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ENVIRONMENTAL STUDIES RELATED TO THE OPERATION OF WIND ENERGY CONVERSION SYSTEMS

FINAL REPORT

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ABSTRACT

This biophysical impact assessment explores the environmental consequences of the emerging wind energy conversion technology through field studies done at the DOE/NASA 100-kW Experimental Wind Turbine located at NASA Lewis Research Center's Plum Brook Station near Sandusky, Ohio.

A micrometeorological field program monitored changes in the downwind wake of the wind turbine. Horizontal and/or vertical measurements of wind speed, temperature, carbon dioxide concentration, precipitation, and incident solar radiation showed measurable variation within the wake only for precipitation and wind speed. The changes were minor and are not likely to result in any secondary effects to vegetation, including crops, because they are within the natural range of variability in the site environment. Effects are negligible beyond the physically altered area of the tower pad, access, and control structures.

The wind turbine has not proved to be a high risk to airborne fauna, including the most vulnerable night-migrating songbirds. Behavioral studies indicate the birds will avoid the turbine if they can see it.

EXECUTIVE SUMMARY

This research program seeks to answer some of the questions concerning the environmental issues related to the use of wind power in the United States. The biophysical environment is the focus of the study. Large two-bladed, horizontal-axis wind turbine generators (WTG) were studied using the DOE/NASA 100 kW Experimental Wind Turbine at NASA Lewis Research Center's Plum Brook Station as the model for field tests.

The results of a literature review program, reported in Rogers et al. (1976) are integrated into this report as required. In that study, the microclimate of the wake of the 100 kW WTG was theoretically studied. The results indicated an anticipated reduction in wake wind speed of approximately one-third of the freestream wind speed at WTG design conditions, e.g., 6 mph (2.7 m/s) reduction in wake wind speed at the 18 mph (8 m/s) design condition. Minor changes in other micrometeorological parameters were also predicted. Theoretical studies resulted in the prediction that birds or other airborne fauna risked collision with the rotating blades of the WTG. The number of organisms exposed to the WTG would be related to the site chosen, the height of the structure, and the design solidity of the blades.

In the research program reviewed here these theoretical predictions were tested at the DOE/NASA 100 kW WTG. Study emphasis was on the microclimate effect of the operating turbine and the potential effect on night-migrating birds. Also, studies were made of the behavior of insects in the WTG flow field and of the infra-sound levels around the WTG.

Operational constraints limiting the 100 kW WTG to approximately 3 hours of operation at design conditions and less than 250 hours total rotation time in highly modified format (typically one-half design speed, no load), affected the significance of this research.

The micrometeorological field program was designed to measure the effect of the 100 kW WTG downstream wake. The following parameters were studied: the horizontal variation in incident precipitation and in incident solar radiation, and the horizontal and vertical distributions of air/surface temperature, wind velocity, and atmospheric carbon dioxide concentrations. Significant variation in any of these parameters could influence the capacity of the affected land to support plants and animals. The theoretically predicted fairly narrow expansion [7.5 ft in 125 ft (2.3 m in 38 m)] of the 100 kW WTG wake, suggested that the wake would not exert influence at the ground level. Field studies in this research effort were designed to measure any effect upon the selected parameters.

In general, the significance of any effect of the 100 kW WTG appears to be minimal, even negligible beyond the area physically altered as a result of construction. The field studies indicate a negligible effect to the area immediately downwind of the tower and blades. When the WTG rotor was not operating, a rainfall deficit was measured within a 3/4 rotor-diameter equivalent distance (28 m) of the 100 kW WTG. Over long periods, this rainfall deficit is estimated at 5 percent. This deficit decreases and can disappear completely during operation as rain falls. Normal meteorological variation can override any tower shadow effect for any short time frame. Thus, even if the WTG had a significant effect on precipitation patterns, natural variation in wind speed and direction in annual precipitation, would overshadow the effects of the WTG. The Plum Brook study predicts that any precipitation variations will be quite small and will be limited to an area within the equivalent of two rotor diameters distance of the turbine.

Results of the other micrometeorological parameters studied (wind speed, temperature, and carbon dioxide concentation) in and out of the wind turbine wake show no significant variation other than a measureable variation in wind speed within two to three diameters of the WTG. The results also show the high variability of the natural environment. Thus, the main conclusion is that plants and animals exposed to the wake of an operating WTG are not likely to be significantly affected, as changes fall well within the variations of their natural environment.

The only probable impact to animal populations considered significant enough to warrant detailed studies was nighttime kills of birds at WTG towers. The number of nocturnal migrants during the peak migration periods for songbirds in the Sandusky area was found to vary from essentially no migration on rainy nights to 17,000 birds per mile of front per hour. For clear nights the rate averaged 5,380 birds/mile of front/hour. The corresponding migration directions were predominantly south or southwest in the fall and northeast or east-northeast in the spring.

During four migratory seasons of searching only three birds were found dead near the meteorological tower (2 birds) and the WTG tower (1 bird). Only one, a blackburnian warbler, was a nocturnal migrant. It was found near the meteorological tower prior to nighttime operation of the WTG. Scavenger studies also indicated that only about 5 percent of tower-killed birds at Sandusky would have been removed by predators during the night.

In spite of the few nighttime WTG operating hours (only 114 nighttime hours at 20 rpm/no load) during this study it is reasonable to conclude that the WTG at Plum Brook is not lethal to a significant number of birds, even on nights of high migration traffic rates combined with favoring winds for migration, a low cloud ceiling, and fog. Migrating birds coming near the WTG at night were seen to take evasive action to avoid the blades. Others flew on a straight line between the rotating blades without incident.

In our opinion, if future WTG designs have blade tips reaching above 500 ft (150 m) (minimum altitude of most nocturnal migration) or WTG's are sited in locations where birds fly closer to the ground, bird collisions could be a greater risk on inclement nights.

Airborne insects and other small invertebrates would be exposed to wind turbines in the future. Three species--ladybird beetles, blow flies, and honey bees--were released to observe their behavior when confronted with the WTG. Simulating a worst case exposure for a wind turbine site, the release was at about 80 ft (24.4 m) height approximately 60 ft (18 m) upwind of the plane of rotation of the WTG. Still and motion picture films of the releases, studied for behavior/movement patterns, showed no evidence of a buildup of these species in the downwind wake of the WTG and little evidence of injuries in passage through the blades. Both the honey bees and blow flies dispersed widely downwind with little apparent effect from the WTG. Ladybird beetles proved to be poor experimental organisms. Because of their heavy body weight, they simply fell to or near the ground before taking flight.

The DOE/NASA 100 kW WTG produces mechanically and electromechically induced sound from equipment located in the alternator nacelle and aerodynamically induced noise resulting from interaction of the tower and the turbine blades moving through the air. NASA-Lewis has studied the audible sound levels and determined that they are low level and do not constitute a harm to man. Infrasound (energy levels below lower limit of human hearing) was briefly studied in this research program. As the WTG had operated only 3 hours at loaded design conditions no sound level measurements were made of "normal operating conditions". Data obtained under unloaded 20 rpm conditions show infrasound levels lower than those believed to cause annoyance or physiological effects in humans. However, there is a noticeable thumping sensation in the immediate vicinity resulting from the interaction of the infrasonic waves with the tower components as each blade tip passes by the tower in its lowest arc.

In summation, an operating wind turbine exerts some measurable effect on the biophysical environment of the immediate vicinity. These effects, however, do not appear to consitute significant impacts. These studies have shown no indication that agricultural row crops or orchards would not be fully compatible land uses near a large WTG. In our opinion, attention to potential interactions with migratory birds and insects during site selection can minimize problems at future WTG sites.

I. INTRODUCTION

RELATIONSHIP TO DOE WIND ENERGY PROGRAM

This research program seeks to answer some of the remaining questions concerning the environmental issues related to the future use of wind power in the United States. The study was funded by the U.S. Department of Energy (DOE) through its Wind Power Branch in the Division of Solar Energy. One main program element of the Federal Wind Energy Program is Program Development and Technology including the subelement Legal/Social/Environmental Issues. This program represents the environmental issues area of that program subelement.

In a previous research program, conducted for the National Science Foundation (NSF) prior to and during the transfer to the Federal Wind Energy Program responsibility from NSF to DOE, Battelle-Columbus completed a comprehensive literature study of the potential environmental impacts of wind energy generation. The results of that study included the design of the study described in this report. The final report of that initial research effort has been published and is available through the National Technical Information Service (NTIS), Springfield, Virginia (Rogers et al., 1976). A brief review of the major findings of that study will be repeated here inasmuch as that study did form the base of information or foundation for this effort. Throughout later chapters of this report an effort is made to integrate the conclusions and recommendations of the earlier literature study with the field research program described here.

PREVIOUS STUDY RESULTS

The DOE/NASA 100 kW Experimental Wind Turbine at NASA Lewis Research Center's Plum Brook Station near Sandusky, Ohio has served as the focus or model for both of these studies. The conventional wind turbine generator (WTG) as devined in this study is a large two-bladed, horizontal-axis rotor mounted on a tower.

An aerodynamic flow analysis of the 100 kW WTG was completed in the earlier study to theoretically define the operational zone of influence of the WTG unit in the wind stream (Figure 1.1). Calculations indicated a maximum wake expansion downwind of the rotor to be 7.5 feet (2.3 m) over the initial 125 feet (38.1 m) disk-diameter distance downwind. Since the hub of this rotor is located 100 feet (30.5 m) above the ground, little or no direct aerodynamic effect of the rotor was anticipated at ground level. Within the wake immediately downwind of the rotor a decrease in wind speed (due to power extracted by the system) of 6 mph (2.7 m/s) was anticipated at the 18-mph (8 m/s) design speed of the system. Coupled with this was an anticipated 0.03 F (0.05 C) decrease in total temperature and a pressure drop of 0.07 in (0.18 cm) H_2O across the disk. It was estimated for the purposes of design of the study which this report covers that these environmental effects would extend from immediately beyond the blades to a point approximately 3-rotor diameter equivalent distances (114 m) downwind at which point atmospheric turbulence would begin to dissipate the wake. Neither this estimated effect limit, nor any other estimate, has yet been confirmed by field observations (Rogers et al., 1976).

An extensive literature review of potential environmental effects of wind energy conversion turned up little information as had been expected. During these searches in the earlier study, however, much information was located concerning the effects of winds on natural environments and of the human-induced alterations of winds, e.g., wind breaks, buildings, towers. More than 600 key-worded references are reported in the final report of that study (Rogers et al., 1976).

Drawing upon the literature identified, the potential for environmental effects from wind energy conversion systems was assessed. First, the size and extent of the microclimate effect of the WTG and, second, the effect this microclimate alteration would have on adjacent plants and animals, including natural and agricultural species, were reviewed. This can be summed up as the effect of the WTG and its compatibility with natural biological processes on the land. Third, the potential for collision of the rotating blades with airborne organisms required review.

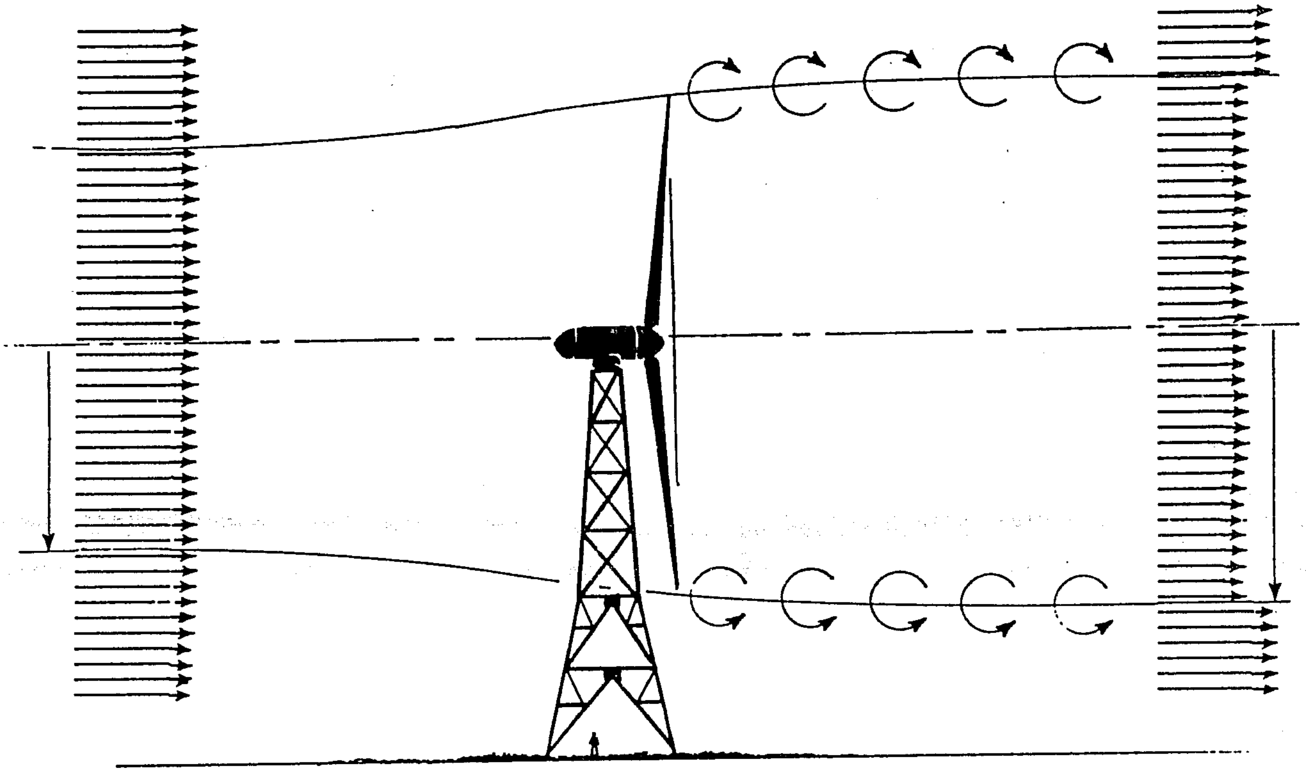

FIGURE 1.1. ZONE OF INFLUENCE OF DOE/NASA 100 kW EXPERIMENTAL WIND TURBINE AT NASA LEWIS RESEARCH CENTER'S PLUM BROOK STATION NEAR SANDUSKY, OHIO

Literature concerning changes in microclimate and resulting potential biological effects were reviewed in the earlier study to determine the extent and degree of the effect and to determine if there were any unique qualities to the rotating blades. Wind turbines, electric transmission towers, and fire towers appear to represent a similar pattern of permeability to the winds. By obstructing the wind these structures reduce air speed, moderate temperature and evaporation downwind to a minor degree, and cast a sun shadow under applicable sun angles and meteorological conditions. These microclimatic changes are measurable, though ordinarily the change is insignificant. Structures with little wind permeability have considerably more effect on their overall environment. Included in this group are the wind barriers of agriculture where tall crops or trees are planted to shelter downwind areas. These shelters serve to increase available moisture and to moderate environmental extremes, particularly wind speed. Altered conditions behind these dense windbreaks may lead to increased or decreased occurrence of frost and substantially altered productivity.

This review suggested that the degree of altered microclimate around a wind turbine tower would depend upon the permeability of the tower and the efficiency of power conversion of the airfoil. As there was no operational experience with large wind turbine systems with regard to their microclimate influence, a research program designed to provide these data represents a major component of the subject study.

As a result of the literature review it did not appear that low ground profile activities and land uses were incompatible with large WTG. From the biological and microclimate standpoint there did not appear to be any reason why an organism living in an environment chosen as a site for a wind turbine would not be able to continue to occupy that area, even though its environment would be slightly altered by the WTG. This would include agricultural row crops, orchards, grain or hay crops, and pasturage for domestic animals. The operational effects studies presented in this report were designed to confirm this hypothesis.

In recent years with the proliferation of tall isolated structures, sizeable bird mortalities caused by disorientation and/or collision have occurred in the United States. These large kills normally occur on nights with favoring winds (for migration) and partial to complete overcast, particularly when there is foggy or misty weather combined with peak flights of nocturnal migrants. Examples of bird kills at tall towers over extended periods of daily searching have been reported for a 308-meter television tower in Florida (average of 2,700 annually over 11 years) and for a 366-meter navigation tower in North Dakota (total kill per season varied from 760 to 1417 for 6 migration seasons).

The number of birds and/or insects which will collide with the rotating blades of a wind turbine is dependent on four factors: (1) design solidity of the rotor, (2) the airfoil design, (3) the number of organisms flying through the disk area, and (4) the behavior of the organisms in this zone. Through particle analysis within the two-dimensional flow field of the airfoil of the 100 kW WTG, it was estimated that a bird, taking no evasive action and passing through the air stream intersected by the blades rotating at design speed would have a 13 percent probability of being struck at a bird speed of 8 m/s. Because of the comparatively smaller size of insects their probability of being swept over the blades in the airstream and missing the blades increases, and thus collision potential decreases. The number of insects striking the blades of the 100 kW WTG was expected to be less than 10 percent of those passing horizontally through the rotor-swept airspace (Rogers et al., 1976).

This number of airborne organisms exposed to the rotating blades is a function of location of the wind turbine and its height above the ground surface. Most songbirds migrate at night at altitudes about 500 feet (150 m), however, wind turbine designs seriously considered to date extend only as high as 350 feet (106.7 m) in height. Thus potential for major bird kill incidents appears to be possible only where wind turbines are sited on isolated hills or coastlines where birds are migrating at low altitudes with respect to the ground surface. Studies reported here were designed to evaluate the number and behavior of birds actually exposed to the 100 kW WTG at Sandusky, Ohio.

RESEARCH PROGRAM CONSTRAINTS

The evidence accumulated through the literature study indicated that a large wind turbine generator generally would represent only minimal influence on the environment into which it was sited and operated. Studies were designed to provide real time measurements, with an operating wind turbine, of (1) ground level microclimatic alterations and (2) possible collisions of migratory organisms, particularly birds, with the rotating blades. Throughout the remaining chapters of this report an effort has been made to place any measured effect within the appropriate context of the highly variable natural environment in which WTG's operate.

The DOE/NASA 100 kW WTG at Sandusky, Ohio, the first large wind turbine built in the U.S. in over 30 years, contained many experimental elements. As would be expected in such a case, this lead to some rather lengthy operational delays interspersed with periods of modified operation during the first two years of operation. To provide a timely input to the Federal Wind Energy Program it was decided to continue this research effort as feasible.* As a result, virtually all of the field experiments were conducted with the 100 kW WTG operating in a 20 rpm/no load configuration. The result of these constraints is significant in relation to the resolution of detail one would wish to have come from this magnitude of study. However, we believe that more favorable conditions would not have altered the main conclusions of the study significantly.

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*For those readers aware of the initial proposed design of this study which included a phenology task, this effort could not be completed due to a grass fire which destroyed the test plots. The micrometeorological task of direct measurement was substituted. That effort was conducted within the remaining funds allocated to the earlier work.

II. MICROCLIMATE

INTRODUCTION

In the previous report (Rogers et al., 1976), an aerodynamic flow analysis of the 100 kW WTG defined the operational zone of influence that the turbine would have on the wind stream. These results are reviewed in Chapter 1. It was shown that there would be little or no direct effect of the rotor on wind movement on the ground. However, the question of an indirect effect resulting from the elevated cylindrical zone of influence downwind of the turbine still remained. One aspect of this question is what effect the turbulence within the zone of influence might have on precipitation falling through the cylinder. Would the precipitation amounts be either reduced or increased in the wake of the rotor? In the temperate latitudes where wind directions are spread out relatively uniformly around the 16 points of the compass, any enhancement or decrease in rainfall amounts would have only a small effect. However, if a WTG were established in subtropical regions where wind directions are more constant or in a mountain pass, canyon, or valley where the wind is forced to blow in either of two directions, the effect of a change in rainfall pattern would be concentrated on the soil and vegetation directly downwind of the turbine. Of course, the precipitation would still fall in the area, but would there be enough deviation from the normal pattern to cause a narrow strip of more moist or more dry soil than the surrounding conditions.

The question of secondary effects to other microclimate parameters resulting from the approximately one-third reduction of wind speed beyond the turbine at design configuration also required verification at an operating wind turbine. In the earlier study (Rogers et al., 1976), it was shown that the effect of windbreaks or towers on the wind is a reduction in wind speed and the production of turbulence, both of which cause changes in the microclimate downwind of the obstruction. Changes have been reported in humidity, evaporation, vapor pressure, temperature, and radiation balance. Altered plant growth patterns result. This is dramatically demonstrated by the use of windbreaks to increase agricultural productivity and to reduce soil erosion by deflation in many windy regions of the world, notably the Great Plains of the United States.

MICROCLIMATOLOGICAL METHODS

The micrometeorological field program was designed to determine if there is a measurable difference between the downstream wake and comparable areas outside of the zone of influence of the operating 100 kW WTG. Height above the ground of all parameters measured (when applicable) as well as horizontal measurements (downwind persistence) were made. Due to the difficulty and expense of monitoring the top half of the zone of influence (above 100 ft or 30.5 m) this study was limited to the lower portion of the zone of influence (hub height to the ground, concentrating below 47 ft or 14.2 m). This is the portion of the zone of influence which if significantly altered would affect the surface biota or result in other observable differences in the surface environment.

The following micrometeorological parameters were studied in an attempt to measure environmental differences induced by operation of the 100 kW WTG.

- Horizontal variation in incident precipitation,
- Horizontal and vertical variation in air and surface temperatures,
- Horizontal and vertical variation in wind velocity,
- Horizontal variation in incident solar radiation, and
- Horizontal and vertical variation in atmospheric carbon dioxide levels as it represents biological activity (respiration).

Precipitation Studies

As noted earlier, the precipitation investigation during the earlier contract of this research program studied variations in snowfall and rainfall patterns in the vicinity of the WTG tower when the rotor was not operating. During this concluding portion of the investigation, the objective was to measure variations in precipitation when the rotor was turning during periods of rain. Since this portion of the investigation would be conducted during individual rainfalls, a better coverage of the area around the Plum Brook WTG was needed than had been the case for longer-term measurements. The raingage network was expanded to include 35 wedge-shaped farm-type plastic gages placed in all directions around the WTG (see Figure 2.1). Previously, the raingages had been primarily in a southwest-northeast alignment along the direction of the prevailing wind (and also the areas where there was the greatest expanse of open fields). Based on the earlier precipitation measurements, it was anticipated that any variations in pattern would be most pronounced close to the turbine, so most of the additional gages were placed within a circle of two blade diameters from the WTG tower. If the turning rotors were to have a major effect, it was expected that the rainfall pattern would be readily apparent within the zone of influence downwind of the tower as compared to the rainfall over the remainder of the network outside the zone of influence.

Many of the previous studies took place in winter and measured both snow and rain. The warm temperatures of the summer program allowed the use of the less-expensive farm-type gages. These gages were mounted on wood frames attached to metal fence posts which could be more easily erected than the "Clearvu" gages which required treated wood posts. While the freeze-resistant "Clearvu" gages were retained in the network during this second portion of the program, their measurements were used only as reference points. The study was directed at determining the variations among rainfalls in identical gages--the farm-type. Reading of the rainfill gages was done by Battelle project team members from Columbus, Ohio, who traveled to Plum Brook in anticipation of a rain or subsequent to a rain. On occassion, the readings were not made until a day after the rain occurred. An estimate of the amount of water evaporated from the open farm-type gages could be made by comparing their measurements with those made of the covered "Clearvu" gages. In analysis of the data, it was assumed that evaporation from all the farm-type gages was approximately equal.

Although conducting the rotor-operation portion of the precipitation study during the warmer months had many advantages, the summer

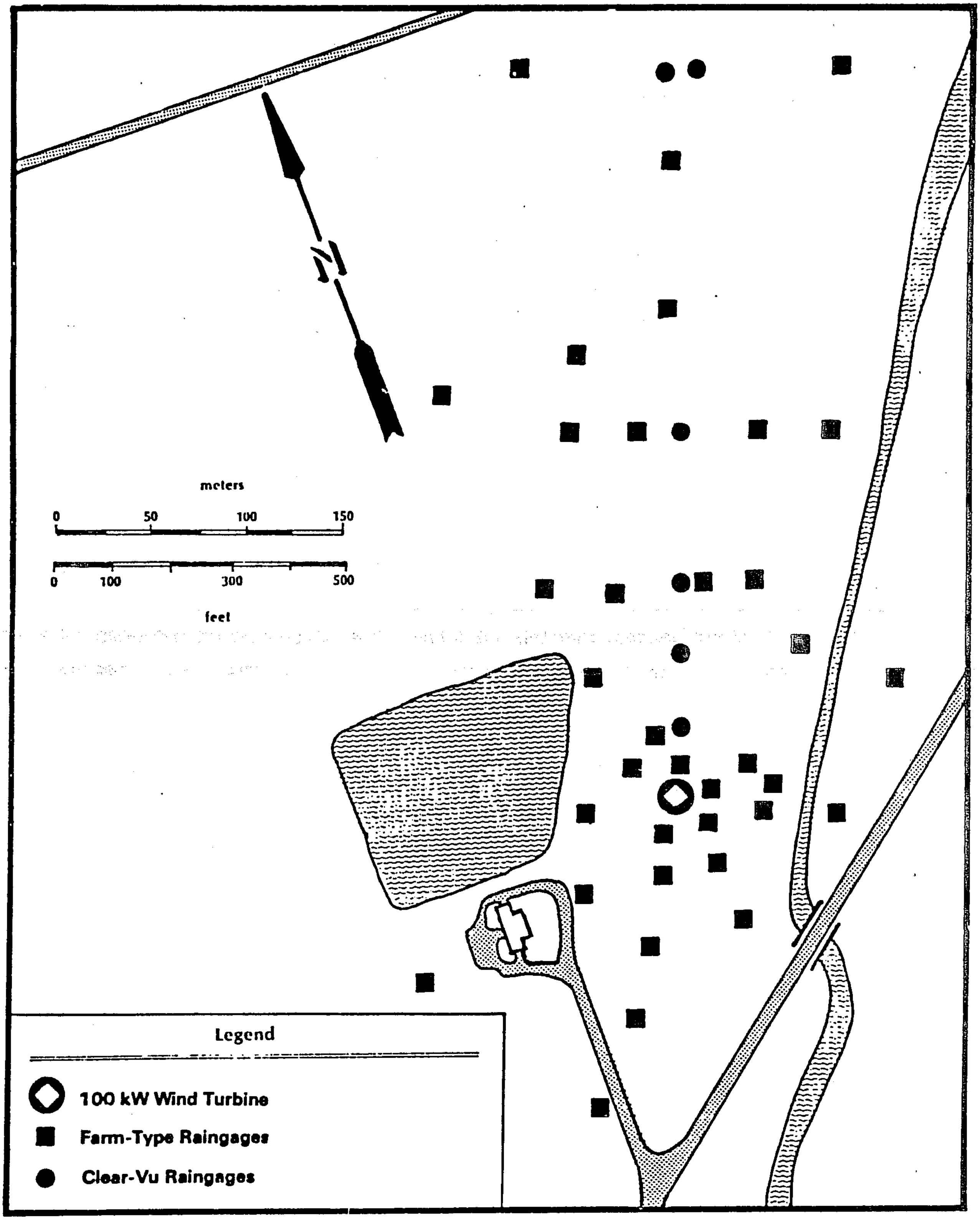

FIGURE 2.1. RAINGAGE NETWORK FOR PRECIPITATION STUDIES

time also had one notable disadvantage. Considerably more foreign material appeared in the raingages during this period than in any other time of the year. Bird droppings and bumble bees were the most frequent material found in the gages. Bird rings constructed out of coat hangers were placed on all the fence posts supporting the gages, but they did not deter the birds significantly. Fortunately most of the foreign material deposits occurred in gages which were about five rotor diameters from the turbine. These were in the high grass where the birds nested. Close to the turbine the grass was cut and there was also frequent human activity. Thus, rainfall amounts close to the turbine where the most significant changes were expected could be analyzed without concern for foreign material. The form on which rainfall amounts were recorded included room for entries covering estimates of foreign material. When the entries indicated foreign material equalling 0.02 cm (0.5 inches) or more, the measurement was not included in the statistical summary.

Other Micrometeorological Parameters

The remaining parameters (air and surface temperatures, wind velocity, incident solar radiation, and atmospheric carbon dioxide) were studied together as a group by doing seasonal measurements on a single selected "typical" day for each season of the year except winter. As called for in the scope of work, individual measurements were made at each distance, each height, and each season.

Sampling Configuration

Microclimatic measurements of air temperature, wind speed, CO_2 concentration, and incident radiation were made during the fall, spring, and summer downwind of the operating wind turbine. Due to operating constraints on the wind turbine, fall and spring measurements were made with the machine operating at 20 rpm (one-half design speed). Wind conditions at the time of the summer sampling were such that 40 rpm could not be constantly maintained, so the turbine was operated at speeds of 30-40 rpm. Tests were made with the blades in a loaded condition (producing power) in the fall and spring, thereby creating the maximum perturbation in the wake environment. However, the summer winds together with operational limitations of the WTG precluded power production in the summer, although the blades were rotating at or near 40 rpm.

