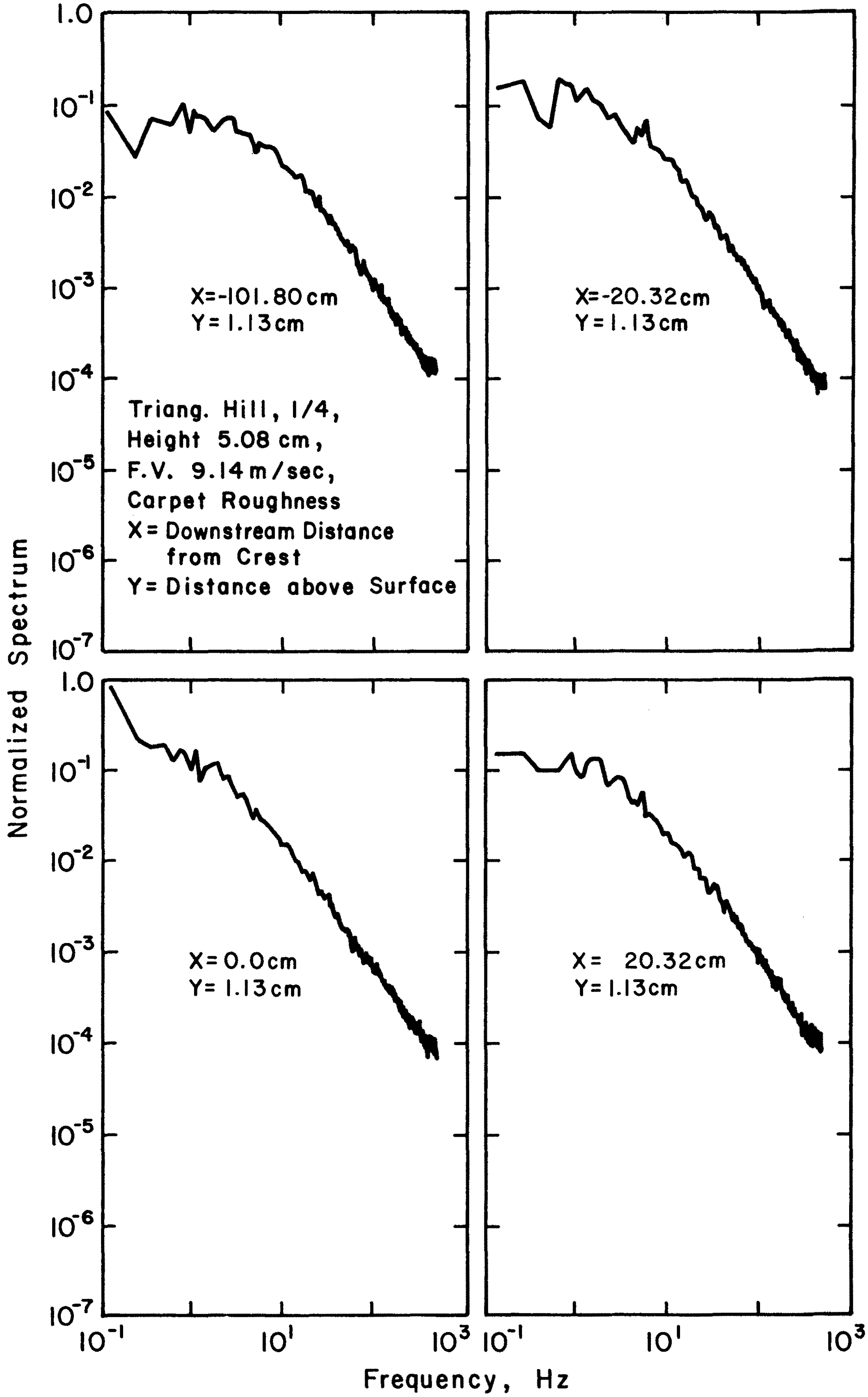
Sinusoidal hill model, 1:4, $U_o(10h)$ = 9.14 m/sec

Figure 8d. Velocity contours (nondimensionalized w.r.t. $U_o(10h)$).