Microclimatic parameters which were measured include horizontal and vertical measurements of temperature and atmospheric carbon dioxide concentrations. Horizontal measurements only were made of solar insolation striking the surface of the ground. Wind velocity was measured vertically and horizontally in the spring and summer, but in the fall due to the failure of the anemometer measures of wind speed were available only from the anemometer at the nacelle of the WTG. However, radio communication with the wind turbine control room allowed selected recording of wind velocity at that location during the fall sampling period. However, these wind speed results are not readily comparable to spring and summer data taken at similar sites. Measurements were made at the following heights for all applicable parameters: ground level (0 m), within the vegetation canopy (1 ft or 0.3 m), and above the canopy at 3, 6, 12, 28, and 47 feet (0.8, 1.8, 3.5, 8.6, and 14.2 meters, respectively). The blade tip of the 100 kW WTG sweeps within 37.4 feet (11.4 m) of the ground. Higher vertical measurements were made with the use of the bucket-truck (Hy-Ranger) to minimize disturbance to the free flowing air stream.

Instrumentation for these efforts include:

- Yellow Springs Instrument, Inc. (YSI) Multichannel Analyzer with surface and air temperature thermistor probes and leads, as appropriate
- YSI Model 68 Direct Reading Pyranometer (incident solar radiation)
- Thermonetics Corps., Inc. HWA-1 Hotwire Anemometer (wind speed)
- Mine Safety Appliance Company (MSA) Model 202 LIRA Solid State Infrared Analyzer (CO_2)

Ambient Conditions

The fall sampling of the microclimate was made on November 3, 1976. This was a "typical" partly cloudy to mostly sunny fall day in which the temperature rose from 45 F (7 C) at 10:00 when sampling began to 42 F (11 C) at 14:30 when activities were completed for the day. Wind speed varied from 6-16 mph (2.8-7 m/s). Wind direction was from the southwest. The samples were taken at selected distances from the operating wind turbine equal to 1, 2, 3, 5, 7, 8, and 10 rotor-diameter-equivalent distances downwind or approximately 125, 250, 375, 625, 875, 1000, and 1250 feet (38, 76, 114, 190, 267, 305, and 381 m) respectively. The 190 m distance was sampled twice.

Spring measurements were taken on May 13, 1977 at 1, 1.5, 2, 2.5, 3, 4, 5, 7, and 10 rotor diameter distances downwind or approximately 125, 188, 250, 313, 375, 500, 625, 875, and 1250 feet (38, 57, 76, 95, 114, 152, 190, 267, and 381 m) respectively. Three control sites near the turbine but away from any possible wind shadow effects caused by turbine, tree or structures were also sampled. The weather was typical of a warm spring day, being sunny with a light wind from the southwest. Wind speed varied from 6 to 16 mph (2.8-7 m/s) and the temperature range from 72-86 F (22-30 C). Additionally, incident solar radiation readings were taken around the tower to evaluate the light shadow effects.

Summer samples were taken on July 27 and 28, 1977 at 1, 3, 5, and 10 rotor diameters or approximately 125, 375, 625 and 1250 feet (38, 114, 190, and 381 m) respectively. Two control sites away from any turbine effects were also sampled. Sampling was initiated on July 27 but was discontinued due to insufficient winds to operate the turbine; sampling was continued the following morning (July 28). Diameters 1 and 3 were sampled the first day; diameters 5 and 10, a repeat of 3, and two controls were sampled the second day. The weather was clear on the 27th but became overcast on the 28th. The wind speeds varied from 4-10 mph (1.7-4.5 m/s) generally from the southwest on both days. Ambient temperatures measured at the meteorological tower near the wind turbine were 79-84 F (26-29 C). More distances would have been sampled had time and weather allowed. This number was, however, the minimum necessary to allow a balanced statistical design.

Statistical Analysis

Data generated in this task were analyzed to provide a descriptive model of the selected near-ground microclimatic parameters as they are influenced at various distances from the tower and operating wind turbine.

Three-Way ANOVA's for Seasonal, Distance, and Elevation Effects. Three-way analyses of variance (ANOVA's) were performed on CO_2, temperature, and wind speed data to test for significant differences caused by the effects of sampling season, distance from the wind turbine, or elevation from the ground. In order to make each three-way ANOVA a balanced design, data were selected and used only for those distances which were sampled in all three sampling seasons. This resulted in four distances (1, 3, 5, and 10 diameters from the wind turbine) for which data were available for use in this statistical design. Therefore, the three-way ANOVA performed significance tests for differences among the various groups or categories within each three main factors; sampling season had three categories (fall, spring, and summer), distance had four categories, and elevation had seven categories. (In the ANOVA performed on wind speed, sampling season only had two categories in the design--spring and summer--since no wind speed observations were taken in the fall.) The analysis also tested for significant differences due to two-way interactions among the main factors.

One-way ANOVA's for Individual Location Effects. In order to utilize data from all sampling stations, one-way analyses of variance were performed on CO_2, temperature, and wind speed data for each season's data separately. This analysis treated each sampling location as an individual group, and data from all seven elevations were pooled together to compute a mean for that location. The location means were then ranked with a multiple comparison procedure called a Duncan's Mean Separation Test. This allowed a determination to be made as to which specific individual means were significantly higher than which others. For example, control stations could be individually compared so that if one control turned out to be significantly different from another control, this would indicate the extent of variability inherent in the natural environment. Also, this analysis would allow the detraction of trends in the data relating to the time that the individual locations were sampled or the order in which they were sampled during the day.

One-way ANOVA's for Overall Distance Effects. One-way analyses of variance followed by Duncan's Multiple Range Tests were also performed on microclimate data by grouping the sampling stations into three major categories based on distance from the wind turbine: (1) 1-5 diameters, (2) 7-10 diameters, and (3) the controls. Again, these analyses were performed for each season's data separately. The multiple range test ranked the three group means so that overall differences due to the effects of distance could be detected. In this way it could determine whether the stations from the 7-10 diameter distances were similar to the controls or whether they were intermediate in their microclimate characteristics between the controls and the stations close to the wind turbine.

Analyses on Changes of Elevation Effects as Related to Distance: Tests for Wake Effects. Analyses were performed on all season's data together to determine the existence of a trend in the effects of elevation which showed some relationship to distance from the wind turbine. The data from the 14.2 and 8.6 meter heights were selected from each sampling location and the difference between them was computed for each microclimate parameter (the value from the 14.2 m elevation minus the value from the 8.6 m elevation). Any observable distance-related trend in these differences would indicate the extent of the wake emanating from the wind turbine.

As a preliminary step after all the differences were computed, these resulting values were plotted on graphs as a function of distance so that any visually observable trends could be noted. Then the differences were used as data input to one-way analyses of variance which tested for significant differences due to overall distance effects. As in the one-way ANOVA's previously described, the sampling stations were grouped into three major cateogries based on distance: 91) 1-5 diameters, (2) 7-10 diameters, and (3) the controls.

RESULTS AND DISCUSSION

Precipitation Studies

In earlier studies reported in Rogers et al. (1976) two raingage networks were set up in the vicinity of the 100 kW WTG to determine the precipitation pattern in the area within 10 rotor diameters of the WTG site. During the period of this earlier study (September, 1975 to May, 1976), the 100 kW WTG was operated for only a small percentage of the time and probably never during times of snow or rain. It was concluded from that study that the WTG tower (and the stationary blade assembly) caused a reduction in the amount of precipitation falling within one blade diameter of the tower. The effect was noted in both single rainfall measurements and in monthly averages during the winter of 1975-1976. Observations indicated that the precipitation reduction was most apparent on the downwind side of the structure. The tower acted as a shield preventing some of the wind-borne raindrops from passing or directing them around the structure.

Precipitation measurements were made the following winter between October, 1976, and January, 1977, again during a period when the WTG was generally not operating. During this period, the largest amount of precipitation was observed to fall at the raingage closest (19.1 m) to the turbine (Table 2.1). It was concluded that the tower might be responsible for the variations in precipitation pattern both years even though the trends were directly opposite. The explanation would be that there were variations in wind direction and wind speed between the 2 years which led to the precipitation differences. Certainly, there was a difference in average temperatures between the two winters. Conditions were relatively mild in 1975-1976 while the winter of 1976-1977 was the coldest on record in Ohio.

Experiments to investigate the effect of the rotating blades were planned for the spring and summer of 1977. The experimental design was altered to increase numbers of raingages at relatively close distances to the tower, as described in the preceeding methods section.

Between June 6 and August 9, 1977, there were 16 days of measurable rain at Plum Brook. The turbine was operated during two of these rains.

TABLE 2.1. PRECIPITATION MEASUREMENTS OVER THE CLEAR-VU NETWORK*
WINTERS OF 1975-76 AND 1976-77

Precipitation (Centimeters)

Gage Numbers	99	84	33	44	55	66	77		
Distance from Turbine (m)**	19.1	38.2	76.4	114.6	191	382	382	Mean	Standard Deviation
Period									
11/11/75 - 12/10/75	5.00	5.28	5.40	5.50	5.45	5.60	5.59	5.40	0.20
12/11/75 - 1/16/76	7.91	7.96	8.40	8.65	8.70	8.98	8.95	8.51	0.40
1/16/76 - 2/13/76	1.47	1.40	1.35	1.43	1.47	1.35	1.52	1.43	0.06
2/13/76 - 3/26/76	2.31	2.49	2.29	2.29	2.31	2.34	2.44	2.35	0.07
3/26/76 - 4/27/76	2.11	2.29	2.29	2.28	2.15	2.21	2.16	2.21	0.07
11/11/75 - 4/27/76 Total	18.80	19.42	19.73	20.15	20.08	20.48	20.66		
10/27/76 - 11/2/76	0.71	0.71	0.72	0.71	0.72	0.71	0.73	0.71	0.01
11/2/76 - 11/8/76	0.08	0.06	0.05	0.05	0.06	0.04	0.05	0.06	0.01
11/8/76 - 11/11/76	0.13	0.10	0.08	0.10	0.10	0.10	0.08	0.10	0.01
11/11/76 - 12/13/76	0.29	0.20	0.18	0.16	0.25	0.23	0.25	0.22	0.04
12/13/76 - 1/21/77	1.73	0.97	0.71	0.61	0.72	0.71	0.67	0.87	0.36
10/27/76 - 1/21/77 Total	2.94	2.04	1.74	1.63	1.85	1.79	1.78		

* The Clear-vu network extends in a line northeast of the 100 kW wind turbine.

** This network of raingages was laid out in a line to the NE (approximately 38°) from the base of the tower, which corresponds to the prevailing wind direction at that location.

Frequently the winds during the rain were too light to operate the rotor, several of the rains occurred when modifications were being made on the turbine, and on one day with tornado activity in the general area, the wind speeds were too strong to allow operating of the wind turbine.

Data for the two rainfall days during which the turbine was operating are shown in Table 2.2. Initial analysis was directed toward determining whether a pattern of rainfall variation occurred over the network. Specifically examination was made for a difference between rainfall amounts downwind of the turbine and rainfall amounts over the remainder of the network. As presented on Figures 2.2 and 2.3, the isohyetal (lines of uniform rainfall amount) pattern for these two rainfalls did not show any distinct anomalies downwind of the turbine. There is a slight rainfall minimum adjacent to the downwind side of the turbine (within one-half rotor diameter) with higher amounts further out (at about one rotor diameter). However, Figure 2.4. for July 24-25 when the rotor was not operating also has a rainfall minimum at one-half rotor diameter downwind (on the ESE side) of the turbine.

In order to study the rainfall patterns more closely, the raingages were divided into groups depending upon their distance from the turbine and rainfall averages over these groups were examined for both the operating and non-operating cases. Since wind direction measurements from Plum Brook were not available for some of the non-operating cases, comparisons of the rainfall amounts were made with regard to operation or non-operation and close-in gages versus gages further away. Three groups of raingages were finally used to study the pattern variations (Figure 2.5):

- A--four gages within 3/4 rotor diameter of the turbine (28 m)
- B--eight gages between 3/4 and 1-1/2 rotor diameters of the turbine (28 and 57 m, respectively)
- C--24 gages spread out over the remainder of the network.

Examination of the differences between the 24 raingages within three rotor diameters of the turbine and seven raingages at five rotor diameters away (as a control group) showed little differences and directed attention to the patterns very close to the turbine. Thus, the three groups were selected. Even among these, the differences were small.

TABLE 2.2. METEOROLOGICAL CONDITIONS ON RAIN DATES WHEN TURBINE WAS OPERATING

	July 18	July 21
Period of Rainfall	1700 - 1900	1755 - 1905
Range of Rainfall Amounts over Network	0.43 to 0.71 cm	2.87 to 3.28 cm
Range of Wind Direction During Period	300 to 336 deg (WNW to NNW)	348 to 044 deg (N to NE)
Range of Wind Speed During Period	6.7 - 13.4 m/s	1.8 - 3.4 m/s
Weather Situation	Non-frontal thunderstorm	Cold front moving across the area from the north

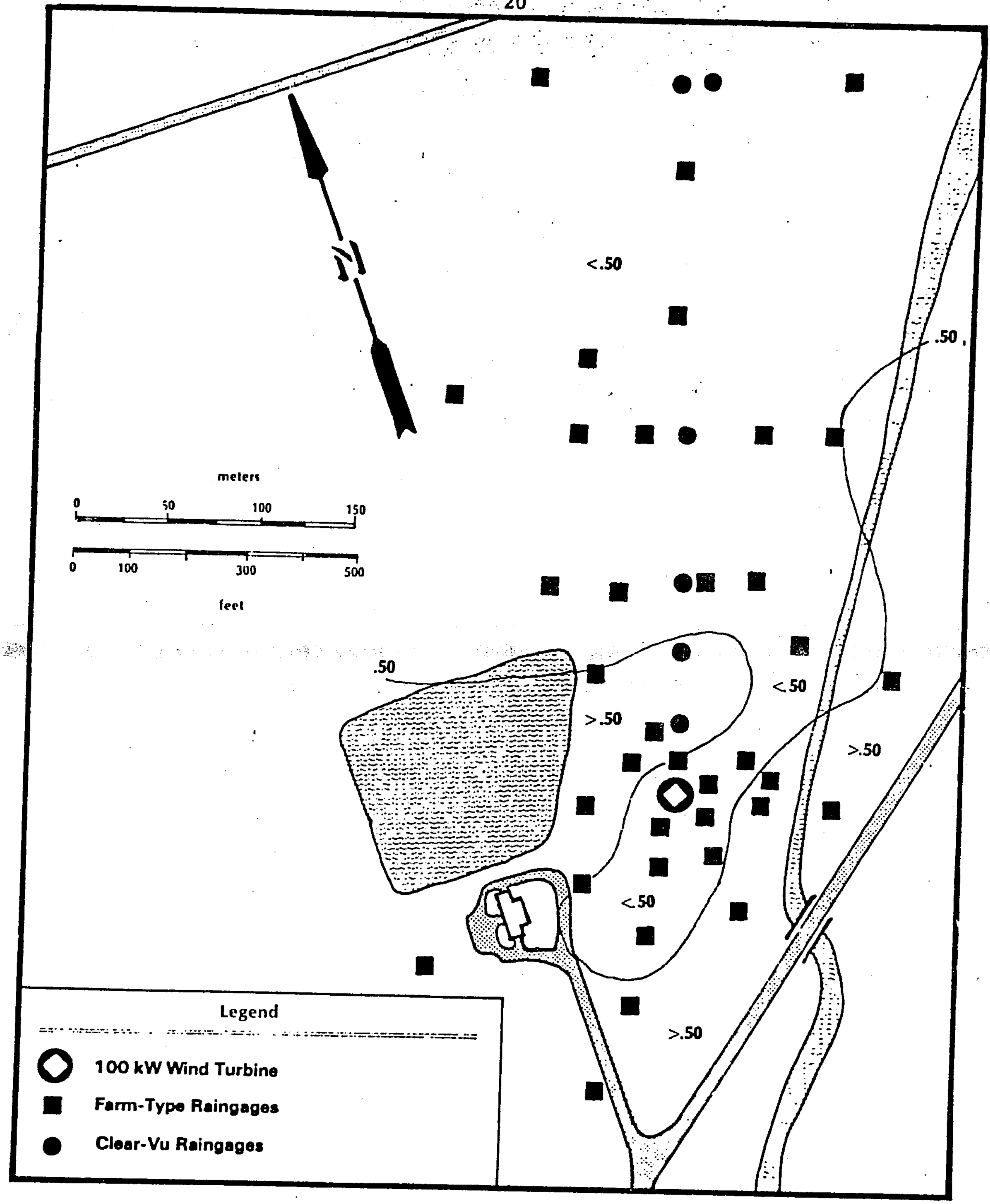

FIGURE 2.2. RAINFALL (IN CM) OVER THE MICROMETEOROLOGICAL NETWORK BETWEEN 1700 and 1945 HOURS ON JULY 18, 1977 WHILE 100 kW TURBINE WAS OPERATING. WIND DIRECTION: 300 TO 336°. WIND SPEED: 6.7 to 13.5 m/s.

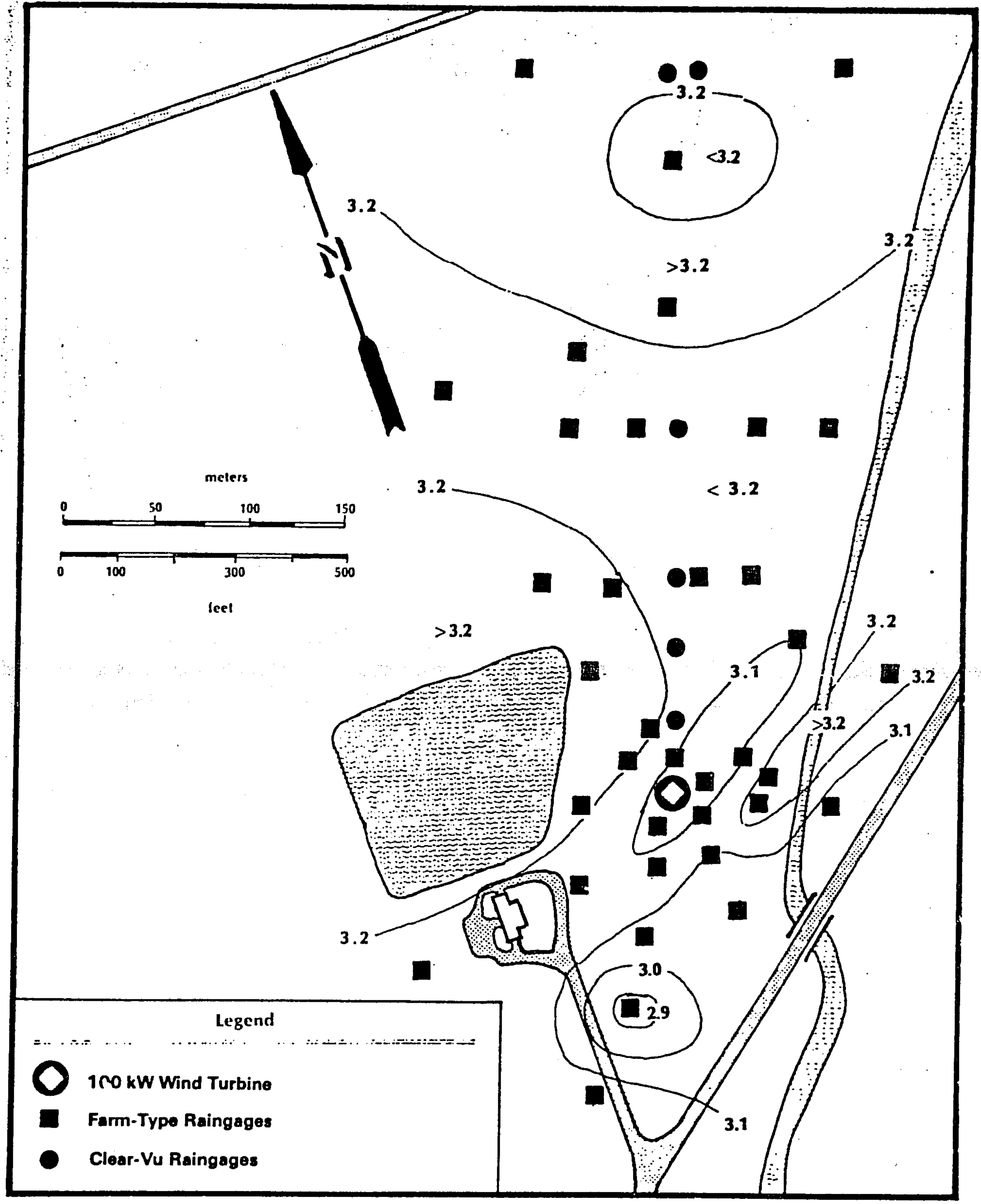

FIGURE 2.3. RAINFALL (IN CM) OVER THE MICROMETEOROLOGICAL NETWORK BETWEEN 1755 AND 1905 HOURS ON JULY 21, 1977 WHILE 100 kW TURBINE WAS OPERATING. WIND DIRECTION: NNW TO NE. WIND SPEED: 1.8 TO 3.4 M/S

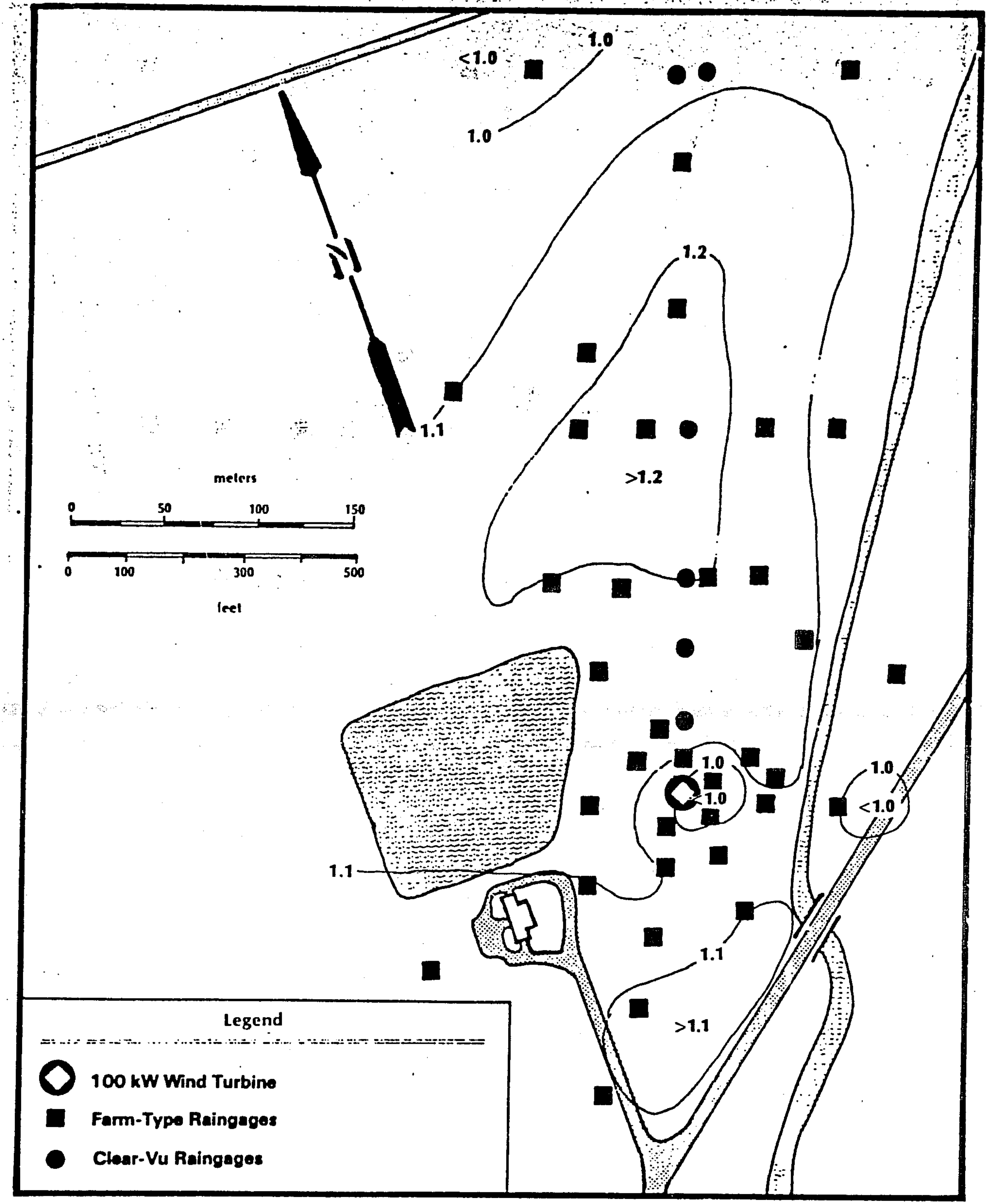

FIGURE 2.4. RAINFALL (IN CM) OVER THE MICROMETEOROLOGICAL NETWORK BETWEEN 2200 and 2400 HOURS ON JULY 24, 1977 WHILE 100 kW TURBINE WAS NOT OPERATING. WIND DIRECTION: W TO NW. WIND SPEED: 11.2 TO 13.5 M/S

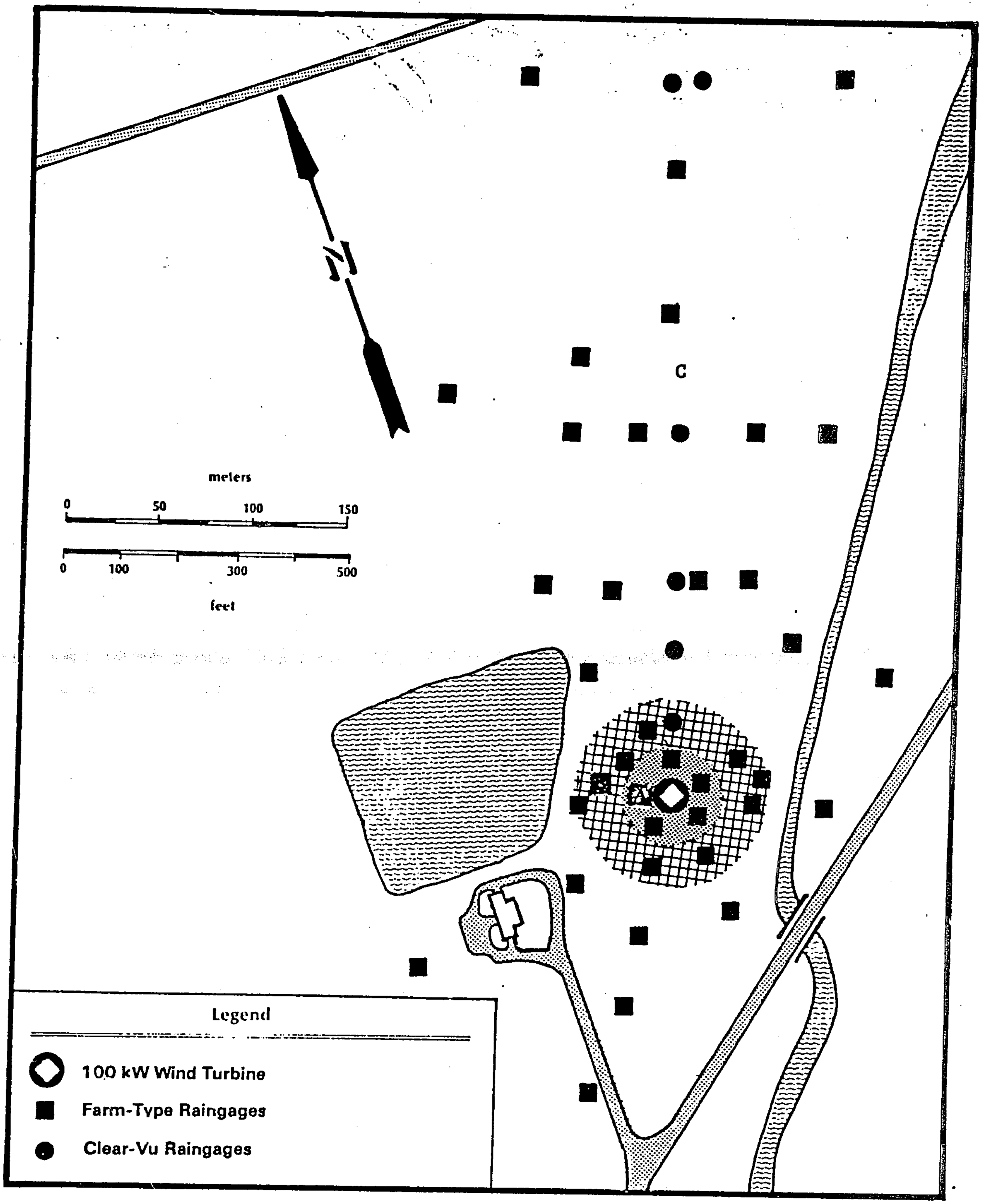

FIGURE 2.5. MICROMETEOROLOGICAL RAINGAGE NETWORK SHOWING THE FARM-TYPE WEDGE-SHAPED GAGES INCLUDED IN GROUPS A AND B

Rainfall statistics for the entire network of 36 farm-type gages and for the three groups are presented in Table 2.3. Data for the rain on July 20 (Rainfall #15) were not included because rainfall amounts were less than .05 cm (.02 inch) on this date and this amount is almost the minimum measurable rainfall.

Three statistical tests were used to compare the three combinations of areas: (1) A with B, (2) B with C, and (3) A with C. In each case the statistical test used was a paired T-test (Steel and Torrie, 1969). For each pair of areas, the mean rainfall from the first area was matched with the mean rainfall from the second area occurring on the same day, and the differences between the means (first means minus second mean) were compared for all days when the WTG was not operating. There were 13 such days, so each T-test used 13 differences to test whether the average difference was significantly less than zero.

The mean difference in rainfall for A-B was -0.070, which was significantly nonzero at the 99 percent significance level. The mean difference for B-C was -0.032, which was significant at the 95 percent level. The mean difference for A-C was -0.102, which was significant at the 99 percent level.

One consistent statistic was that when the turbine was not operating, the rainfall amounts within 3/4 rotor diameter of the turbine (Group A) were less than the amounts slightly further away (Group B). Generally, the deficit between the close-in portion of the network (Group A) and the furthest-out portion (Group C) was greater than the A to B difference. Between Groups A and B, the difference ranged from a 2 to an 18 percent deficit. The amount of this deficit was greatest for small rainfall amounts [(less than 0.5 cm (0.2 inch)] but leveled out at about 4 percent when rainfall amounts reached 2.5 cm (1.0 inch) as shown in Figure 2.6. It is reasonable to assume that this deficit is the result of the shielding effect of the turbine tower. The changes in airflow do not cause a uniform decrease on all sides of the tower, but on the average, about 5 percent less rainfall can be expected within a circle of 30 m radius centered at the tower than in the area further removed. This same effect should be true of any similar tower, such as high-tension line towers.

TABLE 2.3. RAINFALL STATISTICS FOR THE FARM-TYPE RAINGAGE NETWORK--SUMMER, 1977

Rainfall Date	36 Gage Network		Groups A 4 Gages	 B 8 Gages	 C 24 Gages	Relative Variability		
	Mean (cm)	SD (cm)	$\bar{X}_a$ (cm)	$\bar{X}_b$ (cm)	$\bar{X}_c$ (cm)	$\frac{\bar{X}_c - \bar{X}_a}{\bar{X}_a}$	$\frac{\bar{X}_c - \bar{X}_b}{\bar{X}_b}$	$\frac{\bar{X}_b - \bar{X}_a}{\bar{X}_a}$
6-6	3.340	0.117	3.193	3.289	3.381	0.058	0.028	0.030
6-8	1.961	0.064	1.905	1.963	2.055	0.079	0.047	0.030
6-18	0.165	0.025	0.140	0.164	0.170	0.217	0.039	0.183
6-25	1.920	0.053	1.854	1.910	1.933	0.042	0.012	0.030
6-27	0.383	0.074	0.315	0.366	0.406	0.290	0.111	0.161
6-28	0.993	0.063	0.914	0.968	1.018	0.114	0.052	0.058
6-30	4.701	0.180	4.509	4.704	4.724	0.048	0.004	0.043
7-9	1.289	0.051	1.250	1.293	1.295	0.037	0.002	0.032
7-11	0.701	0.081	0.635	0.688	0.737	0.160	0.070	0.084
7-16	0.828	0.063	0.747	0.787	0.856	0.146	0.087	0.054
7-17	1.534	0.066	1.511	1.534	1.537	0.017	0.002	0.015
7-18*	0.495	0.041	0.493	0.516	0.490	-0.005	-0.049	0.046
7-22*	3.078	0.089	3.073	3.165	3.147	0.024	-0.006	0.030
7-24	1.107	0.068	1.046	1.115	1.115	0.065	0.0	0.065
8-4 to 8-9	3.398	0.104	3.289	3.439	3.403	0.035	-0.010	0.045

* Turbine was operating

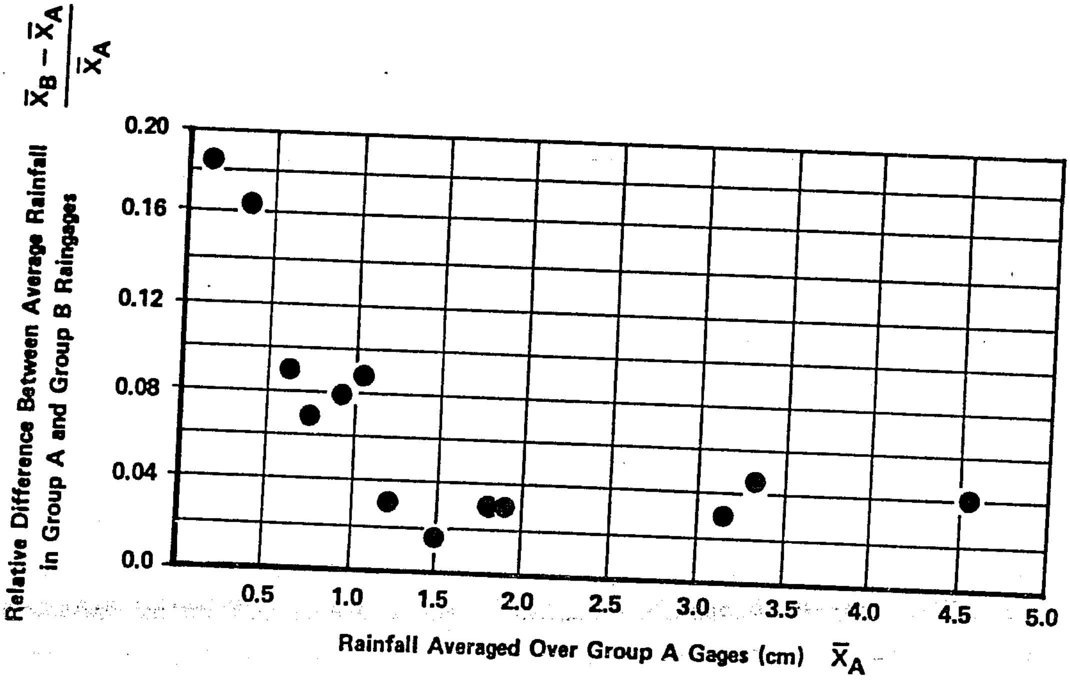

FIGURE 2.6. VARIABILITY BETWEEN THE RAINFALL AT 1/2 ROTOR DIAMETER FROM THE TURBINE TOWER (GROUP A GAGES) AND RAINFALL AT 1 ROTOR DIAMETER AWAY (GROUP B) AS A FUNCTION OF THE RAINFALL DURING A STORM

As was shown during two rainfalls, portions of this observed deficit were probably a result of the horizontal WTG blade* being directly above one of the raingages. On one occasion, this caused the rainfall at this gage to be 17 percent less than the rainfall at the other three gages in the A group. Only on these two occasions was the blade position of the immobile rotor suspected to be a factor in the rainfall deficit close to the turbine tower.

Out of this observation of a samll rainfall deficit caused by he tower (and the blades) when the turbine is not operating evolves the one effect that the turbine has on rainfall. Based on the two occasions when the turbine was operating, the rainfall deficit at the Group A gages disappeared or was noticeably less than for the 13 cases when the turbine was not operating.

Two other factors should be considered before it is concluded that the movement of the turbine blades destroys the shielding effect of the tower and eliminates the rainfall deficit. These two factors were wind speed and wind direction. As noted previously, the turbine was not operated during some rains because the wind speed was not high enough. This factor probably does play a part in the explanation. The wind during turbine operation on July 18 was 6.7 to 13.4 m/s and on this date the Group A gages measured more rainfall than the remainder of the network. However, on the other day of operation (July 22), the wind speed was only 1.8 to 3.4 m/s, a value at which the turbine is generally not operated. Yet the rainfall deficit was only 2.4 percent. Additionally, on the date of strong winds accompanying tornado activity (June 30) there was a rainfall deficit of 4.8 percent at the Group A gages.

Wind directions for the turbine-operation rainfall dates were more northerly than was true or was estimated for the days when it rained but the turbine did not operate. On the non-operational dates, the wind directions generally had a westerly or southerly component. The arrangement of the Group A gages are such that at least one gage would have been downwind of the

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*Blades are feathered and stowed in this position when the WTG is not operating.

turbine for any wind direction except southeast. Thus, wind direction as a cause for the elimination of the rainfall deficit does not appear reasonable. A complete investigation of this possibility would require additional measurements with continuous wind records for both non-operating and operating conditions.

In assessing the impact of the WTG on rainfall, it should be noted that during many of the rainfalls, there were individual gages out in the open field and far from the turbine which measured rainfall amounts significantly less or greater than nearby gages. The rainfall differences were frequently greater than the rainfall deficits observed in the Group A gages. This would indicate that there are rainfall anomalies beneath any thunderstorm or front. Of course, these are random. The deficits near the tower are consistent.

Other Biophysical Parameters

The key justification for the study of the microclimate in the vicinity of an operating wind turbine is to provide experimental evidence of the degree of change which the turbine and tower produce to the micrometeorology within the wake downstream of the turbine. This concern is of particular interest to farmers, who in the not too distant future may have large WTG sited in their agricultural fields.

Through measurements of selected biophysical environmental parameters in the wake of the 100 kW wind turbine this research task sought to define the downwind effect of the wake of the operating WTG and to demonstrate the natural variability in that environment. Precipitation was a key integrating parameter which could be measured. This study is described above. Other parameters included in this discussion are incident solar radiation, temperature, wind speed, and atmospheric carbon dioxide concentration. The CO_2 parameter was measured because it provides an index of the biological activity in the immediate area.

The data from the three seasons of microclimatological sampling are presented in Appendix B. The following graphs and statistical interpretations are self contained, however, and the data is presented only for those who may wish to study the results in depth. Figures 2.7

through 2.9 graphically display the results of this research. They will be referred to from time to time in the discussions of the individaul parameters which follow.

Incident Solar Radiation

Incident solar radiation was measured at each station sampled in each season. This data was not acquired to directly study the potential effect of the wind turbine wake but rather to back up the detailed analysis in the event that a significant difference in other more sensitive parameters was found. Because of the sampling design where several minutes or hours could elapse between sample distances it was necessary to have information on the variation in light level between any two sample locations. These data are presented in Figures 2.7 through 2.9.

On one occasion in the late spring of 1977, measurements of incident radiation, in langleys per minute (ly/min), were made in and around the shadow of the tower and stationary blades of the 100 kW WTG (Table 2.4). The ambient, unobstructed radiation was 0.97 ly/min. In the deep shadows cast by the main tower legs and the nacelle, solar radiation levels were 0.21 and 0.25 ly/min. Other parts of the tower structure and blades cast shadows of intermediate intensity.

Specific interpretation of these figures is not offered at this time but rather they are presented to record these levels for later comparison with measurements for other similar structures. It is unlikely that the reduced solar energy received by the vegetation at the base of the tower contributes significantly to altered productivity in a climate such as that of Sandusky, Ohio where intermittant cloudiness is normal. In climates with very minimal cloud cover (particularly deserts) the effect of the shade of the tower may be a drawing of small animal populations into the vicinity to take advantage of the shelter. This hypothesis could not be tested at NASA-Plum Brook. The significance of the effect would be site dependent and is not expected to be a negative or positive effect of any significance, but rather a phenomenon of the available shade.