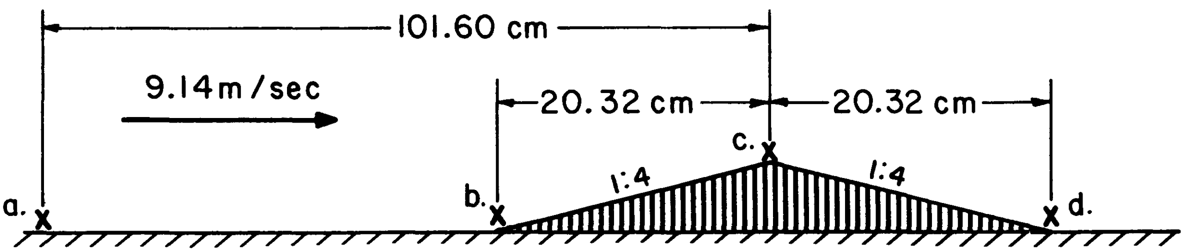
Triangular hill model, 1:4, $U_o(10h)$ = 9.14 m/sec

Figure 9. Velocity profiles above crest with different roughnesses.

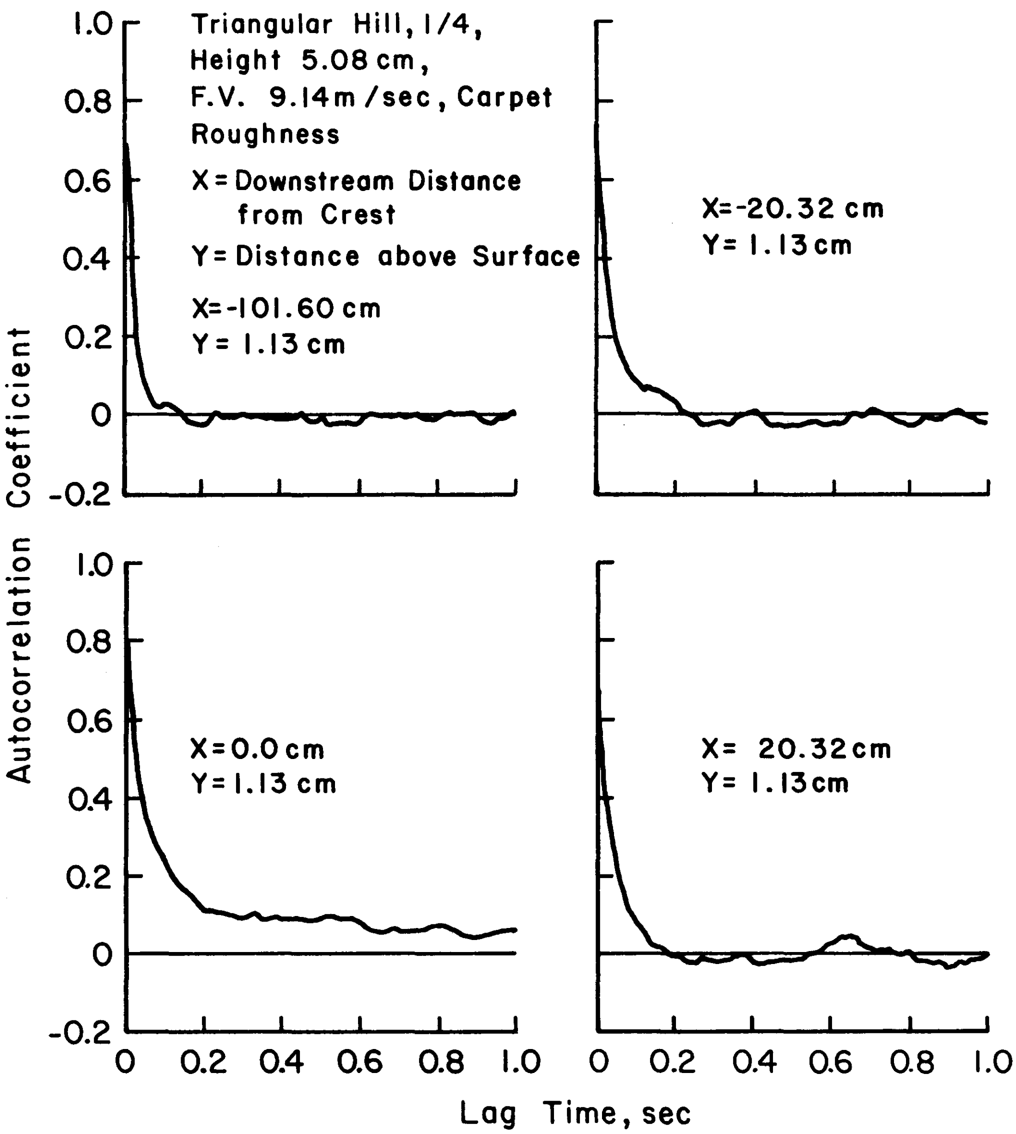


(a) Spectra

Figure 10. Digital evaluation of turbulent spectra and autocorrelations.