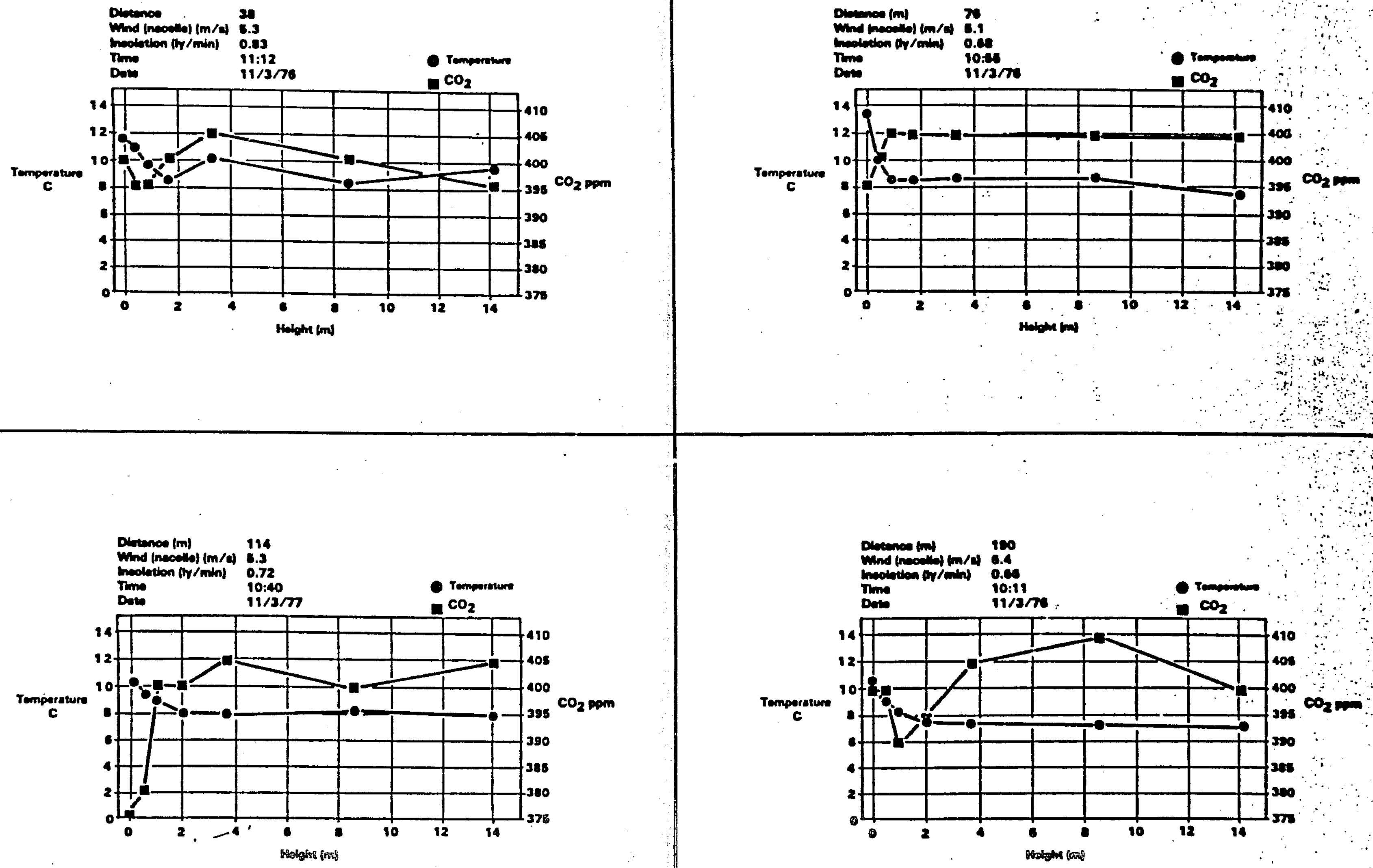

FIGURE 2.7A. FALL MICROMETEOROLOGICAL DATA, 1976

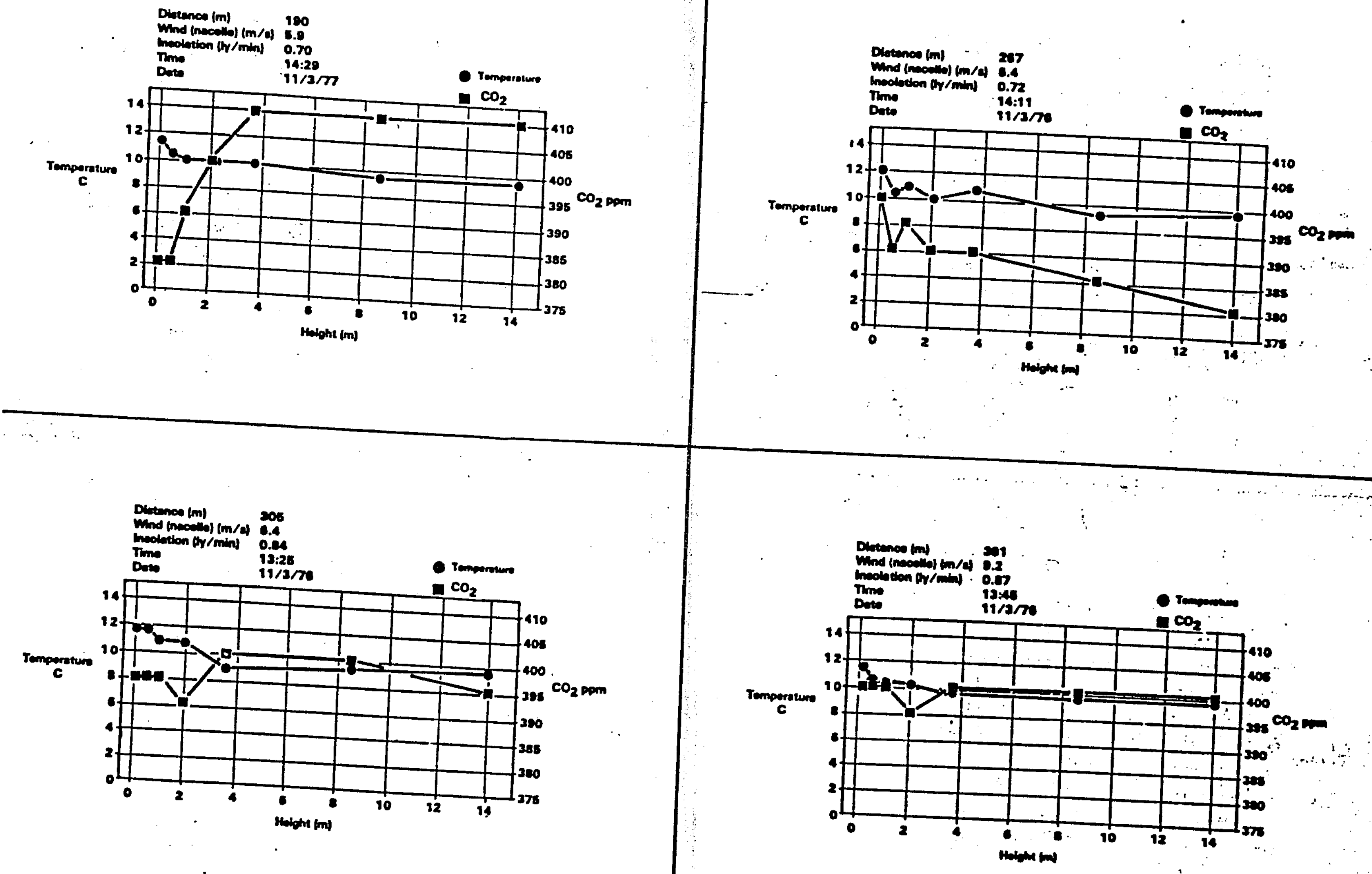

FIGURE 2.7B. FALL MICROMETEOROLOGICAL DATA, 1976

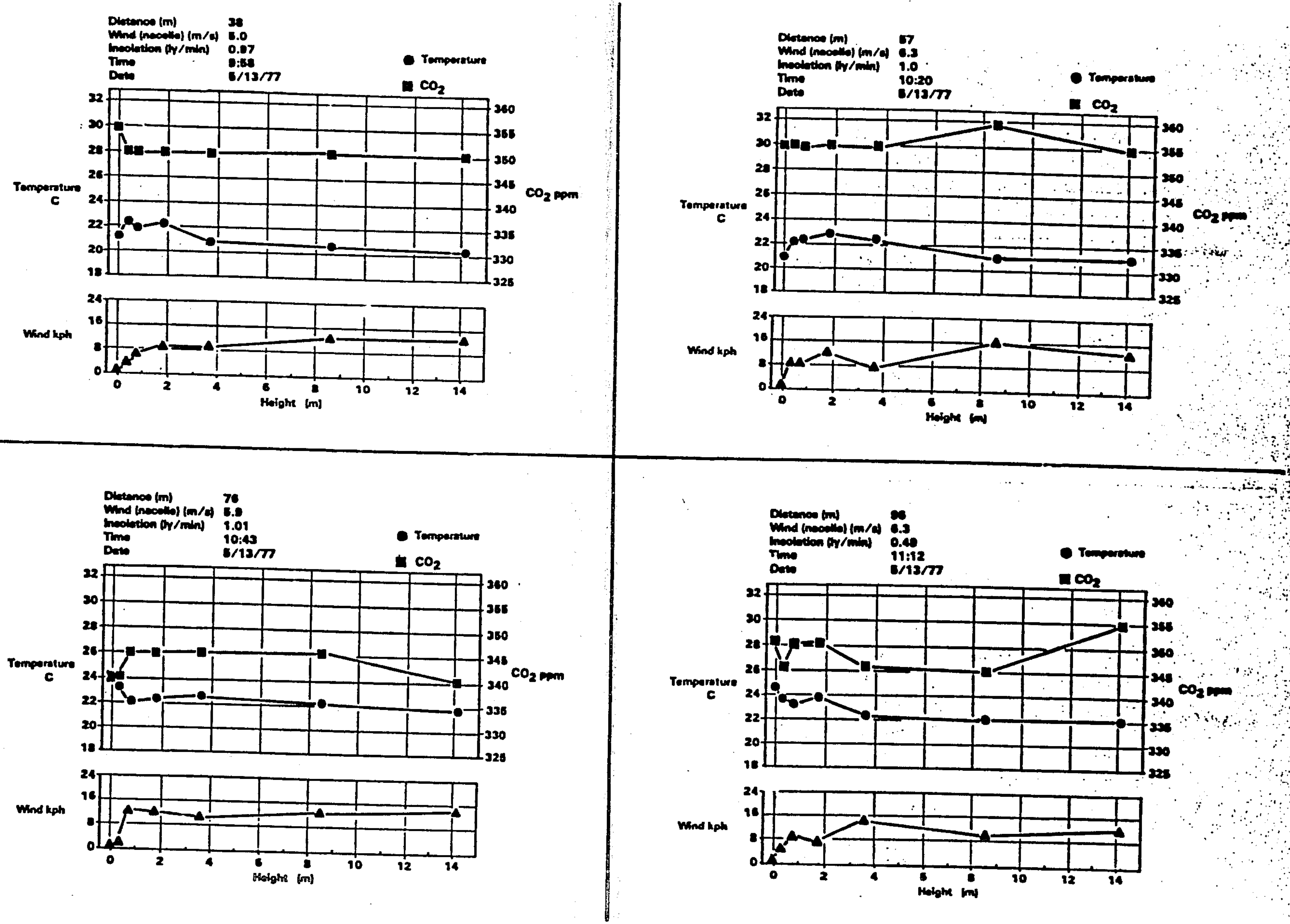

FIGURE 2.8A. SPRING MICROMETEOROLOGICAL DATA, 1977

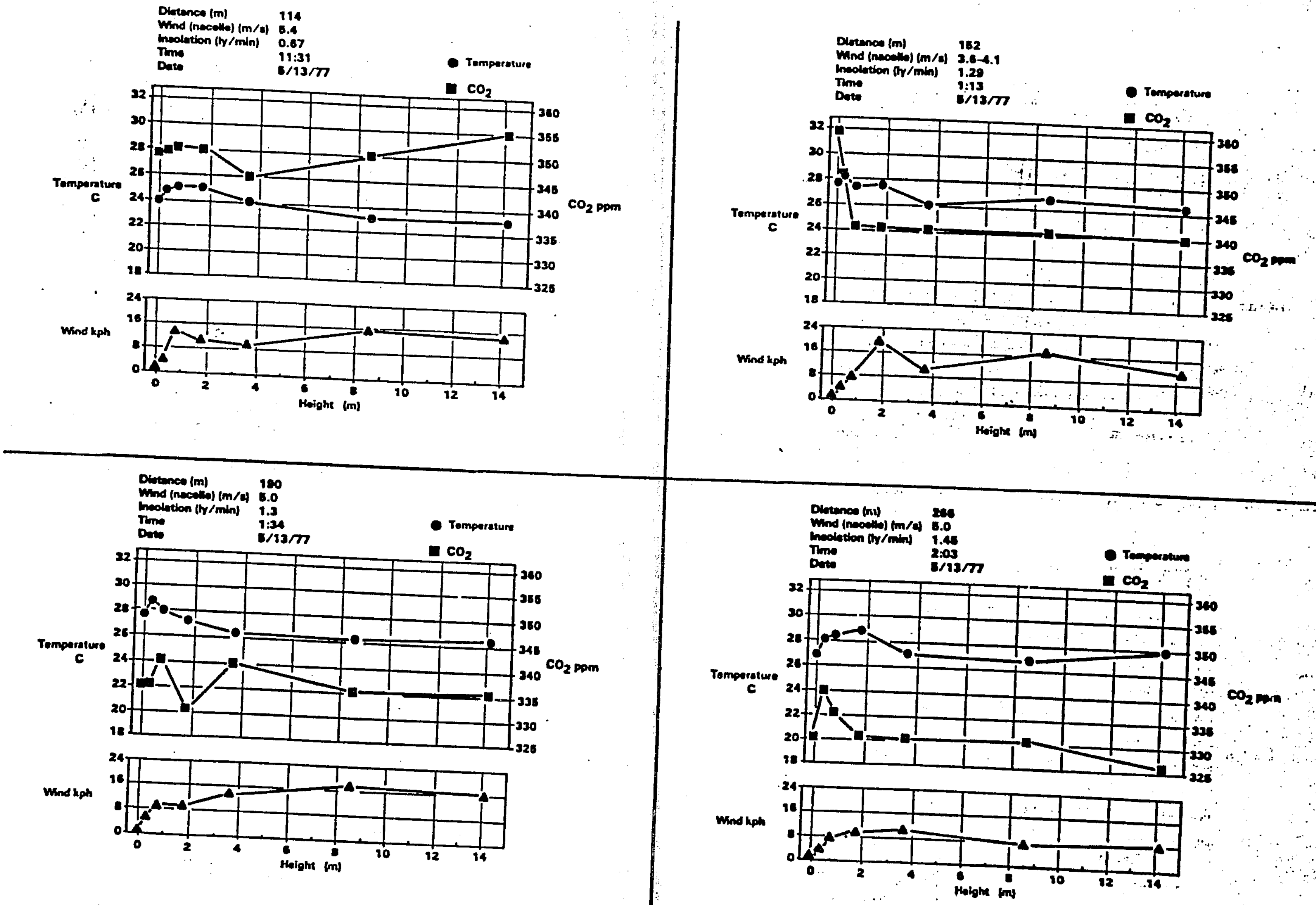

FIGURE 2.8B. SPRING MICROMETEOROLOGICAL DATA, 1977

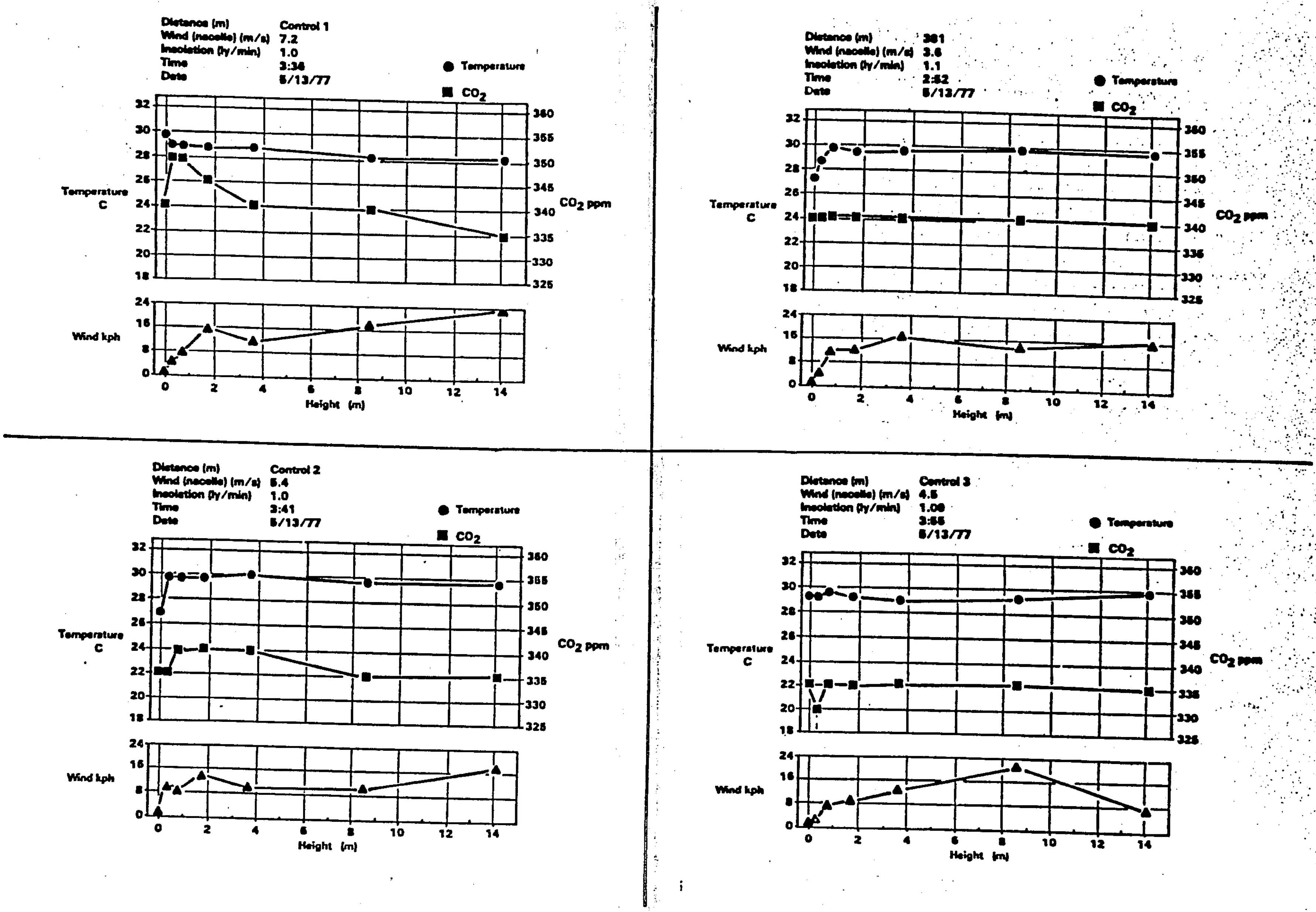

FIGURE 2.8C. SPRING MICROMETEOROLOGICAL DATA, 1977

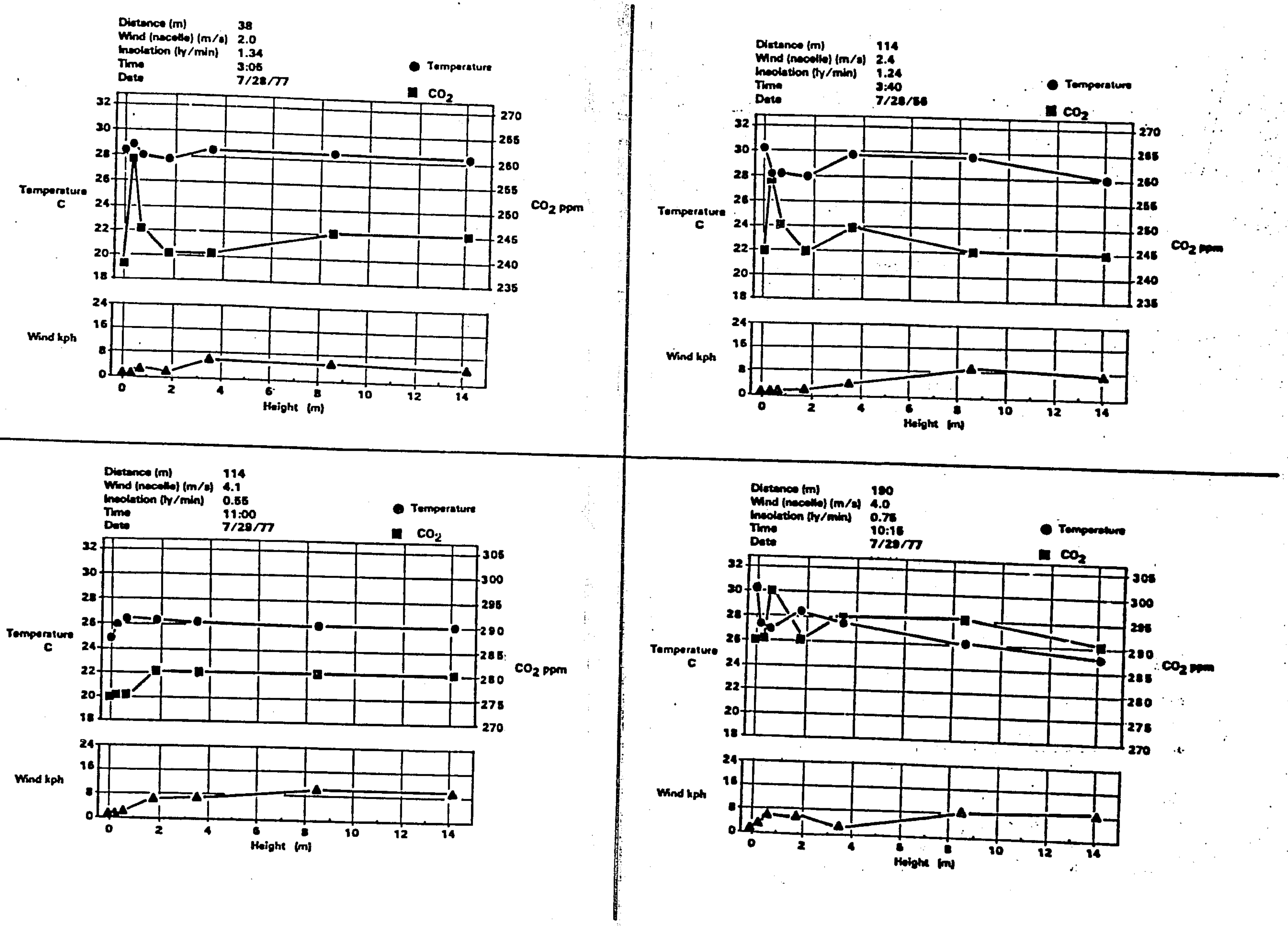

FIGURE 2.9A. SUMMER MICROMETEOROLOGICAL DATA, 1977

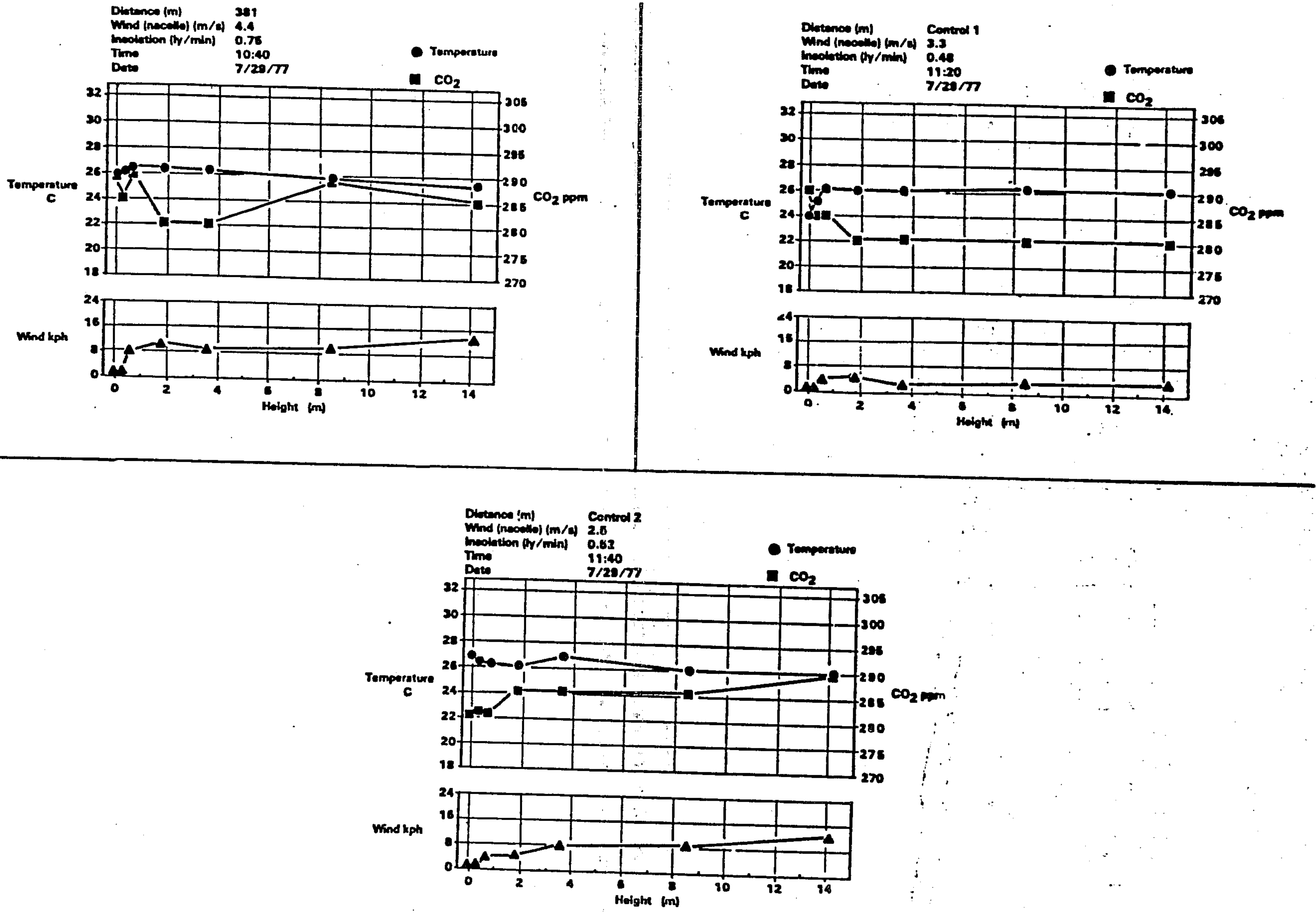

FIGURE 2.9B. SUMMER MICROMETEOROLOGICAL DATA, 1977

TABLE 2.4. INCIDENT SOLAR INSOLATION IN WIND TURBINE SHADOW

Date: May 13, 1977*

Time: 16:27-16:35

Shadow Location	Insolation (ly/min)
5 ft (1.5 m) from tower	0.21
5 ft (1.5 m) from tower	0.4-0.5
15 ft (4.6 m) from tower	0.5
Tower structure	0.75
25 ft (7.6 m) from tower	0.3
Nacelle shadow	0.25-0.30
Blade shadow	0.32
Blade shadow	0.35
Unobstructed sunlight	0.97
Unobstructed sunlight	0.97

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*Date when field team was present closest to summer solstice with most sun and thus most contrasting shadows.

Temperature

The temperature profile above the grassland habitat which predominates in the vicinity of the wind turbine at Plum Brook is representative of similar habitats in similar climates. The temperature declines with increasing altitude above the ground level to the ambient air temperature which is measured above all obstructions above approximately 25 ft (8 m).

In Figure 2.10, a curve has been plotted of the average temperatures from ground level to 47 ft (14.2 m) for all three seasons sampled. This curve approximates a typical average temperature profile with height for that climate. The 0 and 1 ft (0.3 m) heights have the highest average temperatures respectively. This is due to surface heating and reduced air turbulence within the vegetation. The temperature at the 3, 6, and 12 ft (0.8, 1.8, and 3.6 m) levels are similar to one another but lower than those closer to the ground. These temperatures reflect a mixing of the cooler ambient air with the hotter surface layer. Localized anomalies may be present in this zone during periods of rapid surface heating. Many of the apparent aberrations which can be seen in the temperature curves presented in Figures 2.7 to 2.9 are likely a result of this phenomenon.

The three way analyses of variance (ANOVA) performed on the temperature data for all seasons tested for significant variation in temperature with height above the ground, season of the year, and distance from the wind turbine. All three were found to be highly significant. Temperature variation with height and with season would be expected to show significance. Duncan's Multiple Range procedure was applied to distance-grouped data for temperature, averaged for all seasons. All points measured in the following groups were pooled: 1) 1 to 5 diameters (30 to 190 m), 2) 7 to 10 diameters (267 to 381 m), and 3 all controls. Interestingly enough, the separation occurred between the first group (those samples closest to the turbine) and paired the second two groups (those sites farther away and those not influenced by the WTG. Upon close examination two factors appeared to have direct bearing upon this observation and upon those described in later parameter discussions. The innermost ring

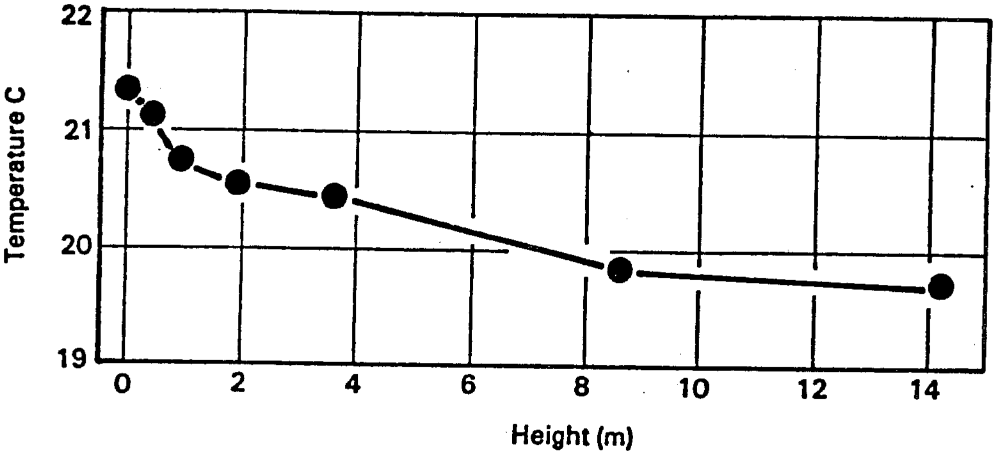

FIGURE 2.10. PROFILE OF AVERAGE MEASURED TEMPERATURES FROM GROUND LEVEL TO 14.2 METERS FOR FALL, SPRING, AND SUMMER SEASONS

around the wind turbine tower (to a distance of approximately 70 m) was mowed in the late fall of 1976 and again in the early spring of 1977 and may have contributed to higher surface and near surface temperatures in this 1 to 5 diameter distance group. Order of sampling appears to have influenced this statistic also. In the spring season, particularly where the temperature rose rather rapidly over a few hours of time, the sequence of sampling distances starting with those closer in to the wind turbine in the early hours influenced the results.

Thus, we are able to rule the wind turbine out as a major contributor to variation in temperature. No measurable shift in temperature could be attributed to the wind turbine with either height or distance. All observed variation was attributed to normal environmental differences.

Wind Speed

Wind speed was recorded at the different test distances during the spring and summer seasons. The spring season sampling was done on a day of higher wind speeds than those of the summer when available winds were barely adequate to operate the WTG. This is a condition we wished to avoid but which is not an atypical summer condition. Higher wind velocities in the summer in northern Ohio are typically associated with storms and operating restrictions on the 100 kW machine at that time precluded operation in such winds.

The average wind speed for the various increasing heights from ground level to 47 ft (14.2 m) for the two sampling seasons is graphed in Figure 2.11. This represents a typical profile of wind speed with increasing height because the averaging of the several numbers tends to reduce variation based on time of measurement. The increasing wind speed with increasing height above the ground is due to the resistances encountered by the wind (frictional losses) at the lower heights. This resistance is contributed to by the ground surface, the vegetation [height approximately 2 ft (0.6 m) at Plum Brook], topography (not a major factor at Plum Brook), and man-made obstructions.

The three way ANOVA performed on the data base established as highly significant the variation in wind speed with height, season, and

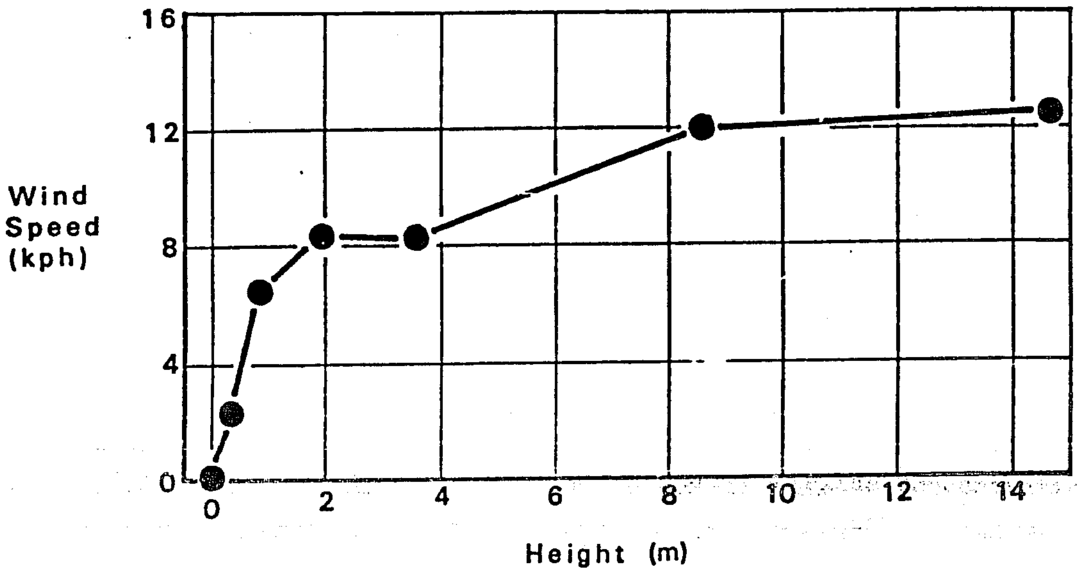

FIGURE 2.11. AVERAGED WIND SPEED FROM GROUND LEVEL TO 14.2 METERS FOR SPRING AND SUMMER SEASONS

distance. As with temperature, the seasonal and height variations were anticipated as this represents the normal condition for wind speed. The significance of wind speed with height was further investigated using Duncan's Multiple Range procedure with the same groupings described for the temperature study. The means again separated with the closer sites (1-5 diameters) being different from the similar 7 to 10 diameter distances and controls.

Based upon the measurements studied statistically, it was possible to construct the tentative hypothesis that the wind turbine was influencing the wind speed in some manner. Because of the sampling design, however, it was necessary to check the ambient wind speeds for the various suspect distances. The wind velocity measures at the nacelle of the wind turbine (100 ft or 30.8 m above the ground) were checked (Figures 2.7 through 2.9). These figures indicate that the wind speeds were probably slightly higher while the more distant readings were being taken. Sample size (n = 2), however, is too small to make valid conclusions based on these measurements alone.

Carbon Dioxide Concentrations

The statistical analyses of the measured CO_2 concentrations revealed highly significant variation with distance and height.* As expected seasonal variation of CO_2 was not significant. Variation with height is a natural phenonena. The normal CO_2 concentration at ambient heights is 320 ppm (Brown and Rosenberg, 1971/1972). Concentrations within the vegetation canopy are typically higher following a fairly high-amplitude diurnal pattern based upon the respiration/photosynthesis cycle of the vegetation (Rosenberg, 1974).

The average CO_2 concentration with height is displayed in Figure 2.12 for four distances relative to the wind turbine. Mean separation tests failed to show any significance with distance. The spread of

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*CO_2 data for two locations (38 and 114 m) sampled on the first day of the summer season (July 28, 1977) were excluded from statistical analyses because these points were so low as to indicate sampling error.

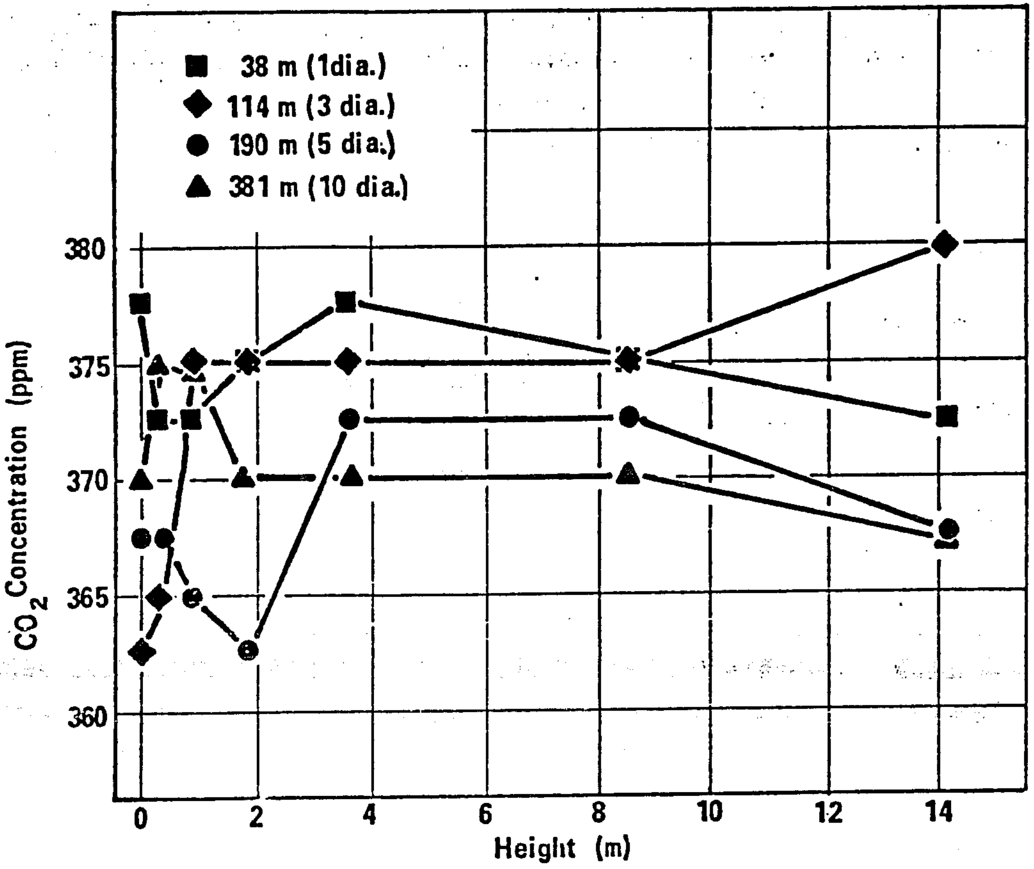

FIGURE 2.12. AVERAGE CO_2 CONCENTRATIONS FOR FALL AND SUMMER SEASONS*

*Summer season excluded due to apparent sampling error.

the values shown in this figure represents normal sampling variability for CO_2 measurement. Anything less than 15 ppm difference in CO_2 concentrations normally represents field instrument sensitivity limits. Significant differences in CO_2 concentration at some point in the wake area would have indicated that the wake passage was altering the normal gaseous mixing patterns within the vegetation canopy. Such a variation was not observed in this study.

Wake Definition

The results of the preceding considerations did not fully answer whether the variations with height and distance may have been influenced by the wind turbine wake. To further test for the boundary of the theoretical wake of the WTG, Duncan's Multiple Range Procedure was applied to all data testing the difference between the 28.2 ft (8.6 m) height (below the tip of the rotor) and the 46.5 ft (14.2 m) height (above the tip of the rotor, thus within the wake). By testing the difference between values (all seasons averaged) measured at these two heights (14.2 m - 8.6 m) and by evaluating various distance grouping, we sought to test for the definition of the lower edge of the wake if it were reflected in these parameters. The results of this test are presented in Table 2.5.

No mean separation was indicated for temperature at any distance. This indicates that no statistical difference was demonstrated between temperature values within the zone of influence of the 100 kW WTG and in areas unaffected by it.

For CO_2 concentrations no mean separation occurred in the testing of two groups (1 to 9 diameters and 10 diameters plus controls). In the three grouping test the 7 to 10 diameter group (267 to 381 m) was shown to be significantly different from the controls and the close in group (1 to 5 diameters), which were not different from one another. It is unlikely, however, that this indicates an effect of the wind turbine, because normal instrument sensitivities for CO_2 concentrations may induce such a shift. The possibility that the wind turbine was a contributing

TABLE 2.5. DUNCAN'S MULTIPLE RANGE TEST RESULTS OF CHANGE WITH DISTANCE OF DIFFERENCE BETWEEN PARAMETER VALUES AT 14.2 METERS AND 8.6 METERS (ALL SEASONS AVERAGED)

TEST ONE

Microclimate Parameters	Distance From Wind Turbine: Group 1 (38 m to 343 m)	Distance From Wind Turbine: Group 2 (381 m plus controls)
Temperature	-- no mean separation --	
Wind Speed	X[a]	Y[a]
CO_2 conc.	-- no mean separation --	

TEST TWO

Microclimate Parameters	Distance From Wind Turbine: Group 1 38 m to 190 m	Distance From Wind Turbine: Group 2 267 m to 381 m	Distance From Wind Turbine: Group 3 Controls
Temperature	--- no mean separation ---		
Wind Speed	X	Y	Y
CO_2 conc.	Y	X	Y

[a] X and Y in any row indicate significantly different means. Two Y's indicate means which were not significantly different.

cause cannot be completely ruled out, however, because the design of the statistical tests (averaging all seasons together) should have minimized any sampling bias.

Significant separation of means for wind speed were found in both tests. This seems highly suggestive that the wind turbine is reducing the velocity of the wind downstream. In both cases the mean values for the closest group to the wind turbine were negative numbers while the one or two groups further away from the turbine were positive numbers. This suggests that at the 14.2 m height (within the hypothetical zone of influence) the average wind speed for all averaged seasons is lower than the corresponding values at the 8.6 m height (well below the tip of the blade), but that this statistical difference disappears at approximately 190 m to 340 m (5 to 9 diameter distances) away from the wind turbine and tower. At this distance all averaged values for the 14.2 m height are slightly higher than those at 8.6 m. This is the normal atmospheric condition.

Summary

The theoretical aerodynamic analysis of the Plum Brook WTG reported in Rogers et al. (1976) predicted a drop in wind speed within the zone of influence of that system for some unknown distance downwind. The data from this study confirm the reduced wind velocity in this zone. The magnitude of that change cannot be determined accurately from this particular research, however. Future studies by NASA and DOE are aimed at sophisticated measurement of the wake dimensions and wind velocity recovery profiles. The scope of this study was to define the effect and to determine if the effect would have any impact on the surface dwelling biota (natural or agricultural) of this zone. Based upon these studies it is possible to state that the inherent range of variability of the natural environment is far greater than the very minimal influences to the microclimate of the zone immediately downwind of the operating and nonoperating wind turbine. We conclude that the siting of a WTG similar to the 100 kW design will not be a significant influence on the microclimate beyond the immediate area which it occupies.

III. BIRDS

INTRODUCTION

A review of the literature concerning potential effects of wind turbines on migratory and resident wildlife indicates that night-migrating birds are the only wildlife likely to sustain any significant impact. Birds which migrate between their breeding and wintering areas by flying at night include such varied groups as rails, woodcocks, cuckoos, woodpeckers, and most songbirds (Berger, 1961; Gauthreaux, 1975). In addition, waterbirds such as loons, geese, ducks, gulls, and shorebirds may migrate during the daytime or nighttime (Pettingill, 1970). Many of the birds in these groups have been found dead at the base of tall towers and buildings following a night of heavy bird migration.

BIRD/TURBINE COLLISION POTENTIAL

Night-migrating birds colliding with a wind turbine was the only potential impact considered significant enough to warrant field studies. The following discussion of the literature on nocturnal bird migration was the basis for that concern and provided the background for development of the field program.

Altitude of Migration

Obviously, birds that migrate at low altitudes are more likely to collide with tall structures. Since songbirds normally migrate between 500 to 1,500 feet (152 to 457 meters) above ground level over the eastern United States (Bellrose, 1971; Able, 1970; and Gauthreaux, 1972), they are much more likely than waterfowl and shorebirds to collide with towers. These stronger flying waterbirds usually fly in flocks and at altitudes above those where songbirds are found (Gauthreaux, 1975). Although the altitude of bird migration above the ground varies with topography, about

15 percent of the nocturnal migrants fly below 492 feet (150 m) and 90 percent fly below 3281 feet (1000 m) (Allerstam, 1977). Altitudinal distribution of migrants may change during the night depending on the altitude of favorable winds (Gauthreaux, 1972 and 1975; Allerstam, 1977), the time of night (Able and Gauthreaux, 1975; Allerstam, 1977), the altitude of air turbulence (Bellrose, 1971), the altitude of the cloud ceiling (Johnston and Haines, 1957; Allerstam, 1977, Gauthreaux, 1972), and precipitation (Bellrose, 1971; Gauthreaux, 1971). Songbirds landing or continuing to migrate at a lower altitude for any of these reasons become much more prone to collision with tall structures.

Bird-Tower Collisions

In recent years, ornithologists have reported an increasing number of instances of sizable bird mortalities in the United States caused by disorientation and/or collision (Vosburgh, 1966). The large kills commonly involve songbirds, such as warblers, vireos, and sparrows, which migrate at low altitudes during the night. The early literature on such large kills in the United States have been reviewed by Brewer and Ellis (1958) and Taylor and Anderson (1973).