(a.) Locations where Records in time were Obtained

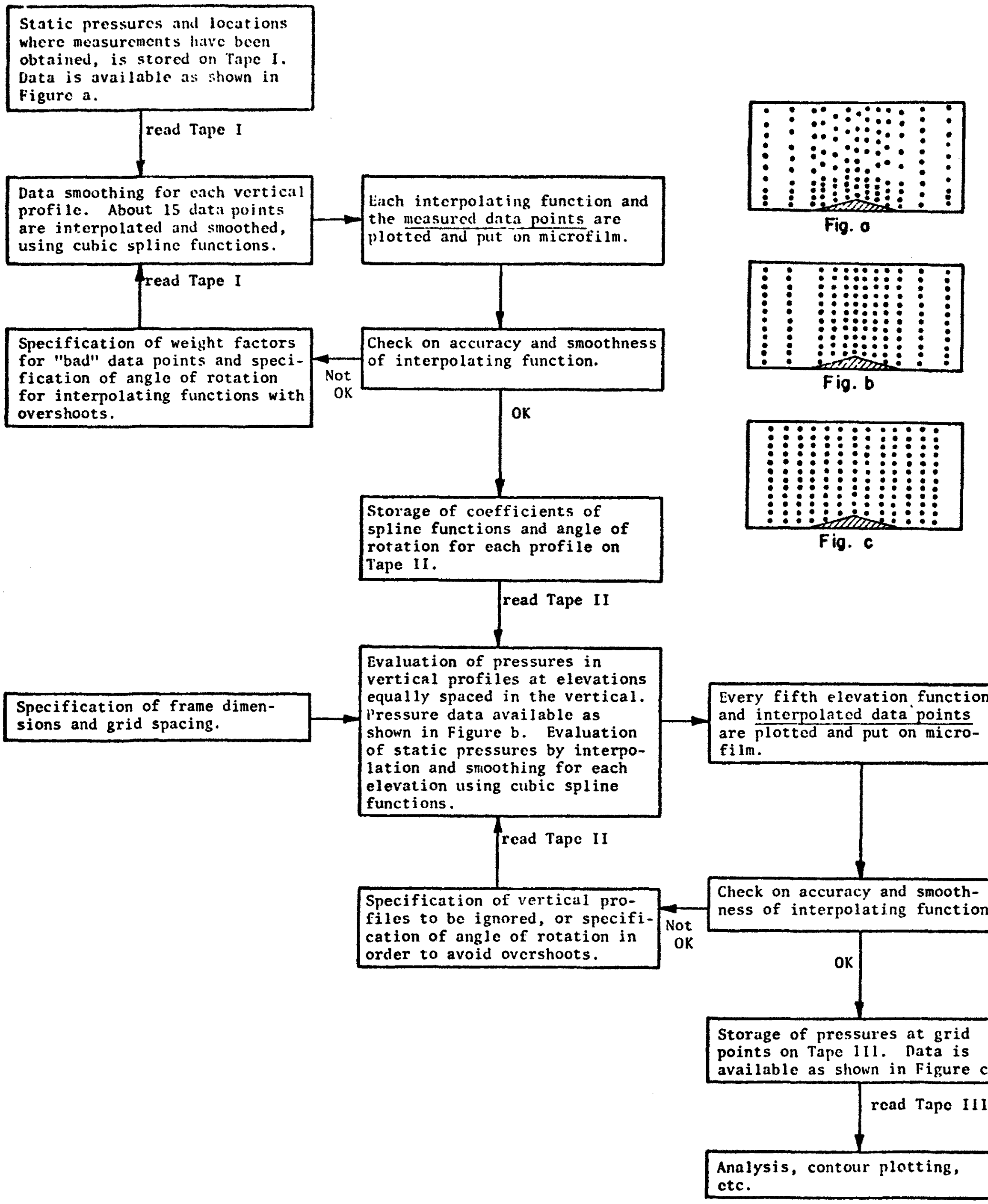


(b.) Autocorrelations

Figure 10. Digital evaluation of the longitudinal turbulent spectra and autocorrelations.

APPENDIX

Evaluation of Static Pressures in an Equally Spaced Grid



Evaluation of Velocities in an Equally Spaced Grid

For the evaluation of velocities essentially the same procedure was used as described in Section I. An additional step was made in the Data Smoothing for each vertical profile. The 2 value (vertical coordinate) was transformed to a logarithmic scale.