Until their use was restricted, ceilometers (see Appendix A for definition) at airports were sometimes the site of large bird kills on overcast or foggy nights (Howell, et al., 1954). Ceilometers are instruments used at airports to measure the height of cloud ceilings. Ceilometers cause the death of birds by visual disorientation of the migrant, who eventually simply flies into nearby buildings or the ground. These instruments will not be associated with wind turbine facilities. Information on ceilometers is mentioned to put kills at towers in context and to illustrate the attraction of birds to lights.

Many nocturnal migrants also have been killed at tall buildings (Vosburgh, 1966) and lighthouses (Baldwin, 1965). Alteration or reduction of lighting during migratory seasons has helped to reduce this mortality.

Television towers are particularly lethal to night-migrating birds due to the many supporting cables and guy wires which are frequently invisible to the nocturnal flyers. Examples of bird kills at tall towers over extended periods of daily searching have been reported by Stoddard and Norris (1967) for a 1,010-foot (308-meter) television tower in Florida (average of 2,700 annually over 11 years) and by the U.S. Department of the Interior (1974) for a 1,200-foot (366-meter) navigation tower in North Dakota (total estimated kill per season varied from 760 to 1,417 for five migration seasons).

Recently, studies have been made of bird collisions with a 495-foot (150-meter) high cooling tower for a nuclear power plant on the south-eastern Ohio shoreline of Lake Erie (Jackson, et al., 1974). Bird kills at this cooling tower prior to its operation varied from 44 to 103 per season for two seasons of collecting. The height of this structure is greater than the height of wind turbines presently under consideration. For example, the tallest tower for wind turbines will probably be 200 feet (61 meters) (Metz, 1977), and have a blade diameter of 300 feet (91.4 meters), for a total height of 350 feet (106.7 meters) from the ground to the blade tip.

Size of bird kills varies considerably depending on weather conditions, type of structure, and number of nocturnal migrants in the air (Johnston and Haines, 1957). The largest recorded kill occurred at a ceilometer in Georgia, when an estimated 50,000 individuals of 53 species were killed on one night. Long-term studies, such as that by Stoddard and Norris (1967), have found that the interval between really big kills at tall towers (the largest was estimated at 4,000 to 7,000 dead birds on one night) is usually several years. These large kills occurred on nights with favoring winds (for migration) and partial to complete overcast, particularly when foggy or misty weather combined with peak flights of nocturnal migrants.

Effect of Tower Lights

Apparently night-migrating birds are attracted to, and/or confused by, lights on overcast, misty, or foggy nights. Spotlights, ceilometers, and even red navigation warning lights are sufficient to attract migrants into an area where the disoriented birds collide with buildings, towers, and the ground (Vosburgh, 1966; Cochran and Graber, 1958; Howell, et al., 1954; and Baldwin, 1965).

The type of lighting on a structure apparently is often a major factor in the number of birds that collide with it. As the effects of lighting become better understood, lighting patterns such as the intermittent strobes being used on tall structures today may serve to reduce kills.

Topographic and Geographic Considerations

In general, the far west has much lower numbers of nocturnal migrants than the eastern half of the continent (Lowery and Newman, 1966). Therefore, potential wind energy sites in the midwestern and eastern United States are of greatest concern in avian impact prediction.

Coastlines and mountain ridges are two general topographic configurations which offer potential for wind turbine sites (Meroney, 1975; Soucie, 1974). For topographic and geographic reasons, however, these areas may also have heavy use by migratory birds. A comparison of potential wind-power sites on coastlines and mountains to flyway concentrations led to the identification of two areas of overlap. The Green and White Mountains of New England (Soucie, 1974) and the Texas Gulf Coast have been identified as areas which have high sustained winds (Reed, 1974) and are also areas crossed by large numbers of nocturnal migrants (Lowery and Newman, 1966). Although nocturnal migrants normally fly more than 500 feet (152 meters) above the ground (Bellrose, 1971), they may cross a mountain ridge at much lower heights, resulting in exposure to potential collision with wind turbines located on such mountain tops.

BIRD SURVEY METHODS

Four observation techniques were used to identify, quantify, analyze behavior, and determine the direction of low-level, nocturnal bird migration over NASA-Plum Brook Station during fall 1976 and spring 1977. These techniques included ceilometer, night vision scope, and radar study of night migrants, plus daytime surveys of grounded night migrants. The potential for these night-migrating birds to collide with the 100 kW WTG or meterological tower was assessed by early-morning searches for dead birds and by studies to determine the percent of dead birds likely to be removed by scavengers. All surveys were made during the peak months for songbird migration (September, October, April, and May).

Several techniques used by other investigators to study nighttime bird migration were not considered desirable for studying low-level songbird migration at potential or existing WTG sites. Graber and Cochran (1960) recorded amplified calls of nocturnal migrants on tapes controlled by an automatic timer to sample short intervals throughout the night. Many night migrants do not give their individualized daytime species call at night, however, so most calls could only be placed in a bird group and not identified to species. In addition, the number of calls do not give a good indication of migration volume (Berger, 1961). Finally, this method gives no information on the altitude of migrants. Bellrose (1971) described another technique for determining the number of individual birds migrating at different altitudes and their geographic distribution. He used a light aircraft equipped with auxiliary landing lights to count birds flying through the light as the plane cruised at different altitudes. Although counting birds from a plane might be useful in assessing migration altitude and volume in relation to topographic features over large areas, it has deficiencies when trying to assess nocturnal migration over a specific site. Use of planes is far more expensive than the other available techniques, and the technique cannot be used to determine flight direction, identify species of migrants, or calculate migration traffic rates. This technique would prove most useful in assessing nocturnal migration over several hundred miles of mountain range or coastline.

Nighttime Studies

Ceilometer Surveys

Surveys of low-level nocturnal migrants were made between 1 and 2.5 hours after sunset during 13 nights in fall 1976 and 13 nights in spring 1977 using an intense vertical beam of light (two 100-watt ceilometer bulbs) and the techniques described by Gauthreaux (1969) and Able and Gauthreaux (1975) (Figure 3.1). Both 10 x 50 binoculars and 5X night vision scope (model 220 by Javelin with a binocular viewer) were used to observe birds passing through the ceilometer beam.

Migration traffic rates for each night were computed by multiplying the number of birds observed per hour (as viewed through the ceilometer beam with 10 x 50 binoculars) times a conversion factor of 230 recommended by Dr. Sidney Gauthreaux, Jr. (personal communication, 1976). This conversion factor is a modification of the number reported in Able and Gauthreaux (1975), which was determined independently by calculation of the physical dimensions of the space sampled by the ceilometer and by a correlation between ceilometer counts and simultaneous radar traffic rates. The resulting migration traffic rate represents the number of birds crossing an imaginary mile of front per hour.

The mean nightly direction of migration was computed using circular statistical procedures as outlined by Batschelet (1965), Zar (1974), and Mardia (1972). These procedures were preformed on the azimuth data (direction in degrees) obtained during ceilometer observations of individual birds in flight. Separate calculation were made on azimuth data obtained with binoculars and data obtained with the night vision scope. The azimuth directions were used to generate (1) a mean vector of migration in degrees, (2) the length of the resultant vector (0 to 1), and (3) the angular deviation (0° to 360°). When the direction of migration is ill-defined the value of the length of the resultant vector is closer to zero and the angular deviation is high. When a night's migration is well oriented, the length of the resultant vector is close to one and the angular deviation is small. Angular deviation is a function of the length

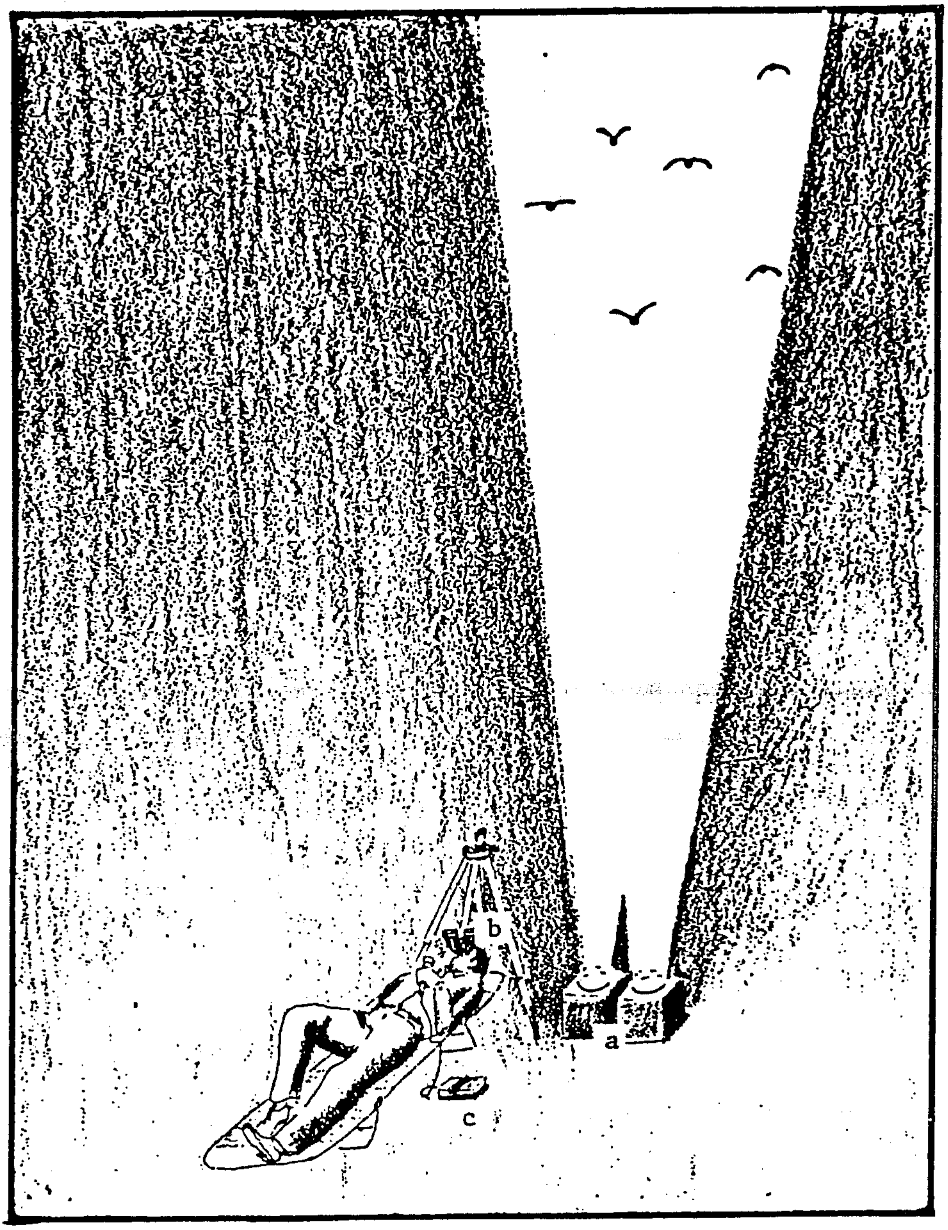

FIGURE 3.1. CEILOMETER TECHNIQUE FOR SURVEY OF NIGHT-MIGRATING SONGBIRDS: (a) CEILOMETER BULBS, (b) 10 x 50 BINOCULARS, AND (c) TAPE RECORDER

of the resultant vector and can be accurately estimated from the length of the resultant vector (Zar, 1974).

Radar Surveys

Radar displays on the plan position indicator (PPI) of ARSR-2 radar units at the Oberlin Airway Facilities Sector, Oberlin, Ohio were studied and photographed on the same nights as the ceilometer surveys. In addition, radar surveys were made on one night during each of the migration seasons when rain prevented use of the ceilometers. These surveillance radars have a 23-cm wavelength and 2 MW of power. Photographs of the radar unit showing the display from Brecksville (adjacent to Cleveland, Ohio) were used to compare with migration information obtained by ceilometer surveys at NASA-Plum Brook. Time-exposure, Polaroid photographs were taken of the radar screen to determine the magnitude and direction of both low- and high-level bird migration. Analysis of radar photographs follows suggestions made by Gauthreaux (1975 and personal communication, 1976).

Statistical Analysis of Radar and Ceilometer Data

Linear regression analysis was performed to fit a straight line to the observed ceilometer traffic rates as a function of radar echo ranges, using the 12 data points obtained under clear skies from both fall 1976 and spring 1977. A "packaged" statistical computer program (Nie et al., 1975) was used to calculate the values of a and b in the equation $Y = a + bX$, employing standard methods of least-squares regression. Here X represents the greatest range of bird echoes appearing on radar and Y represents the corresponding ceilometer traffic rate as observed with binoculars. The same computer program was used to produce a plot showing the 12 raw data points, the fitted regression line, and two curves representing the bounds of a 95% confidence band for the line. The equation for the confidence band was calculated by this program in accordance with standard methods of multiple inference (Draper and Smith, 1966).

Avoidance Behavior

A night vision scope was used on seven nights to observe the behavior of night-migrating birds as they approached the revolving (at approximately 20 rpm) WTG. Observations such as: (1) the direction of the birds' flight in relation to the plane of the revolving blades, and (2) flight patterns used to avoid the blades, were tape recorded for future analysis.

Daytime Studies

Grounded Migrant Surveys

Areas heavily used by migratory birds were surveyed at NASA-Plum Brook and two nearby, wooded areas on the Lake Erie shoreline (Bay Point and Sheldon's Folly) that are traditionally good spots to observe migratory birds. The objective was to determine the species of low-altitude nocturnal migrants that might have been observed during ceilometer or radar surveys on the previous few nights. None of the other survey techniques available (including tape-recording of "chip" notes), allow consistant identification to species. Surveys were normally conducted for 1 hour at each of the two locations during mid-day. Both "squeaking" and tape recorded screech owl calls were used to attract birds into view. An automobile was used to cover as much area of possible, and frequent stops were made at areas where birds were observed from the car or where the habitat looked appropriate to attract migratory songbirds. No special effort was made to record waterfowl or shorebirds, since they are considered high-level migrants.

Searches for Tower-Killed Birds

Daily searches were made at the base of the WTG and meterological tower between the following dates: (1) May 14 through 31, 1975; (2) September 1 through October 24, 1975; (3) September 1 through

October 24, 1976; and (4) April 1 through May 31, 1977, by NASA-Plum Brook personnel. In addition, a double-check of the area around the towers was made by Battelle's ornithologist on 12 mornings in the fall and 12 mornings in the spring. The ground within a 150-foot (45.7 m) radius of both towers was searched on foot beginning at dawn. Any dead birds found at the base of the towers were tagged and stored in a freezer until positive identification was made. Weather conditions occurring the morning of the kill and the distance and direction from the tower where each bird was found were noted in a record book.

Scavenger Studies

Scavenger studies were conducted on the nights of September 21 and 22, 1976, and May 12, 1977, to determine the percent loss of tower-killed birds due to scavenger removal during the night. In the fall of 1976, 17 bird carcasses (tower-killed birds from another location) were randomly placed on the ground around both the WTG and the meteorological tower. In the spring of 1977, 10 birds (4 tower-kills plus 6 starlings) were placed around the WTG. In both experiments, the dead birds were tagged and their positions were marked on a map. The next morning each map location was checked by Battelle's ornithologist for a marked bird. In the fall 1976 study, 17 bird carcasses were available to predators the first night and 15 caracasses were available the second night for a total of 32 "carcass nights".

These same tagged birds used for scavenger studies were also used to test the efficiency of search personnel in locating tower-killed birds. Notes were made on the number of marked birds the searchers were able to find without using the scavenger survey map.

RESULTS AND DISCUSSION

Ceilometer Surveys

Ceilometer surveys of low-level nocturnal bird migration were made during a variety of weather frontal system conditions, cloud cover, wind speeds, and wind directions (Tables 3.1 and 3.2). These surveys were conducted during the peak of both spring and fall passerine (songbird) migrations. Rain prevented the use of the ceilometers during only 1 of 14 survey nights in fall 1975 and 1 of 14 survey nights in spring 1977.

Volume of bird migration during the 26 nights of spring and fall ceilometer surveys varied from essentially no migration up to 17,000 birds per mile of front per hour. The migration traffic rates observed on overcast (10-100 percent cloud cover) nights are not included in the following analyses, since Able and Gauthreaux (1975) have determined that it is impossible to develop a reliable relationship between ceilometer counts and traffic rates with heavy cloud cover.

Migration and Frontal Systems

The largest fall migration traffic rates (15,200 and 6,900 birds per mile of front per hour) observed under clear skies with the ceilometers (Table 3.3) occurred on nights when a cold front had recently passed over the Sandusky area (Table 3.1). On the other hand, the fewest migrants were observed on nights when a cold, stationary, or warm front was approaching Sandusky. This is in general agreement with Able's (1973) findings that in autumn the heaviest songbird migrations occur in the southward flow of dry polar air immediately following the passage of a cold front.

The largest spring migration traffic rate (17,000 birds/mile of front/hr) was observed immediately after the passage of a warm front over the Sandusky area (Tables 3.2 and 3.4). Traffic rates were moderate (3,000-10,000 birds/mile of front/hr) when the Sandusky area was near the center of

TABLE 3.1. WEATHER DATA FOR MIGRATION SURVEY NIGHTS DURING FALL 1976

Date	Estimated Percent of Cloud Cover	Status of Frontal Systems Over Sandusky, Ohio(a)	Precipitation	Wind(b) Range of Speeds, MPH(KPH)	Wind(b) Average Direction
September					
21	60	Immediately behind cold front	None	8-10(12.9-16.1)	WNW
22	0	Ahead of warm front	None	1-4(1.6-6.4)	S
23	0	Immediately behind cold front	None	8-12(a)(12.9-19.3)	WNW(a)
24	0	Ahead of stationary front on west side of high	None	4-5(6.4-8.0)	ESE
25	100	Cold front just north of area	Slight mist for 5 minutes	4-5(6.4-8.0)	E
26	100	Stationary front near center of low pressure area	Rain	8-12(a)(12.9-19.3)	W(a)
27	0	On southwest side of low pressure area	None	7-9(11.3-14.5)	N
28	0	Behind cold front on east side of high	None	2-6(3.2-9.6)	ESE
29	60	Cold front just north of area	None	3-8(4.8-12.9)	SW
30	5	Stationary front just north of area	None	2-4(3.2-6.4)	ESE
October					
7	100	Immediately behind cold front	None	10-12(16.1-19.3)	NNE
8	100	Behind stationary front	None	1-8(1.6-12.9)	NNE
11	5	Behind cold front on west side of high	None	3-7(4.8-11.3)	SE
12	10	Ahead of cold front	None	10-17(16.1-27.4)	S

(a) Determined from the National Weather Service 00Z synoptic weather maps for 8 P.M., EDT.

(b) Wind data from 90-foot level of meterological tower at NASA-Plum Brook for period of ceilometer surveys (2030-2200 hours EDT).

TABLE 3.2. WEATHER DATA FOR MIGRATION SURVEY NIGHTS DURING SPRING 1977

Date	Estimated Percent of Cloud Cover	Status of Frontal Systems Over Sandusky, Ohio(a)	Precipitation	Wind(b)	
				Range of Speeds, MPH(KPH)	Average Direction
April					
20	100	Behind Cold Front on West Side of High	None	7-8(11.3-12.9)	S
21	"	Ditto	Intermittent Light Sprinkle	10-17(16.1-27.4)	SSW
25	"	Behind Cold Front on East Side of High	Mist and Rain	5-9(8.0-14.5)	N
26	0	West Side of Low	None	7-9(11.3-14.5)	SW
May					
1	100	Ahead of Stationary Front on Southwest Side of High	"	6-10(9.7-16.1)	SSW
2	"	Immediately Behind Stationary Front on South Side of High	Intermittent Mist	2-4(3.2-6.4)	NE
3	"	Behind Stationary Front on South Side of High	None	9-13(14.5-20.9)	ENE
4	"	Immediately Ahead of Stationary Front	"	4-5(6.4-8.0)	WNW
5	0	Immediately Behind Warm Front on West Side of High	"	10-14(16.1-22.5)	SSW
9	"	Behind Cold Front on Southeast Side of High	"	7-9(11.3-14.5)	NE
10	"	Near Center of High (East Side)	"	3-4(4.8-6.4)	SSW
11	"	Ditto	"	3-7(4.8-11.3)	SSW
12	5	"	"	11-12(17.7-19.3)	WSW
13	10	On North Side of High	"	9-12(14.5-19.3)	W

(a) Determined from the National Weather Service 00Z synoptic weather maps for 8 p.m. EDT.

(b) Wind data from 90-foot level of meterological tower at NASA-Plum Brook for the period of ceilometer surveys (2125-2300 hours EDT).

TABLE 3.3. MIGRATION TRAFFIC RATES OVER NASA-PLUM BROOK DETERMINED BY CEILOMETER WATCHING, FALL 1976

Date	Results of Ceilometer Surveys in Birds/Hour		Migration Traffic Rate(a)
	10x50 Binoculars	Night Vision Scope	
September			
21	15	--	3,400
22	15	--	3,400
23	66	--	15,200
24	16	24	3,700
25	10	8	2,300
27	10	42	2,300
28	30	68	6,900
29	2	6	500
30	16	13	3,700
October			
7	0	32	--
8	2	28	500
11	18	46	4,100
12	0	22	--

(a) Computed by using the conversion factor of 230 recommended by S. Gauthreaux for data obtained using binoculars with two ceilometers. The migration traffic rate is given in birds/mile of front/hour.

TABLE 3.4.. MIGRATION TRAFFIC RATES OVER NASA-PLUM BROOK DETERMINED BY CEILOMETER WATCHING, SPRING 1977

	Results of Ceilometer Surveys in Birds/Hour		
Date	10 x 50 Binoculars	Night Vision Scope	Migration Traffic Rate(a)
April			
20	8	6	1,800
21	0	8	—
26	10	26	2,300
May			
1	4	16	900
2	0	2	—
3	2	6	500
4	34	20	7,800
5	74	154	17,000
9	0	4	—
10	16	30	3,700
11	42	98	9,700
12	34	66	7,800
13	30	52	6,900

(a) Computed by using the conversion factor of 230 recommended by S. Gauthreaux for data obtained using binoculars with two ceilometers. The migration traffic rate is given in birds/mile of front/hour.

a high pressure area. The lowest traffic rates occurred when cold or stationary fronts were nearby or after the passage of a low pressure area. The spring ceilometer data confirms Able's (1973) statement that the heaviest spring movements take place in warm southerly air flows on the west side of a high pressure area. However, reasonably good migration was also observed when the center of a high pressure area was in the Sandusky area.

Average Traffic Rate

The average migration traffic rate for 12 nights with clear skies at NASA-Plum Brook was 5,383 birds/mile of front/hr during spring and fall ceilometer surveys. This figure is slightly lower than the 6,800 birds/mile of front/hr average for the same time of the night reported by Lowery and Newman (1966) for 235 moon-watching survey locations throughout the United States on four nights in October. They also found that migration traffic rates for the Gulf Coast states were higher than the U.S. average, while traffic rates for the western U.S. were considerably lower (Newman and Lowery, 1964). For comparison, eight reporting stations in Ohio averaged 1,275 birds/mile of front/hr in counts from 2200-2300 DST during the three day period of October 2-4, 1952, by using the moon-watching technique.

Direction of Migration

Only general trends have been drawn from the summaries of migration direction data calculated from fall 1976 (Table 3.5) and spring 1977 (Table 3.6) observations of individual birds flying through the ceilometer beam. For example, resultant directions of migration during the fall for data obtained with binoculars were primarily (six nights) between 137 degrees (SE) and 234 degrees (SW), with only two nights when the birds were headed west-northwest or west. On both of the two nights, September 25 and October 11, when the nocturnal migration was in an inappropriate direction for autumn, the winds were also blowing respectively toward the west and northwest.

TABLE 3.5. DIRECTION OF MIGRATION DETERMINED FROM CEILOMETER SURVEYS OF NIGHT-MIGRATING BIRDS, FALL 1976

	Directional Data for September								Directional Data for October			
	21	22	24	25	27	28	29	30	7	8	11	12
							10 x 50 Binoculars Plus Ceilometers					
Resultant Direction (in degrees)	137.2	139.5	233.3	300.7	176.25	200.3	Only one bird observed	206.1	No birds observed	Only one bird observed	278.6	No birds observed
Length of Resultant Vector	.5920	.5610	.6168	.6678	.9978	.6560	--	.6207	--	--	.1651	--
Angular Dispersion (in degrees)	58.67	61.60	56.31	51.47	8.90	51.61	--	55.93	--	--	108.77	--
							Night Vision Scope Plus Ceilometers					
Resultant Direction (in degrees)	Scope not used	Scope not used	249.5	Only one bird observed	208.4	168.2	228.75	201.7	195.2	177.5	334.8	23.0
Length of Resultant Vector	--	--	.8378	--	.9374	.3805	.6593	.4989	.7790	.7517	.8472	.9504
Angular Dispersion (in degrees)	--	--	34.06	--	20.67	79.70	52.33	67.56	40.49	43.26	33.02	18.35

TABLE 3.6. DIRECTION OF MIGRATION DETERMINED FROM CEILOMETER SURVEYS OF NIGHT-MIGRATING BIRDS, SPRING 1977

	Directional Data for April			Directional Data for May									
	20	21	26	1	2	3	4	5	9	10	11	12	13
					10 x 50 Binoculars Plus Ceilometers								
Resultant Direction (in degrees)	62.58	No Birds Observed	35.43	7.5	No Birds Observed	292.5	9.7	33.13	No Birds Observed	3.87	10.90	67.96	63.78
Length of Resultant Vector	.8548		.8904	.9914		Only One Bird Observed	.5014	.8524		.8753	.8081	.9213	.7754
Angular Dispersion (in degrees)	30.07		27.66	7.7			67.36	32.43		29.60	37.41	23.24	40.91
					Night Vision Scope Plus Ceilometers								
Resultant Direction (in degrees)	30.0	76.86	61.05	19.03	270.0	285.0	256.92	34.21	277.5	51.37	11.26	71.26	68.85
Length of Resultant Vector	.6159	.9898	.7182	.6318	Only One Bird Observed	.9492	.5487	.9355	.1305	.8183	.7686	.9104	.8619
Angular Dispersion (in degrees)	56.40	8.12	46.64	54.89		18.54	62.75	20.84	115.74	36.32	41.53	24.88	31.22

All of the nine nights when more than one bird was observed in the ceilometer beam during the spring had resultant directions of migration between 7 degrees (N) and 68 degrees (ENE). In fact, six of the nine nights had resultant directions of migration between 7 degrees (N) and 36 degrees (NE). Two of the three nights when migration was to the east-northeast were nights when the winds blew predominantly in the same direction.

The direction of the heaviest fall migrations were to the south and southwest, while the heaviest spring migrations were oriented to the northeast and east-northeast. These primary directions of migration are in agreement with radar studies in eastern Canada for fall (Richardson, 1972a) and spring (Richardson, 1971). Richardson noted that this orientation corresponds to the NE-SW alignment of the eastern North America coastline.

On 19 of the 23 nights when ceilometer surveys were made with both binoculars and night vision scope, approximately twice as many birds were seen with the night vision scope (Tables 3.3 and 3.4). On five of these nights (September 27 and 28, October 11, April 26, and May 10) there was greater than a 25 degree difference in the resultant direction calculated for each of the two observation instruments (Tables 3.4 and 3.6). On these five nights, it appeared that some of the high-flying birds seen through the night vision scope were flying in a slightly different direction from the lower-flying birds observed with binoculars. Although winds aloft were not measured, it is highly possible that the different resultant directions were due to different wind directions at different altitudes.

Radar Surveys

Radar surveys were made at the en route radar facility in Oberlin, Ohio, on 14 nights each during the fall 1976 and spring 1977 songbird migration seasons. Although broadband radar from four locations arrives via micro-wave link, only the radar at Brecksville (near Cleveland, Ohio) consistantly maintained circuitry appropriate for viewing both heavy and light bird migration. For example, sensitivity time control (STC) circuitry was frequently used on the other radars, which markedly reduces the number of birds visible near the center of the radar display (Richardson, 1972b; Gauthreaux, 1975).

Polaroid, time-exposure photographs of the radar's plan position indicator (PPI) display, such as those shown in Figures 3.2-3.5, were taken on each of the 28 spring and fall survey nights. Photos were made at exposures of both one revolution and 10 revolutions in order to differentiate between rain clouds (Figure 3.2) and heavy songbird migration (Figure 3.3). The thin white streaks showing in the 10-revolution exposures were helpful in determining the direction of migration on nights when birds at different altitudes were flying in different directions (Figure 3.4) or in a direction inappropriate for the season (Figure 3.5). Normally, the photographs were taken with a radar display of 25 nautical miles. However, if the songbird migration appeared to be moderate or heavy, additional photos were taken at greater radar ranges (50 or 100 nm) in order to determine the maximum range that bird echoes were visible on the radar (Figure 3.3).

Although the capabilities of some radars, such as the weather service radars (WSR-57), have been studied sufficiently by ornithologists to permit rapid quantification of bird migration (Gauthreaux, 1970), methods for quantifying bird migration using the ARSR-2 radar are limited to one relatively inaccurate and time-consuming technique described by Nisbet (1963). This method requires counting the radar "angels" in each of several concentric rings and mutiplying that number by an empirical factor which depends on range. Extremely dense migrations can not be estimated by this method. It was desireable, therefore, to develop a more rapid migration quantification technique for this study, since nights with overcast skies did not permit the collection of reliable direct visual (ceilometer) data for computing the migration traffic rate. Use of the following ARSR-2 bird migration quantification method permits the selection of an approximate value for the migration traffic rate when radar photos are the only reliable record of a night's migration available.

In order to quantify bird migration with the ARSR-2, the first step was to compare statistically the data from ceilometer studies and

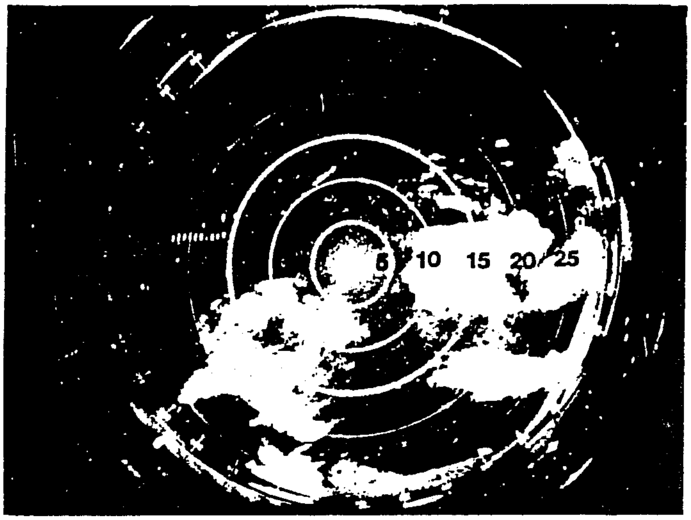

FIGURE 3.2. RADAR PHOTO OF A NIGHT WITH ALMOST NO SONGBIRD MIGRATION DUE TO RAIN AND A STATIONARY FRONT. LARGE WHITE AREAS AT 90, 120, AND 230 DEGREES ARE RAIN CLOUDS. (26 SEPT. 76; 23:30 EDT; MTI ON; 25 nm RANGE; 5 nm RANGE MARKERS; EXPOSURE OF 10 REVOLUTIONS; ARSR-2, BRECKSVILLE, OHIO).

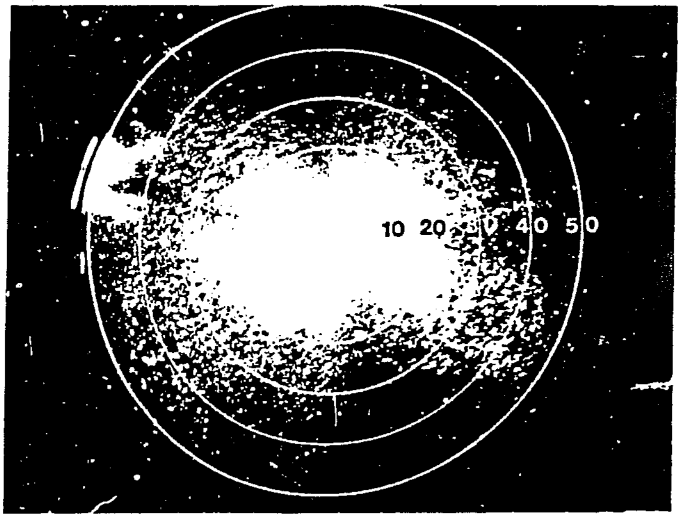

FIGURE 3.3. RADAR PHOTO OF THE NIGHT OF HEAVIEST SONGBIRD MIGRATION OBSERVED IN THIS STUDY. MIGRATION TRAFFIC RATE DETERMINED BY CEILOMETER SURVEY WAS 17,000 BIRDS/MI. FRONT/HR. (6 MAY 77; 0:33 EDT; MTI ON; 50 nm RANGE; 10 nm RANGE MARKERS; EXPOSURE OF 10 REVOLUTIONS; ARSR-2 RADAR; BRECKSVILLE, OHIO).

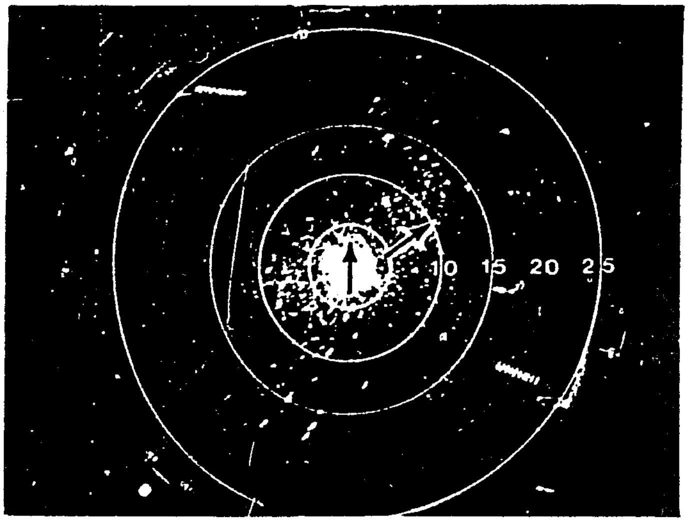

FIGURE 3.4. RADAR PHOTO OF A NIGHT WITH DIFFERENT SONGBIRD MIGRATION DIRECTIONS AT DIFFERENT ALTITUDES. CEILOMETER SURVEYS SHOWED RESULTANT MIGRATION DIRECTIONS AS FOLLOWS: (1) LOW-LEVEL (WITH BINOCULARS) +3.87 DEGREES (2) HIGH-LEVEL (WITH NIGHT VISION SCOPE) +51.37. (11 MAY 77; 00:36 EDT; MTI ON; 25 nm RANGE; 5 nm RANGE MARKERS; EXPOSURE OF 10 REVOLUTIONS: ARSR-2 RADAR; BRECKSVILLE, OHIO).

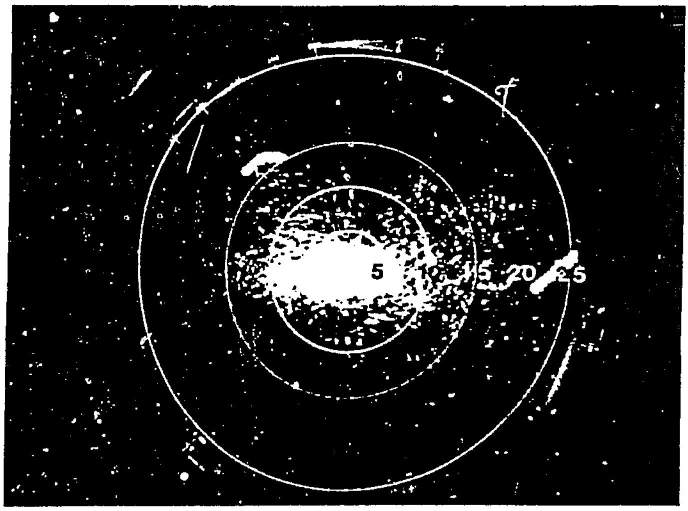

FIGURE 3.5. RADAR PHOTO OF EASTERLY SONGBIRD MIGRATION DURING THE SPRING WITH FOLLOWING SURFACE WINDS OF 9-12 MPH (4.1-5.4 m/s) (14 MAY 77; 00:17 EDT; MTI ON; 25 nm RANGE; 5 nm RANGE MARKERS: EXPOSURE OF 10 REVOLUTIONS: ARSR-2 RADAR: BRECKSVILLE, OHIO).

radar studies on the 12 nights during this study when clear skies prevailed (Table 3.7). These data were used in a linear regression analysis which calculated the values of "a" (-2203.1) and "b" (313.9) in the equation Y = A + B X.

The same computer program that ran the regression also produced a plot of the raw data points, the fitted regression line, and two curves representing the bounds of a 95 percent confidence band for the line (Figure 3.6). For any given value of X (range of radar echoes), the confidence band gives the lower and upper bounds of an interval which contains the true average traffic rate with 95 percent probability. These bounds are listed in Table 3.8, and contain the <u>average</u> traffic rate, which is the value that would result if many observers with ceilometers simultaneously took readings at different locations within some area. The average of mean value of these readings results in a more accurate value than if just one reading were taken, since the averaging process "smooths out" variability present among the individual points observed. Therefore, individual data points in Figure 3.5 may fall outside the confidence band, but the true average traffic rates associated with given radar echo ranges should fall within the confidence band with 95 percent probability.

Using the migration traffic rate ranges in Table 3.8, it is possible to determine the migration traffic rate range for every night photographs were taken of the ARSR-2 radar at Brecksville (Table 3.9). This table gives the approximate migration traffic rate for both clear and overcast nights.

Grounded Migrant Surveys

Although it is recognized that daytime surveys of night-migrating birds are <u>not</u> good indicators of nocturnal migration volume, (Able, 1973) the summaries of daytime observations of grounded nocturnal migrants (Appendix C, Tables C-1 and C-2) do show the groups of birds which were probably migrating at low levels on the nights of radar and ceilometer surveys. Since only birds known to be low-level nocturnal migrants were included in the summary table, it is likely that many of

TABLE 3.7. CEILOMETER TRAFFIC RATES COMPARED TO RANGE OF BIRD ECHOES ON RADAR

Date[a] (Clear Nights Only)	Ceilometer Traffic Rate[b]	Greatest Range of Bird Echoes on Radar[c]
September 1976		
22	3,400	25 nm
24	3,700	25 nm
27	2,300	20 nm
28	6,900	30 nm
30	3,700	15 nm
October 1976		
11	4,100	15 nm
April 1977		
26	2,300	20 nm
May 1977		
5	17,000	60 nm
9	0	10 nm
10	3,700	20 nm
11	9,700	30 nm
12	7,800	25 nm

(a) Data from nights with more than 9 percent cloud cover, fog, or rain were not included in this table due to the inaccuracy of ceilometer survey data on those nights with poor visibility. Ceilometer surveys were made about 65 air-miles (120.5 air-km) from the radar site.

(b) Given in birds/mile of front/hour.

(c) "nm" means nautical miles on the plan position indicator (PPI) of an ARSR-2 radar. These ranges were determined from time-exposure, polaroid photographs of the Brecksville, Ohio radar display.

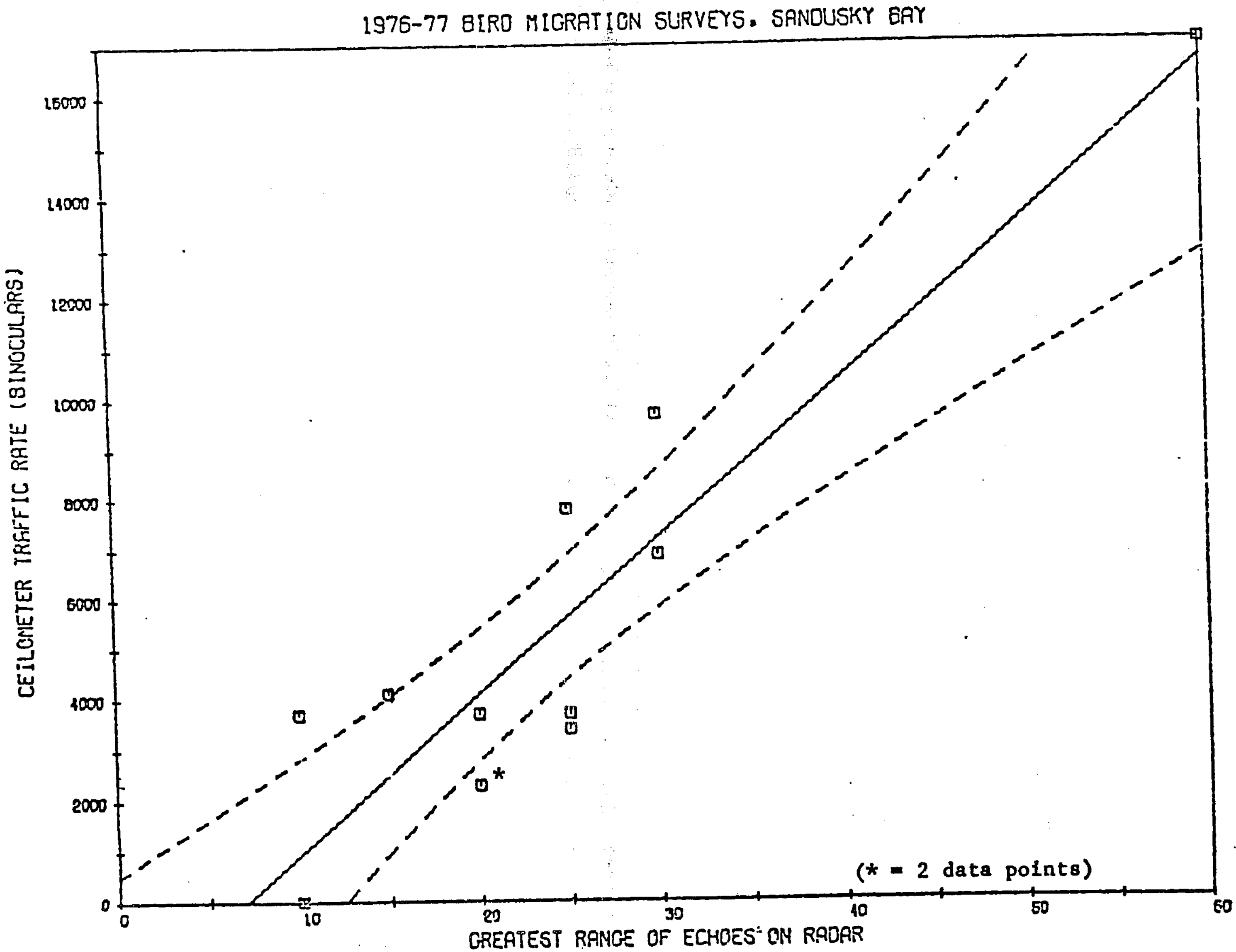

FIGURE 3.6. RAW DATA POINTS, FITTED REGRESSION LINE, AND CONFIDENCE BAND FOR RADAR RANGE VS. CEILOMETER TRAFFIC RATE ON 12 NIGHTS DURING THE FALL 1976 AND SPRING 1977 SONGBIRD MIGRATION SEASONS.

TABLE 3.8. MIGRATION QUANTIFICATION DATA FOR ARSR-2 RADAR

Greatest Range of Bird Echoes on Radar (in nautical miles)	Range of Migration Traffic Rates in Birds/Mile of Front/Hour (Calculated from Graph)[a]
5	0 - 1,600
10	0 - 2,800
15	900 - 4,000
20	2,800 - 5,200
25	4,400 - 6,900
30	5,800 - 8,600
35	7,100 - 10,400
40	8,200 - 12,500
45	9,300 - 14,400
50	10,400 - 16,500
55	11,600 - 18,600
60	12,700 - 20,700

(a)Graph with regression line and confidence band are shown in Figure 3.6.

TABLE 3.9. MIGRATION TRAFFIC RATES COMPUTED FROM RADAR PHOTOS[(a)]

Date During Fall 1976	Range of Migration Traffic Rates	Date During Spring 1977	Range of Migration Traffic Rates
<u>Sept</u>		<u>April</u>	
21	4,400 - 6,900	20	8,200 - 12,500
22	4,400 - 6,900	21	2,800 - 5,200
23	4,400 - 6,900	25	0 - 2,800
24	4,400 - 6,900	26	2,800 - 5,200
25	0 - 1,600	<u>May</u>	
26	0 - 1,600	1	2,800 - 5,200
27	2,800 - 5,200	2	0 - 1,600
28	5,800 - 8,600	3	0 - 2,800
29	0 - 2,800	4	4,400 - 6,900
30	0 - 1,600	5	12,700 - 20,700
<u>Oct</u>		9	0 - 2,800
7	900 - 4,000	10	2,800 - 5,200
8	900 - 4,000	11	5,800 - 8,600
11	0 - 2,800	12	4,400 - 6,900
12	4,400 - 6,900	13	7,100 - 10,400

(a) Traffic rate ranges were determined using the data in Table 3.8 derived from the confidence bands in Figure 3.6.

them had migrated, or would continue to migrate, at night by flying on one of the nights (without rain) preceeding or following their enumeration during a daytime survey. Obviously, in a few groups of nocturnal migrants counted during the spring, the individuals counted may have been locally breeding species that were already on territory and not recent migrants. It is highly probably, however, that the species which were not recorded on one day, but were extremely numerous the next day must have arrived during the intervening night.

During the fall survey period, the highest migration traffic rates occurred on September 23 and 28 (Table 3.3). Judging from the groups of nocturnal migrants observed during the day within two days on either side of these dates (Appendix C, Table C-1), the migrants involved were probably as follows: (1) The night of September 23 probably involved the migration of kinglets, vireos, warblers, and sparrows; and (2) the night of September 28 probably involved the migration of thrushes, kinglets, warblers, finches, and sparrows.

The highest migration traffic rates during spring surveys were on May 4, 5, 11, 12, and 13 (Table 3.4). Groups of nocturnal migrants (Appendix C, Table C-2) which were probably flying on those nights are as follows: (1) The nights of May 4 and 5 probably involved the migration of flycatchers, mimics, thrushes, kinglets, and many species of warblers and sparrows; and (2) The nights of May 11 and 12 probably involved the migration of flycatchers, mimics, thrushes, vireos, warblers, orioles, and sparrows.

Searches for Tower Killed Birds

Only one bird, a female blackburnian warbler (_Dendroica_ _fusca_) was found dead during the spring and fall 1975 searches (71 days) for tower-killed birds. This warbler was collected near the base of the meteorological tower on May 27. This species is considered a common transient, but not a breeding species, in north-central Ohio (Campbell, 1968; Trautman and Trautman, 1968). However, the WTG was not operational at night during these two seasons. Therefore data from these two migratory seasons are included as baseline (pre-operational) data for comparison with data obtained when the WTG was operating at night.

Only two birds were found dead near the WTG or meteorological tower during the fall of 1975 and the spring of 1976, but neither bird is considered a nocturnal migrant. A starling (*Sturnus vulgaris*) was found at the base of the WTG on May 16, 1977 and a common grackle (*Quiscalus quiscula*) was found on May 22, 1977, in a driveway about 55 yards (50.2 m) from the meteorological tower.

The absense of tower-killed nocturnal migrants at the WTG may not be representative of the maximum potential kill, however, because the WTG was only operational for a fraction of the nighttime hours during each migratory season. During the fall of 1976 the WTG was operating at 20 rpm for the first 3 hours of darkness on each of six nights (approximately 18 of 550 nighttime hours from September 1 through October 25). In the spring of 1977 the WTG was operating at 20 rpm during the late evening and/or early morning hours of darkness on five days in late April and 14 days in May. The 14 late evening (beginning about 0.5 hour after sunset) and 10 early morning (ending about 0.5 hour before sunrise) periods of operation were each 4 hours in length, for a total of 96 hours of nighttime operation out of approximately 610 hours of darkness during the April and May songbird migration season.

In review, it is apparent that the WTG is not particularly lethal to low-level, night-migrating birds, even on nights of heavy migration for the Sandusky area. Only one nocturnal migrant was found dead, and that was at the base of the meteorological tower prior to operation of the wind turbine at night. Admittedly, major kills only occur at some towers in intervals of several years (Stoddard and Norris, 1967), and the total hours of nighttime operation of the WTG were only 114. However, the combined conditions of foggy weather due to a low cloud ceiling, favoring winds for migration, and substantial nocturnal migration, a combination usually associated with mass mortality (Stoddard and Norris, 1967; Johnston and Haines, 1954; Howell et al., 1954; Avery et al., 1977), were experienced on May 4, 1977. On this night, the WTG was operating for 4 hours at night and the estimated migration traffic rate was in excess of 7,800 birds/mile of front/hr. (This was undoubtedly an underestimate due to the fog partially obscuring birds flying through the ceilometer beam.) In spite of these conditions appropriate for a mass bird kill, no birds were observed striking the WTG during the first 45 minutes of darkness (using the night vision scope), and no birds were found dead at the base of the WTG during the early morning searches.

Scavenger Studies

Although the first two seasons of searching for tower-killed birds indicated that the number of dead birds (only one migratory bird was found) was too low to attract scavengers on a regular basis, a minimum effort was made to determine the percent loss of tower-killed birds due to scavenger removal during the night. During the three nights of study, only two bird carcasses were removed by scavengers out of a potential 42 "carcass nights" of exposure (Table 3.10). This indicates that less than 5 percent of the tower-killed birds at NASA-Plum Brook are removed by scavengers during the night and therefore are not available for recording by early-morning search crews. The 5 percent scavenger removal rate is considerably lower than the 80-90 percent removal rate reported by Crawford (1971) at a TV tower in Florida or the 58 percent removal rate determined by Vessey et al., (ND) at a nuclear power plant and its cooling tower located near Port Clinton, Ohio.

The major reason for the difference in scavenger removal rates between studies is probably due to the magnitude of the tower-kills normally occurring at each site. Only one nocturnal migrant was collected during four migratory seasons under the meteorological tower or WTG tower in this study. Stoddard and Norris (1967), however, collected an annual average of 2,700 birds over an 11-year period at a TV tower in Florida. Similarly, Vessey et al. (ND) collected 157 birds during three migratory seasons of searching around a nuclear power plant and its cooling tower. Understandably, scavengers are attracted to an area which consistantly provides tower-killed birds; a situation which does not occur at the WTG or meteorological towers.

TABLE 3.10. SCAVENGER SURVEYS AT WTG AND METEOROLOGICAL TOWERS

	Number of Bird Carcasses					
	September 21-22, 1976		September 22-23, 1976		May 12-13, 1977	
	Tagged(a)	Eaten(b)	Tagged(a)	Eaten(b)	Tagged(a)	Eaten(b)
WTG Tower	10	2	8	0	10	0
Met Tower	7	0	7	0	--	--

(a) Tower-kills from another site and dead starlings were placed on the ground with a numbered tag and their location was marked on a map.

(b) Majority of the carcass eaten or removed by scavengers.

Avoidance Behavior Observations

Twenty-seven birds were observed shortly after dark flying near the WTG operating at 20 rpm (Table 3.11). Of these nocturnal migrants, 18 were flying parallel to the plane of the blades and therefore in little danger of impact with the WTG. Nine birds, however, were flying perpendicular or oblique to the plane of the blades and thus in imminent danger of being hit by or running into the blades. Two-thirds of the latter birds (six individuals) appeared to take evasive action and missed the revolving blades. The remaining three birds flew in between the blades without changing course and without a collision. Whether the birds changing course saw and/or heard the WTG is not known, but it was fairly obvious that some birds did perceive the presence of the WTG in time to take evasive action.

TABLE 3.11. STUDY OF NIGHT-MIGRATING BIRD INTERACTIONS WITH THE EXPERIMENTAL WIND TURBINE[a]

Birds Flying Parallel To Plane of Blades		Birds Flying Perpendicular or Oblique to Plane of Blades	
Flight Altered	Flight Not Altered	Flight Altered	Flight Not Altered
1	17	6	3

(a) Dates when night vision scope observations were made of the WTG operating at 20 rpm are as follows: April 20, 21, 26, and May 3, 4, 5, and 13.

IV. AERIAL ARTHROPODS

INTRODUCTION

Insects and other small invertebrates populate the air above both land and water habitats. While there are no known studies of distribution on arthropods relative to wind turbines, published literature permits the synthesis of a general profile of aerial distribution (Glick, 1931; Hardy and Milne, 1938; Freeman, 1945; Johnson, 1969). Briefly, this vertical profile shows that aerial arthropods have been collected thousands of feet above the ground but that the majority of these organisms are within 80 ft (30 m) of the ground. For example, numerous articles refer particularly to aphids (Shands et al., 1965; Kring, 1972) which are a conspicuous insect group in the air; these articles indicate that 50 percent of the aphids may be within several feet of the ground. Thus, a considerable portion of aerial insects would probably be located within and below an altered wind stream tube created by a wind turbine.

Wind turbines could affect aerial arthropods. The movement of the organisms could be obstructed by the towers. Also, they could be impacted by the moving blades. Such effects may be especially noticeable during swarms of bees, migrations of such insects as locusts or butterflies, and concentration of insects by deposition after storms. However, such effects are conjectural.

Field tests were conducted and literature summaries were developed to quantitatively assess the potential affect of a wind turbine on aerial arthropods. This chapter explains the approach taken, the results obtained, and discusses the general patterns of aerial arthropods relative to wind turbines.

MATERIALS AND METHODS

Three interrelated activities were conducted for the assessment of the possible affect of wind turbines on aerial arthropods. These activities were as follows: (1) samples of insects were collected and analyzed from foliage near the wind turbine, (2) pertinent literature on aerial arthropods was summarized, and (3) experimental releases of three species of insects were conducted in front of an operating wind turbine.

To determine what insect types to use in the experimental release, active insects close to the wind turbine were sampled with a 15 inch (38 cm) aerial sweep net in mid-August 1975. Six samples were taken in the various habitats adjacent to the WTG site, three in the managed grasslands, one on the bank of Plum Brook, one in emergent/shoreline vegetation adjacent to the reservoir, and one in the infrequently mowed grasslands adjacent to the wind turbine. Each sample consisted of 100 sweeps except for the sample along the reservoir edge which had 50 sweeps. The adult insects from each sample were sorted to taxonomic groups, except for wingless forms which were discarded; aerial arthropods other than insects, such as spiders, were also excluded. The number of insects captured per sweep was calculated.

Published literature about aerial arthropods was obtained and summarized for general patterns of vertical distribution, migration, and other flight characteristics relative to temperature, time of day, and other environmental conditions.

Three species of insects were used in the experimental releases. They were ladybird beetles (Hippodamia convergens), blow flies (Sarcophaga sp.), and honey bees (Apis mellifera). Specimens were obtained from Bio-Control Company, Auburn, California (ladybird beetles), Carolina Biological Supply Company, Burlington, North Carolina (blow flies), and N. C. Berry and Sons Company, Montgomery, Alabama (honey bees). The honey bees and ladybird beetles were obtained as adults while the blow flies were obtained as pupae and were allowed to emerge in time for the experimental release. The bees and flies were fed maintenance diets of sugar water or sugar cubes and water until time of release.

Each batch of insects was released from a carriage that was raised and lowered with the use of large outdoor weather balloons (Figure 4.1). The release carriage consisted of a plywood box, 11 x 11 x 6 inches (28 x 28 x 15 cm), which was cut into halves; one side was secured with hinges and equipped with spring-loaded coils so that the box would open automatically when the latching mechanism was released. The hinged end

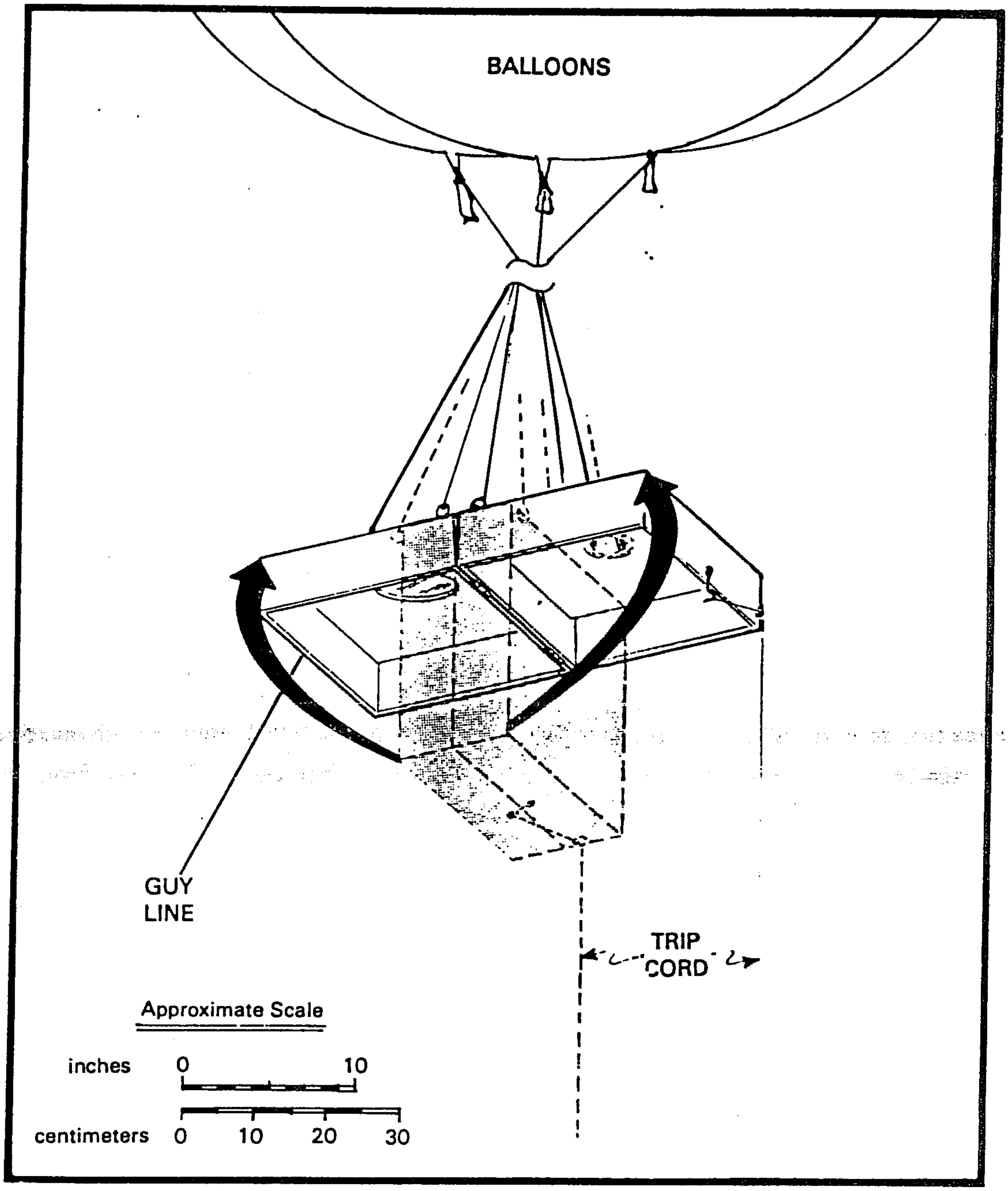

FIGURE 4.1. INSECT RELEASE CARRIAGE ILLUSTRATING RELEASE MECHANISM, SUSPENSION LINES TO BALLOONS, AND OTHER LINES TO FACILITATE THE MID-AIR RELEASE OF INSECTS.

of the box was attached by ropes to the balloons; a guy line and trip cord extended from the release carriage to the ground where each was held by a person. Thus, the insects could be released when the desired height above the ground and distance from the wind turbine were obtained. Upon tripping the latch, the suspended box would open instantaneously, releasing the insects into mid-air. Insects, held in 1 gal jars (3.7 ℓ), were placed into the box through a cloth sleeve attached to a 3 inch (7.5 cm) diameter hole on one side of the box. The sleeve was tied off after loading the insects. A 5 inch (12.5 cm) diameter hole covered with acetate was located on the opposite side of the box; this served as an observation port. The empty carriage weighed approximately 2-7/8 lb (1.3 kg); the carriage plus attached ropes weighed approximately 4-3/4 lb (2.2 kg). Three weather balloons were needed to lift the insects and carriage mechanism to the desired height. The balloons, two with a 5.5 ft (1.68 m) diameter and one with a 4.0 ft (1.22 m) diameter were filled with helium and tethered together. The balloons and carriage, Battelle scientists, and wind turbine are shown in Figure 4.2.

The insect release experiment was conducted on 27 June 1977 between approximately 1500 and 1740 EDT at the NASA/ERDA 100 kW Experimental Wind Turbine while it was in operation. Wind speeds ranged from 6-11 mph (2.7-4.5 m/s) from a northeasterly direction. Air temperatures ranged from 75-80 F (24-27 C). Twelve releases of insects were made at heights of approximately 60-80 ft (18.3-24.4 m) and approximately 60-80 ft (18.3-24.4 m) upwind from the plane of rotation of the wind turbine. The experiment consisted of four releases each of ladybird beetles, blow flies, and bees. There were an estimated 8,000-9,000 beetles, 200-300 blow flies, and 3,000-4,000 bees per release for a total of 12 releases and about 50,000 individuals. Each release was recorded by 16 mm motion picture cameras with supplementary still photographs. Later, the film record was carefully scrutinized for movement patterns of each species. After the final release, a 70 x 70 ft (21.3 x 21.3 m) area under the wind turbine was searched in transects and the number of indivduals of each of the released species was recorded.

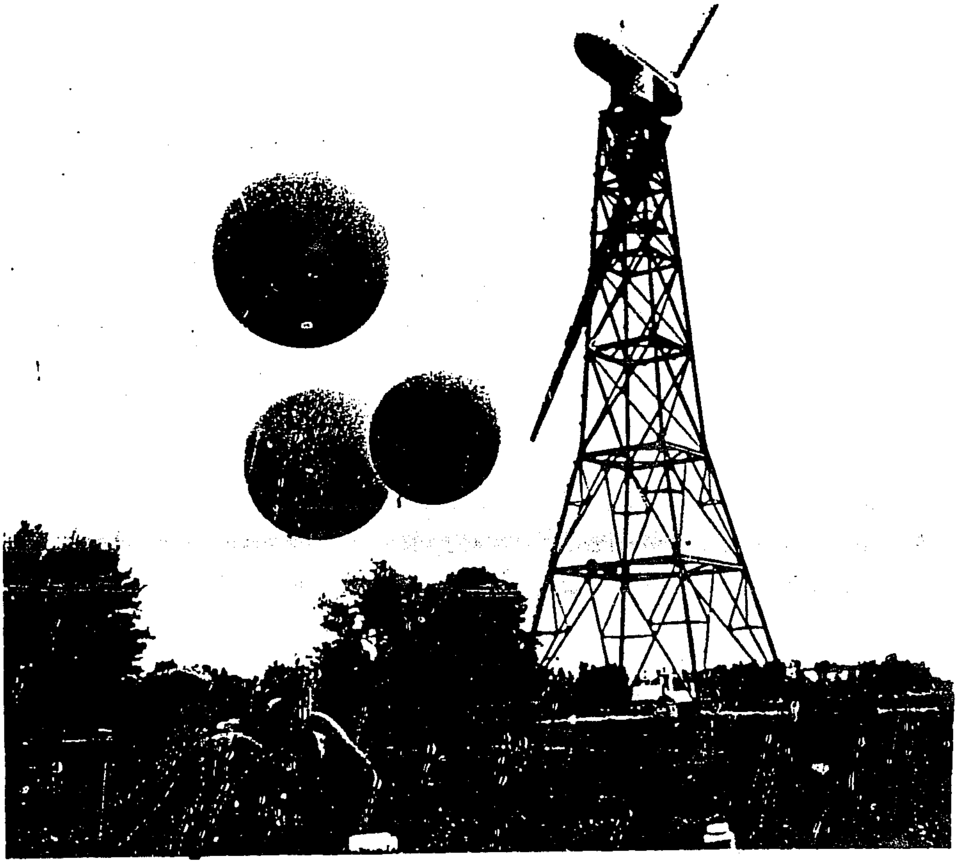

FIGURE 4.2. HONEY BEES BEING LOADED BY BATTELLE SCIENTISTS (WEARING PROTECTIVE CLOTHING) INTO INSECT CARRIAGE FOR RELEASE AT APPROXIMATELY 80 FT (24 M) ABOVE THE GROUND DIRECTLY UPWIND FROM THE WIND TURBINE. NOTE THE BALLOONS REQUIRED TO LIFT THE CARRIAGE AND INSECTS TO THE DESIRED HEIGHT.

RESULTS

Sweep Samples

The six sweep samples showed that at least nine major insect groups (orders) were found in vegetation communities around the wind turbine. The most common orders were flies (Diptera) and hoppers (Homoptera); they represented 40 and 29 percent, respectively, of the total 374 individuals collected (Figure 4.3). Of the remaining 31 percent, beetles (Coleoptera) and bees, ants, and wasps (Hymenoptera) comprised 6 and 5 percent, respectively. Finally, crickets and grasshopeers (Orthoptera), butterflies and moths (Lepidoptera), caddis flies (Trichoptera) and dragon flies (Odonata) comprised a total of 20 percent of the captures.

The number of species varied from 20 near the stream bank to 46 in the mowed grass (Appendix D, Table D-1). The number of individuals varied from 28 to 112. The number of individuals per sweep sample varied from 0.28 individuals to 1.13. These differences reflect differing environmental conditions such as food and cover in vegetation. Midges were the most abundant insect and were found in all sweep samples. Tree crickets, froghoppers, leafhoppers, and leaf beetles were also common.

Most of the insects were plant-eaters (herbivores). Some froghoppers and leafhoppers feed on clover, alfalfa, strawberries, apples, potatoes, and sugarbeets and can be economic pests (Borror and DeLong, 1971; Metcalf et al., 1962). Grasshoppers and crickets were found in nearly all herbaceous communities; tree crickets may be encountered in trees, shrubs, and weeds. Tree crickets lay their eggs in bark and stems which can result in damage to the trees (Borror and DeLong, 1971); adults may become pests by eating holes in ripe fruit (Metcalf et al., 1962).

Other Observations

Several other observations of arthropods/wind turbine interactions have been made. A swarm of honey bees landed on the SW leg of the tower in the spring of 1976; the swarm attached to a place about 10 ft (3 m) above the ground and was removed by extermination (pers. comm.,

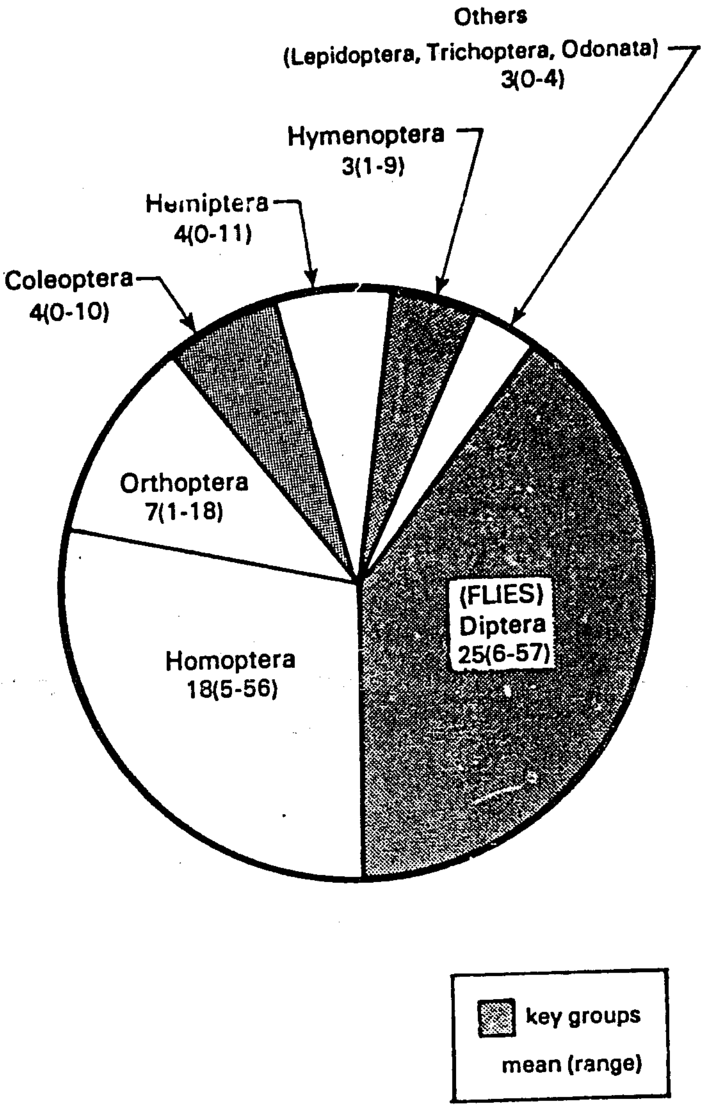

FIGURE 4.3. DIAGRAM OF RELATIVE PROPORTIONS (PERCENT) OF INSECTS COLLECTED IN FOLIAGE NEAR THE WIND TURBINE. NUMBERS IN SECTORS ARE MEAN NUMBERS OF INDIVIDUALS FOR EACH SAMPLE; RANGE OF THE SIX SAMPLES IS PROVIDED IN PARENTHESES.

R. Rogers, June 27, 1977, Experimental Wind Turbine at NASA-Plum Brook). Also, a butterfly was observed passing through the disk of the operating WTG near the hub, about 100 ft (30 m) above the ground on August 5, 1977, (pers. comm., S. Rogers, August 8, 1977, Battelle). The butterfly seemed to be lifted 2 to 3 ft (1 m) each time a WTG blade passed behind it. The butterfly continued on its path apparently unharmed and undetered by the passage.

Experimental Releases

Individual insects from all 12 releases dispersed downward and toward the wind turbine; some individuals seemed to move into and through the disk of the wind turbine, although this was difficult to document because of the small size of the insects. Figure 4.4 provides a graphic synthesis of the four releases for each species. Further information on wind speed, temperature, and wind direction is available (Appendix D, Table D-2). Ladybird beetles tended to fall from the opened release carriage and within a few seconds some landed on the ground in small clumps. Other individuals took wing, but the overall vector of dispersal was downward. By way of contrast, many honey bees remained flying in the air after their release and were moved by the wind toward the wind turbine. Some bees even hovered around the release carriage (there was no queen present to attract them) and accompanied the carriage as it was pulled back to the ground for the next loading. Blow flies were intermediate in the principal vector of their dispersal (Figure 4.4); this organism tended to fly more randomly in several directions than did the other two species.

Counts of released species were made at completion of the 12 releases on the gravelly area under the wind turbine. Tens of individuals of all three species were observed. Any organisms killed by the rotating wind turbine were minimal in number.

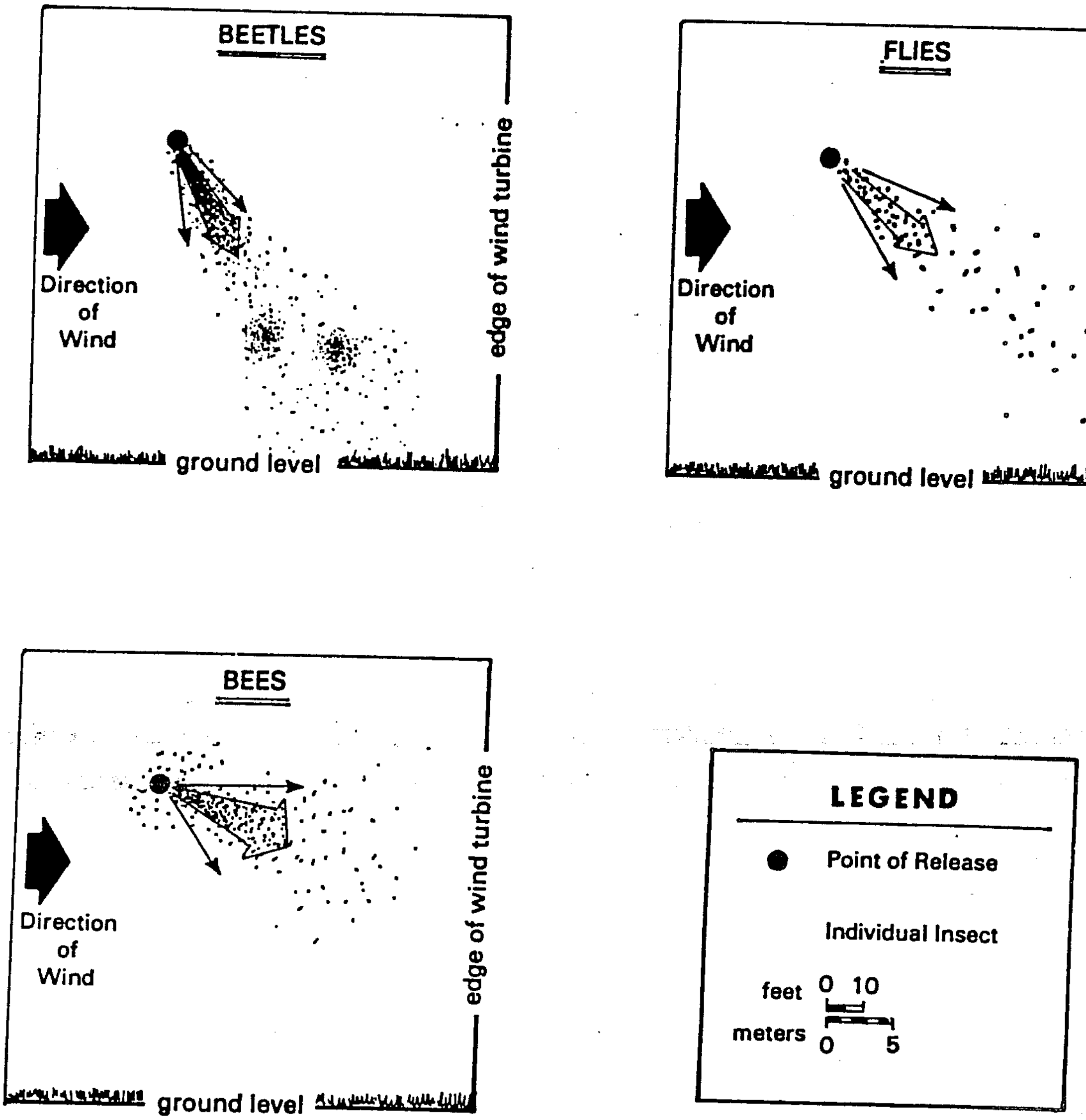

FIGURE 4.4. GENERAL DISPERSAL PATTERNS OF THREE SPECIES OF COMMERCIALLY AVAILABLE INSECTS THAT WERE EXPERIMENTALLY RELEASED IN FRONT OF A WIND TURBINE.

DISCUSSION

The absolute distribution and abundance of aerial arthropods differs seasonally, daily, and indeed from hour to hour. The complex interactions of wind turbulence, light, temperature, relative humidity, and other physical properties of air interact in different ways to maintain a fluctuating profile and movement pattern of arthropods. In temperate zones, the greatest population densities occur in the late spring and summer of the year and are small in the winter. Tropical profiles are usually a reflection of the dry/wet season cycle. The profile also changes on a daily basis. In Louisiana, densities were higher during the night than the day (Glick, 1939). In England, it was the reverse (Freeman, 1945; Taylor, 1960). Finally, another study reveals that some species are more active an hour after sunset and before sunrise (Butler, 1972).

The greatest recorded density seems to be about 400,000 insects per 10^6 ft^3 (2.0×10^7 ℓ) with a minimum density [altitude of 840 ft (304 m)] of about two insects per 10^6 ft^3 (2.8×10^7 ℓ) (Johnson, 1969). Extremely dense swarms are atypical and the general magnitude of aerial arthropods can be expressed in another way. It has been estimated that an average of 12,500,000 arthropods per hour passed through a rectangular area 250 ft (91.5 m) high by 4400 ft (1.6 km) wide. For the above study, Freeman (1945) used collecting devices fixed to a series of radio towers in a vegetation background similar to many in the temperate zones of the world. Freeman reported a maximum observed rate of 50,600,000 and a minimum of 457,900 insects per hour. Furthermore, 75 percent of the moving populations was below 80 ft (30 m). These general patterns are summarized in Figure 4.5. Thus, the majority of aerial arthropods will likely be found in the lower portion of the air stream around a wind turbine.

The number of insects in free flight is affected by climate, especially temperature and light. Temperature acts as the most important threshold; consequently, the amount of time per year at temperatures above the threshold has more effect than mean temperature on the size of the aerial population (Taylor, 1963; Lewis and Hurst, 1967). If all the

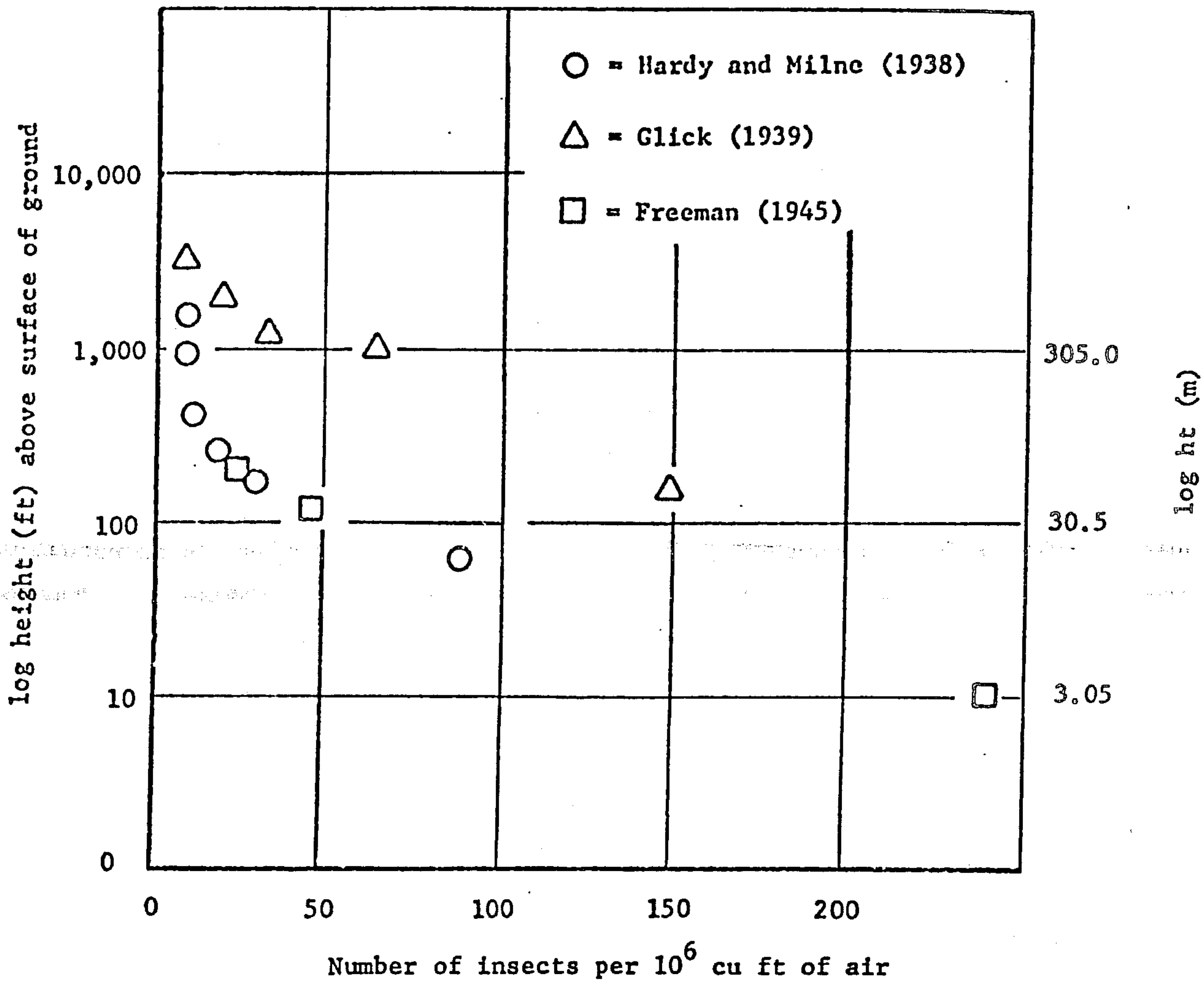

FIGURE 4.5. THE VERTICAL PROFILE OF ARTHROPODS DISTRIBUTED IN THE AIR SHOWS THAT THE MAJORITY ARE WITHIN A FEW FEET OF GROUND.

meteorological factors necessary for takeoff were known, we could predict the days when large migrations occur. Most mass flights occur in sunny, settled weather. Table 4.1 provides a view of the temperature thresholds for four species of insects. Most other insects probably fit within these ranges. For example, the temperature threshold of various species of thrips is about 49 F (19 C) (Lewis and Hurst, 1967).

Flying insects accumulate in the air leeward of artificial windbreaks. No known work is available for objects as high as wind turbines. However, upright, 45 percent permeable barriers create "sheltered" zones in which concentrations of insects occur (Lewis, 1967; Lewis and Dibley, 1970). They suggest that the accumulation level of small insects (body area <3 mm^2) would be determined by the way inert particles, drifting in an air stream, are affected by obstacles. It is expected that some insects will accumulate behind objects as high and as permeable as wind turbines and their towers.

Aerial insects tend to be small. It has been estimated that 84 percent of the flying population was no larger than fruit flies, Drosophila spp., or large aphids (wing span x body length is about 10-30 mm^2); and only 2 percent were larger than the common house fly (Johnson, 1969). Observations of large migrating butterflies or locusts bias the fact to the observer that the majority of aerial insects are small.

Migrations of populations occur when food sources are depleted and climate suitable for their existence changes for the worst. For example, over 15 orders of insects were observed flying in a southerly direction through one high elevation pass, 3,727 ft (1,136 m), in Venezuela (Beebe, 1949, 1951a,b; Beebe and Flemming, 1951). Such migrations through passes have been observed elsewhere (Urquhart, 1960; Williams, 1968). Locations of these migratory paths include tropical and temperate regions. As with bird migration, the dispersal of insects is positively related to the direction of prevailing wind-carry (Shade and Curtis, 1964; Meyer and Norris, 1973). It has been demonstrated in the review by Rainey (1976) that prior to migration, widely dispersed, airborne insects can be collected or brought together at the emergence of cold and warm fronts. The longer time the front remains stationary,

TABLE 4.1. TEMPERATURE THRESHOLDS FOR FLIGHT IN FOUR SPECIES OF INSECTS

Temperature (C)	Day Fliers				Night Fliers			
	Blackbean Aphid		Soldier Beetle		Moth sp. 1		Moth sp. 2	
	A	B	A	B	A	B	A	B
<1					4	0		
1-2					3	0	1	0
2-3					1	0	3	0
3-4					3	0	5	0
4-5					1	0	12	0
5-6					3	0	29	2
6-7			4	0	7	0	29	0
7-8	1	0	7	0	10	1	42	2
8-9			3	0	15	3	42	3
9-10	1	0	2	0	16	5	71	6
10-11	2	0	12	0	26	5	82	13
11-12	5	0	21	0	23	6	91	16
12-13	12	0	36	0	18	7 *	127	25
13-14	18	0	33	1	6	2	134	27 *
14-15	20	1	23	1	11	4	116	22
15-16	24	2	43	4	13	4	114	22
16-17	20	7	48	9	5	1	69	20
17-18	32	20	51	12	6	0	43	18
18-19	44	29	75	25 *	1	0	25	9
19-20	60	50	40	14			15	6
20-21	84	58	28	9			6	2
21-22	68	67 *	17	6			6	1
22-23	62	62	20	7				
23-24	45	44	22	8			1	0
24-25	29	28	18	5				
25-26	31	31	26	6				
26-27	37	37	17	1				
27-28	28	28	10	0				
28-29	27	27	3	0				
29-30	22	22	4	0				
30-31	23	19						
31-32	11	8	1	0				
32-33	10	8						
33-34	1	1						
34-35	1	1						
35-36	-	2						

A = No. of times the temperature occurred.

B = No. of times a catch occurred at this temperature.

* = Maximum number of insects observed relative to the temperature profile.

(from Taylor, 1963).

the greater the concentration of insects of the particular migratory species. Following the decay of storms, insects that had been involuntarily trapped aloft by the winds may be deposited over a limited area (Henson and Waggoner, 1965). Few specific relationships of fronts along Lake Erie and insect migration have been made. However, one of the observers of the Insect Migration Association cited a large wave of migrating monarch butterflies along the shore of Lake Erie just west of Cleveland, but they were too high in the air to adequately document (Urquhart, 1960).

The speed of migratory insects varies from 6.6 to 49 fps (2 to 15 m/s) (Table 4.2) and they travel with the wind. Monarchs tend to travel over bodies of water (lakes and rivers) during the daytime. They always seek suitable trees and shrubs for night-time resting. Little information exists about the speed of migratory insect waves or populations vs. the speed of the wind. However, insect flight probably diminishes when wind speed exceeds flight speed. For example, Freeman (1945) reported that number of species [heights 8 ft (3 m), 50 ft (54 m), and 230 ft (84.5 m)] rose in wind speeds up to about 25 fps (9 m/s) and then diminished. Flies were the only group well represented at the higher wind velocities. Table 4.2 supplies particulars about other migratory species of arthropods. In general, migrating dragon flies and butterflies will fly close to the ground and individuals will be separated by many feet. Locusts will exhibit swarm behavior and will be at many elevations. Local insect activity patterns such as swarms, heavy migration, and deposition may result in large numbers of insects in a particular location for some limited period of time.

This review and brief experimentation does not lead us to any conclusion of significant conflict between flying insect populations and wind turbines.

TABLE 4.2. SELECTED INFORMATION ON INSECT MIGRATIONS

Migrating Insect Species	General Characteristics						Source
	Location	Direction	Time	Height, ft (m)	Speed, fps (m/s)	Density	
Dragonfly, <u>Libellula quadrumaculata</u>	N. shore Lake Ontario	SSW to NNE	mid-June	13-20 (4-6)	23-49 (7-15)	Massive[a]	SI, CS-LP, 1975b; Dalton, 1975
Desert Locusts	Africa	E to WNW	August	328 (1 km or more)[b]	40-100% of wind speed	10^9	Rainey, 1976
Night-flying grasshopper <u>Aiolopus</u> <u>simulatrix</u>	Africa	—	January	1,478 (450)	—	3937^3 (1200^3)	Rainey, 1976
Snout butterfly <u>Libytheana</u> <u>bachmanii</u>	Texas	—	Sept.-Oct.	—	—	300/min/100 yd (91)	Williams, 1968
Painted lady butterfly <u>Vanessa</u> <u>cardui</u>	Western U.S.	S to NE	Spring	—	6.6-13 (2-4)	—	SI, CS-LP, 1975a; Dalton, 1975
Monarch butterfly <u>Danaus</u> <u>p.</u> <u>plexippus</u>	U.S. and Canada	To Mexico and S. California	Fall, 1973[c]	16 (5)[d]	16.4 (5)	Millions[e]	SI, CS-LP, 1975a; Urquhart, 1960
Spruce budworm <u>Choristoneura</u> <u>fumifera</u>	E. Canada	—	July (night)	1,180 (360)[f]	—	—	Rainey, 1976

[a] Newly emerged adults (SI, CS-LP, 1975b).
[b] Height is limited by daily thermal currents.
[c] One of greatest build-ups of its kind for the last 24 years (SI, CS-LP, 1975a).
[d] But soar over tall buildings, forests and through mountain passes of over 10,000 ft (3400 m) elevations (Urquhart, 1960).
[e] But 1-2 per mile (pers. comm. with F. A. Urquhart, Scarborough College, University of Toronto, August 15, 1977).
[f] Convergence of warm and cold fronts.

V. SOUND

INTRODUCTION

Sound generation by the DOE/NASA 100 kW Experimental Wind Turbine Generator (WTG) is the result of (a) mechanically and electromechanically induced sound from the equipment located in the alternator nacelle, and (b) aerodynamically induced noise resulting from interaction of the tower and the turbine with moving air. Sound at frequencies audible to humans is generated at low level and is not considered to be of concern to the environment (NASA-Lewis, 1977). Infrasound, i.e., acoustic energy generated at frequencies below the lower limit of human hearing, was investigated briefly in this study to determine whether or not it would occur at an intensity of sufficient magnitude to degrade the environment. Data, which was obtained only under unloaded conditions, show levels of infrasound which are lower than those believed to cause annoyance of physiological effects (Johnson, et al., 1976).

Infrasonic Noise

Although research in the area of physiological and psychological effects of infrasound has been limited in extent, the work which has been reported in the literature (e.g., Gavreau, 1968; Evans and Tempest, 1972; Andreeva and Galamina, 1971) indicates that high levels of infrasound intensity can be a problem. The threshold of physiological damage from airborne sound is as low as 120 dB at 20 Hz, but increases to 140 dB at 0.2 Hz (Johnson et al., 1976, CHABA, 1977).

Human annoyance resulting from exposure to infrasound in the frequency range of 0.1 Hz to approximately 5 Hz begins at levels on the order of 120 dB. Above 5 Hz the threshold of annoyance decreases. At 20 Hz, for example, the threshold is as low as 90 dB.

Audibility of infrasound decreases with decreasing frequency. According to criteria published by the U.S. Environmental Protection Agency (CHABA, 1977), the average threshold of audibility, is approximately 80 dB at 20 Hz, increasing to 125 dB at 2 Hz.

Another aspect of infrasound is the small amount of attenuation occurring as the low-frequency waves propagate. The long wavelength is believed to be a contributing factor to this phenomenon, as is the presence of vertical thermal gradients which tend to channel the acoustic energy of the waves (Cook, 1962). Because of this, propagation can influence larger areas than audible sound of the same level.

Infrasound is frequently translated in frequency through interaction with building walls or large windows which respond to the low frequency pressure fluctuations by vibrating and radiating audible sound. While structural damage is not a consideration, except in cases where extraordinary pressure pulsations are involved, the translated sound can be annoying to building occupants.

In the case of the WTG, some infrasound is generated when vortices are generated by air flowing past an obstruction such as the supporting tower or the turbine blades. The intensity and frequency of the sound are dependent on the size and shape of the obstruction and the wind velocity.

The principal source of infrasound, however, is believed to be the interaction of the tower wake with the turbine blades as they pass through the leeward side of the tower. Even at no-load conditions, a distinct "thump" can be heard occurring at a rate corresponding to blade passage frequency. The "thump" consists of an impulse which occurs at blade passage frequency (1 Hz in the case of 30 rpm operation). Because of the impulsive nature of the occurrence, sound at audible frequencies is also generated. Acoustical measurements were made, using a low-frequency microphone system(1), of the air pressure fluctuations at a point approximately 10 feet (3 m) above the ground, and in the near acoustic field in front of the turbine. The voltage output of the microphone system was recorded on a moving chart for observation(2). With the turbine stationary,

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(1) Bruel and Kjaer type 2631 carrier system with type 4147 microphone.

(2) Sound at audible frequency and noise due to wind interaction with the microphone were masked by the low-frequency response of the recorder.

the only low-frequency pressure fluctuations observed were very low-frequency, (.01 Hz), large amplitude signals attributable to instrument drift. When the turbine was in operation, however, a 1 Hz signal, approximately sinusoidal in nature, was observed to be superimposed on the low-frequency component of the microphone output. The amplitude of the low-frequency signal was determined to be in the range of 90 to 100 dB, relative to 2×10^{-5} pascal, and the frequency was the same as turbine blade passage frequency, i.e., 1 Hz at speed of 30 rpm.

Although no attempt has been made to develop a model for scaling the sound level, the literature indicates one might expect an increase in level on the order of 3.4 dB for an increase in wind speed from 10 mph (4.5 m/s) to 20 mph (9.0 m/s) (Lindquist, 1977). For increases in power level, an estimate could be based on the assumption that the increase in sound power would be at most proportional to the power output of the turbine. Assuming the power required to drive the WTG is 33 kW, the increase in acoustic output resulting from operating at an output power of 100 kW, as compared to no output power, would be 6 dB. Combining the level increases due to wind velocity and power output, a 9.5 dB increase would result.

From this data, it is possible to conclude that operating at full load and 20 mph (9 m/s) wind velocity, the maximum level of the infrasound would not be increased by any more than 9.5 dB over the level measured at no load and 10 mph (4.5 m/s). At this level (100 to 110 dB) there would be a substantial margin between the level of infrasound produced and the threshold criteria reported by Johnson, et al. (1976) for annoyance and physiological damage.

VI. CONCLUSIONS

MICROCLIMATE

The physical presence of an open lattice tower and the operating or nonoperating blades of a large wind turbine affects the natural environment in which it is sited. However, the significance of these effects appears minimal, even negligible, beyond the physical construction area of the tower pad and any other control/maintenance facilities. The environmental impact of this small area--less than several acres even for large, single-tower operations--is a measureable effect. However, this impact is not different from that found at similarly constructed facilities. A small concrete or gravel pad, foundations for the tower, a small control/operations building (in some cases, others may be operated remotely), access roads, and transmission rights of way all occupy small areas of land, modify the adjacent microclimates, and if located in agricultural areas represent a loss of those acres to production.

The field studies of the microclimate of a large operating wind turbine indicate negligible effect to a small area immediately downwind of the tower and blades.

When the WTG rotor is not operating, a rainfall deficit has been observed within a 3/4 rotor diameter (28 m) equivalent of the Plum Brook wind turbine tower. This deficit decreases and can disappear completely if the WTG is operating. For individual rainfalls, the nonoperational deficit can range between 1 and 30 percent, the higher values occurring with rainfalls of less than 0.05 cm (0.1 inch). Over a long period, this deficit is estimated to be about 5 percent. It is apparently due to the changes in windflow produced by the presence of the tower and the blades. Over parts of two successive winters, the precipitation pattern downwind of the tower in the prevailing wind direction has shown increases with distance one year and decreases the next year with the WTG not operating. Apparently meteorological variability overrides any tower shadow effect. Thus, it is expected that the operation of a WTG at Plum Brook will have an insignificant effect on rainfall in the vicinity. If there is a deficit in rainfall, it will occur within 1 or 2 rotor diameters (38 to 76 m) of the turbine where most of the human activity will be occurring. Even if the WTG had a significant effect on precipitation patterns in its vicinity, the variability of wind directions and speeds at Plum Brook, plus the large amount of annual precipitation which falls there, would ameliorate the effects of the WTG by naturally distributing the precipitation decrements and increments within the area.

In areas where topography or climate are different than that at Plum Brook, rainfall anomalies caused by a WTG could have a measurable effect. However, the results of the Plum Brook study, although hampered by a short observation period, predict that any precipitation variations will be quite small and will be limited to an area within two rotor diameters of the turbine. Consequently, even in areas where the wind may persist from a single quadrant or the annual rainfall is quite small, the presence of a WTG will create few precipitation variations which can be distinguished from the normal variabilities of rainfall or snowfall.

The study of the micrometeorological parameters, wind speed, temperature, and carbon dioxide concentration, in and out of the wake of the wind turbine do not indicate a significant variation in that wake. A significant difference was measured for wind speed within and outside of the wake of the wind turbine only for a distance of from one to five rotor-diameter equivalent distances downwind.

These measurements demonstrate the high variability of the natural environment. Thus, the main conclusion to be drawn is that plants and animals exposed to the wake of an operating WTG, while theoretically exposed to different micrometeorological conditions, are not likely to be significantly affected. What minor changes there are, which were not measured in this study, fall well within the natural variability of the environment to which these plants and animals are adapted. Furthermore, only in cases of a very narrow wind direction variation and very high constancy of winds such as a mountain pass, would the plants and animals be exposed to this wake for a large percentage of the time.

In such cases, the biota are typically adapted to the winds and minor variations, again, are unlikely to cause measureable or significant changes. Due to the extreme exposures and variability such sites are not usually prime agricultural lands.

BIRDS

The number of nocturnal migrants, expressed as the migration traffic rate, during the peak periods for fall and spring songbird migration in the Sandusky area varied from essentially no migration on rainy nights to as many as 17,000 birds/mile of front/hr. The average migration traffic rate for 12 nights with clear skies at NASA-Plum Brook was about 5,300 birds/mile of front/hr. for both spring and fall ceilometer surveys. This figure is slightly lower than the average for the same time of the night reported by Lowery and Newman (1966) for moon-watching surveys throughout the United States on four nights in October. The greatest migration volume during fall 1976 surveys was after the passage of a cold front, and greatest during spring 1977 surveys was immediately after the passage of a warm front.

A linear regression analysis of data from ceilometer and radar surveys on clear nights produced a table of migration density ranges that permits rapid quantification of migration from photographs of an ARSR-2 radar display. This method permits an estimate of migration traffic rates on rainy and overcast nights when ceilometer surveys are unreliable.

Heaviest fall migrations were to the S and SW, while heaviest spring migrations were to the NE and ENE. This orientation may be influenced by the NE-SW alignment of the eastern North America coastline.

During four migratory seasons of searching for tower-killed birds, only one nocturnal migrant was found, and this bird was found near the base of the meteorological tower prior to nighttime operation of the WTG.

Three circumstances prevented a completely accurate determination of the maximum potential kill of nocturnal bird migrants by an operating WTG. First, the WTG was operative only 10 percent of the nighttime hours of two (out of four seasons of study) migratory seasons. Thus, the WTG only operated for 114 nighttime hours during the peak songbird migration dates in fall 1976 and spring 1977. Second, three nights of scavenger studies indicated that about 5 percent of the tower-killed birds would be removed during the night before early-morning rounds are made by searchers to collect dead birds, Third, searches for tower-killed birds were only made during four migratory seasons, while major kills at other locations are known to be separated by intervals of several years (Stoddard and Norris, 1967).

In spite of the above limiting circumstances, it appears that the WTG at NASA-Plum Brook is not consistently lethal to a significant number of low-level, night-migrating birds, even on nights favoring high migration traffic rates combined with a low cloud ceiling and fog. Possibly a WTG could become more significant to nocturnal migrants if a taller WTG were built or if the WTG were located where large numbers of birds fly closer to ground level than they do in the Sandusky area.

Even when migrating birds do come near a WTG at night it appears that many of the birds perceive the structure and take evasive action. In this study, six of nine birds on a collision course toward the WTG operating at 20 rpm took evasive action in time to avoid the blades. The other three birds headed for the WTG flew on a straight line between the blades without incident.

Heavy migration of low-level nocturnal migrants can be forecasted for the Sandusky area with some accuracy during the peak songbird migration months in fall (September and October) and in spring (April and May). Heavy migration normally occurs in the fall shortly after the passage of a cold front and in northerly winds. Heavy spring migration normally occurs immediately after a warm front or on the trailing side of a high pressure area and in southerly winds. Rain during either season usually brings most songbird migration to a halt.

AERIAL ARTHROPODS

Foliage-inhabiting insects were sampled near the wind turbine. Flies and hoppers were the most abundant groups but beetles, bees, and other insects were present. Twelve tests were conducted to experimentally stage a reasonable, albeit infrequently encountered "worst case" example for the wind turbine site. Releases totalling 50,000 individuals (ladybird beetles, blow flies, and honey bees) were made from a mid-air point in front of an active wind turbine. The releases were recorded on film and analyzed. The results confirmed that the wind turbine will have little to no significant effect on aerial arthropods.

The seasonal, day-to-day, and hourly movement patterns of aerial arthropods are regulated by temperature, light, and other climatic and weather conditions. Densities of aerial arthropods are greatest within 80 ft (30 m) of the ground, according to the literature. Localized densities are much greater during migrations (locusts, butterflies, and other species) and swarms (honey bees). Migrations are expected to be more dense in mountain passes than over flat land. Geographical areas where individual insects in migration may be affected include sites of desert locust cycles in western United States and other desert areas of the world, e.g., the Sahara.

SOUND

Data obtained by NASA show that for wind velocities in the range of 15-20 mph (7-9 m/s) the WTG does not generate audible noise of intensity high enough to degrade the environment or to cause physiological damage. Measurement of audible noise at greater wind speeds is extremely difficult because of natural wind-related noise sources in the outdoors and the interaction of the wind with the microphone. It is unlikely that audible noise exceeding a comfortable level will be present in the accessible vicinity of the WTG except at points in proximity to the nacelle.

Comparisons of measured and predicted infrasound levels with existing criteria show that the Plum Brook WTG should not produce infrasound intensities capable of causing human annoyance or physiological damage.

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APPENDIX A

SELECTED DEFINITIONS

Arthropod - Any one of a large group of invertebrate animals which have a segmented hard external body covering and jointed limbs. Included in this group are the insects, crustaceans, and spiders, among others.

Ceilometer - (1) An instrument used at airports to measure the height of the cloud ceiling; it consists of a 25 million candlepower beam of light produced by a mercury-vapor lamp, with a parabolic reflector that focuses the light into a very narrow vertical beam. A receiver detects the light reflected from the clouds and automatically determines the height. (2) A portable lamp(s) used with binoculars, telescope, or night vision scope to view nocturnal bird migration using the techniques described by Gauthreaux (1969). Usually, two, 6-volt, 100 watt, narrow beam spotlights are directed vertically upward, so that they illuminate low-level bird migrants for enumeration and directional determination by a supine observer.

Nacelle - The streamlined center body of the wind turbine which houses the conversion mechanisms for the system.

Zone of Influence - An operating wind energy conversion system extracts energy from the free flowing air stream. This extraction is manifest in reduced wind speed and slight modification of other parameters, e.g., temperature, pressure. At some point downwind from the turbine, normal atmospheric turbulence serves to mix the wake with ambient air to an extent that the wake can no longer be identified. Because of the reduced pressure in the wake immediately downwind of the blades, there is some expansion of this zone as it travels along with the air stream. The zone of influence is that area downwind of the rotating blades of a wind turbine in which the micrometeorological parameters are significantly different from the free flowing air stream. Figure 1.1 of this report schematically portrays the zone of influence of the 100 kW WTG at NASA-Plum Brook.

APPENDIX B

MICROCLIMATOLOGY DATA

TABLE B-1

Fall Microclimatology Data

DATE: November 3, 1976

TIME: 11:12

DISTANCE: 1 diameter; 125 ft (38 m)

DIRECTION TO TURBINE: 220°

NACELLE WIND SPEED: 12 mph (5.3 m/s)

INSOLATION: 0.83 ly/min

HEIGHT(m)	CO_2 (ppm)	Temp. (C)	Windspeed (fps)
0	400	11.6	--
0.3	395	10.8	--
0.8	395	9.4	--
1.8	400	8.3	--
3.6	405	10.1	--
8.6	400	8.2	--
14.2	395	9.4	--

TABLE B-2

Fall Microclimatology Data

DATE: November 3, 1976

TIME: 10:55

DISTANCE: 2 diameters; 250 ft (75 m)

DIRECTION TO TURBINE: 210°

NACELLE WIND SPEED: 11 mph (5.1 m/s)

INSOLATION: 0.68 ly/min

HEIGHT(m)	CO_2 (ppm)	Temp. (C)	Windspeed (fps)
0	395	13.8	--
0.3	400	10.1	--
0.8	405	8.8	--
1.8	405	8.6	--
3.6	405	8.8	--
8.6	405	8.8	--
14.2	405	7.5	--

TABLE B-3

Fall Microclimatology Data

DATE: November 3, 1976

TIME: 10:40

DISTANCE: 3 diameters; 375 ft (114 m)

DIRECTION TO TURBINE: 215°

NACELLE WIND SPEED: 12 mph (5.3 m/s)

INSOLATION: 0.72 ly/min

HEIGHT(m)	CO_2 (ppm)	Temp. (C)	Windspeed (fps)
0	375	10.3	--
0.3	380	9.4	--
0.8	400	8.9	--
1.8	400	7.9	--
3.6	405	7.9	--
8.6	400	8.3	--
14.2	405	7.8	

TABLE B-4

Fall Microclimatology Data

DATE: November 3, 1976

TIME: 10:11

DISTANCE: 5 diameters; 625 ft (190 m)

DIRECTION TO TURBINE: 215°

NACELLE WIND SPEED: 14 mph (6.4 m/s)

INSOLATION: 0.66 ly/min

HEIGHT(m)	CO_2 (ppm)	Temp. (C)	Windspeed (fps)
0	400	10.7	--
0.3	400	9.3	--
0.8	390	8.3	--
1.8	395	7.6	--
3.6	405	7.7	--
8.6	410	7.4	--
14.2	400	7.2	--

TABLE B-5

Fall Microclimatology Data

DATE: November 3, 1976

DISTANCE: 5 diameters; 625 ft (190 m)

NACELLE WIND SPEED: 13 mph (5.9 m/s)

TIME: 14:29

DIRECTION TO TURBINE: 220°

INSOLATION: 0.70 ly/min

HEIGHT (m)	CO_2 (ppm)	Temp. (C)	Windspeed (fps)
0	380	11.6	--
0.3	380	10.6	--
0.8	390	9.9	--
1.8	400	10.1	--
3.6	410	9.9	--
8.6	410	9.3	--
14.2	410	9.4	--

A NDIX C

BIRD SURVEY DATA

TABLE C-1. DAYTIME SURVEYS FOR GROUNDED NOCTURNAL MIGRANTS, FALL 1976

Groups of Low Altitude Nocturnal Migrants	Number of Species and Individuals per Group by Date											
	Sept. 22		Sept. 23		Sept. 24		Sept. 25		Sept. 26		Sept. 27	
	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.
Cuckoos	0		0		0		1	(1)	0		0	
Swifts	0		0		0		1	(30)	0		1	(2)
Hummingbird	0		0		0		0		1	(1)	0	
Sapsucker	1	(2)	1	(1)	1	(1)	1	(3)	1	(1)	0	
Flycatchers	0		0		0		0		0		0	
Nuthatches	0		0		0		1	(1)	0		1	(1)
Creeper	0		0		0		1	(2)	0		0	
Wrens	0		0		0		2	(5)	0		1	(1)
Mimics[a]	1	(1)	1	(1)	2	(2)	1	(1)	0		0	
Thrushes	2	(3)	0		0		3	(4)	0		2	(11)
Kinglets	1	(1)	1	(5)	1	(1)	2	(9)	2	(3)	1	(1)
Vireos	0		0		1	(1)	3	(8)	0		0	
Warblers	4	(4)	2	(5)	2	(2)	14	(86)	7	(31)	5	(13)
Orioles	0		0		0		0		0		0	
Grosbeaks	0		0		0		0		0		0	
Buntings	0		0		0		0		0		0	
Finches	0		0		0		0		0		0	
Sparrows	2	(8)	2	(15)	2	(6)	3	(10)	1	(1)	2	(3)
Total Species	11		7		9		33		12		13	
Total Individuals		(19)		(27)		(13)		(160)		(37)		(32)

TABLE C-1. (Continued)

Groups of Low Altitude Nocturnal Migrants	Number of Species and Individuals per Group by Date									
	Sept. 28		Sept. 29		Sept. 30		Oct. 8		Oct. 12	
	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.
Cuckoos	0		0		0		0		0	
Swifts	1	(1)	0		0		0		0	
Hummingbird	0		0		0		0		0	
Sapsucker	1	(2)	0		1	(7)	1	(2)	1	(1)
Flycatchers	0		0		1	(1)	2	(3)	0	
Nuthatches	0		0		1	(1)	1	(2)	1	(1)
Creeper	1	(1)	0		0		1	(2)	1	(1)
Wrens	0		2	(2)	0		1	(1)	1	(1)
Mimics[a]	1	(4)	1	(1)	0		1	(1)	0	
Thrushes	1	(6)	1	(2)	2	(7)	1	(36)	1	(8)
Kinglets	1	(20)	1	(12)	1	(22)	2	(62)	2	(22)
Vireos	0		0		1	(3)	0		0	
Warblers	3	(4)	4	(17)	7	(22)	3	(6)	2	(4)
Orioles	0		0		0		0		0	
Grosbeaks	0		0		0		0		0	
Buntings	0		0		0		0		0	
Finches	1	(10)	1	(2)	1	(5)	1	(2)	0	
Sparrows	3	(7)	1	(8)	3	(16)	2	(8)	3	(16)
Total Species	13		11		18		16		12	
Total Individuals		(55)		(44)		(84)		(125)		(54)

[a] Brown Thrasher, Gray Catbird, Mockingbird.

TABLE C-2. DAYTIME SURVEYS FOR GROUNDED NOCTURNAL MIGRANTS, SPRING 1977

Groups of Low-Altitude Nocturnal Migrants	Number of Species and Individuals per Group by Date											
	Apr. 21		Apr. 22		Apr. 26		May 2		May 3		May 4	
	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.
Cuckoos	0		0		0		0		0		0	
Swifts	0		1	(1)	0		0		0		0	
Hummingbird	0		0		0		0		0		0	
Sapsucker	0		0		1	(1)	0		0		0	
Flycatchers	0		0		0		0		0		0	
Nuthatches	0		0		0		0		0		0	
Creeper	0		0		0		0		0		0	
Wrens	1	(1)	0		1	(4)	1	(1)	1	(2)	0	
Mimics	0		0		1	(4)	2	(9)	1	(1)	0	
Thrushes	1	(3)	0		1	(3)	1	(2)	0		2	(7)
Kinglets	1	(1)	1	(2)	1	(3)	1	(1)	1	(2)	3	(6)
Vireos	0		1	(1)	0		0		1	(1)	1	(2)
Warblers	0		2	(8)	2	(3)	1	(6)	4	(14)	0	
Orioles	0		0		0		0		0		4	(7)
Grosbeaks	0		0		0		0		0		1	(3)
Buntings	0		0		0		0		0		0	
Finches	1	(4)	1	(10)	1	(8)	1	(10)	0		0	
Sparrows	4	(42)	2	(19)	3	(6)	3	(9)	2	(13)	1	(1)
Total Species	8		8		11		10		10		2	(11)
Total Individuals		(51)		(41)		(32)		(48)		(33)	14	(37)

TABLE C-2. (Continued)

Groups of Low-Altitude Nocturnal Migrants	Number of Species and Individuals per Group by Date											
	May 5		May 6		May 10		May 11		May 12		May 13	
	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.	Spp.	Ind.
Cuckoos	0		0		0		0		0		0	
Swifts	1	(2)	1	(12)	0		0		0		0	
Hummingbird	1	(1)	0		0		1	(1)	0		0	
Sapsucker	0		1	(1)	0		0		0		0	
Flycatchers	4	(19)	2	(8)	1	(3)	1	(2)	3	(5)	3	(14)
Nuthatches	0		1	(1)	1	(1)	0		0		1	(1)
Creeper	0		0		0		0		0		1	(2)
Wrens	1	(4)	1	(2)	1	(6)	1	(6)	1	(7)	1	(4)
Mimics	2	(2)	2	(11)	2	(6)	1	(6)	2	(7)	2	(6)
Thrushes	4	(7)	2	(4)	0		1	(2)	2	(4)	1	(10)
Kinglets	1	(6)	1	(3)	1	(5)	0		0		1	(2)
Vireos	1	(1)	1	(2)	2	(2)	1	(1)	1	(3)	1	(9)
Warblers	11	(32)	9	(39)	7	(10)	10	(19)	4	(14)	5	(20)
Orioles	1	(1)	1	(8)	1	(2)	1	(4)	1	(4)	1	(7)
Grosbeaks	1	(3)	1	(4)	1	(2)	1	(1)	0		1	(1)
Buntings			1	(3)	0		0		0		0	
Finches	1	(1)	1	(4)	0		1	(2)	0		1	(1)
Sparrows	6	(35)	3	(18)	3	(13)	4	(20)	4	(11)	4	(27)
Total Species	35		28		20		23		18		23	
Total Individuals		(114)		(120)		(50)		(64)		(55)		(104)

APPENDIX D

ARTHROPOD SURVEY DATA

TABLE D-1. SUMMARY OF NUMBER OF SPECIES AND INDIVIDUAL WINGED INSECTS FOR NINE ORDERS SWEPT FROM VEGETATION IN HABITATS AROUND WIND TURBINE AT NASA-PLUM BROOK

Order	Managed Grassland						Mowed Grass		Near Water			
	Queen Anne's Lace		Scouring Rush, Thistle		Blackberry, Goldenrod				Stream Bank		Edge of Reservoir[(a)]	
	S	I	S	I	S	I	S	I	S	I	S	I
Odonata	--	--	--	--	--	--	--	--	--	--	1	1
Orthoptera	3	18	2	6	1	2	3	5	1	8	1	1
Hemiptera	5	11	1	1	3	4	1	6	2	2	--	--
Homoptera	10	17	5	11	8	11	13	56	6	7	4	5
Coleoptera	2	4	--	--	3	3	4	4	--	--	6	10
Tricoptera	--	--	1	1	--	--	--	--	--	--	--	--
Lepidoptera	3	4	2	3	--	--	1	1	2	3	2	2
Diptera	13	57	6	17	4	6	17	32	8	17	4	19
Hymenoptera	1	1	2	2	2	2	7	9	1	1	4	4
Total	37	112	19	41	21	28	46	113	20	38	22	42
Average Individuals/Sweep	1.12		0.41		0.28		1.13		0.38		0.84	

S = Number of species.
I = Number of individuals.
(a) 50 sweeps in sample; 100 sweeps in all other samples.

TABLE D-2. ENVIRONMENTAL CONDITIONS FOR EXPERIMENTAL RELEASES OF INSECTS IN FRONT OF THE WIND TURBINE [MEASUREMENTS MADE AT HUB (WHICH IS 100 FT (30.4 M) ABOVE GROUND LEVEL) OF WIND TURBINE]

Insects	Release	Environmental Conditions				Comments
		Time, EDT	Temperature, F (C)	Wind Speed, MPH (M/S)	Wind Direction, degrees	
Ladybird Beetles	1	1506	79.7 (26.5)	7.6 (3.4)	—	Tend to stay in clumps
	2	1539	77.4 (25.2)	10.1 (4.6)	047	Higher wind speeds fan out beetles in mid-air
	3	1556	77.3 (25.2)	7.8 (3.5)	069	—
	4	1605	77.3 (25.2)	10.0 (4.5)	055	Higher wind speeds fan out beetles in mid-air
Blow Flies	1	1525	78.4 (25.8)	8.2 (3.7)	045	Disperse immediately
	2	1531	78.1 (25.6)	6.0 (2.7)	037	—
	3	1537	77.7 (25.4)	10.8 (4.9)	047	—
	4	1542	77.8 (25.4)	8.4 (3.8)	044	—
Honey Bees	1	1706	76.0 (24.4)	9.6 (4.3)	061	Bees hover around carriage
	2	1715	75.9 (24.4)	10.7 (4.8)	069	Release not filmed
	3	1733	75.7 (24.3)	6.9 (3.1)	063	—
	4	1739	75.7 (24.3)	7.8 (3.5)	065	—
Averages			77.3	8.7	055	
Range			75.7-79.7	6.0-10.8	037-069	

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