EASTERN LAKE ONTARIO
ON-SHORE FLOW FIELD STUDY

RESEARCH
REPORT
EP 91-28

PREPARED BY:
GALSON CORPORATION

FINAL REPORT
APRIL 1994

ESEERCO

EMPIRE STATE ELECTRIC ENERGY RESEARCH CORPORATION

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Abstract

The Eastern Lake Ontario On-Shore Flow Field Study was designed to address several nuclear-specific meteorological issues in the coastal zone near Lake Ontario. Specifically, the following issues were investigated: Location and height of elevated stability layers; stability classification problems; vertical variation of wind speed; data bases for model validation studies; and suitability of new remote sensing technology. These issues were studied through one-year of continuous site-specific meteorological monitoring using acoustic sounders, meteorological towers, a microwave profiler, and a Radio Acoustic Sounding System (RASS). Continuous monitoring data was supplemented with intensive observations to collect detailed information during targeted meteorological conditions.

Acoustic sounders were used to observe the occurrence of elevated mixed layers and stability gradients. The monitoring failed to identify a statistically significant number of thermal internal boundary layers (TIBL). It is recommended that TIBL heights be estimated using robust empirical expressions. No justification for relocating the tall meteorological tower was determined. The current tall tower should be used to estimate release height winds. A 10 m tower located inland should be used to provide TIBL stability. Permanent installation of an acoustic sounder is also recommended.

A micrometeorological tower was installed and operated for a one-year period to measure stability using several techniques and investigate stability classification problems in near-shore areas. The results show that local conditions must be factored into determining the most appropriate stability class for dispersion modeling. In cases involving complex meteorology (i.e. coastal zones), consideration should be given to the collection of stability data at heights close to release elevation.

The vertical variation of wind speed was investigated by obtaining wind speed measurements at potential release elevations using a tethersonde and concurrent measurements from the 200 ft meteorological tower. The results indicated difficulty in estimating instantaneous wind speed at release elevations using established empirical expressions. Continuous measurements at release elevations are recommended for emergency response applications along with refined profile exponents for average winds used in routine release impact assessments.

Detailed measurements of meteorological regimes were collected in order to develop detailed data for the development and validation of numerical models for predicting the transport and dispersion of pollutants in shoreline environments.This data, combined with the other measurements taken during this study should provide researchers with a data set suitable for developing and validating conceptual and numerical models of the dispersion meteorology along the southern shore of Lake Ontario.

A 915 MHz Profiler and RASS were operated for a period of one year to evaluate the technology as a possible replacement for existing tall meteorological towers at nuclear facilities. It was concluded that the new technology is not a replacement for tall towers but can provide important supplemental information. Combined with an existing 200 ft meteorological tower and sodar for profiling in the lowest portion of the boundary layer, the profiler and RASS can provide valuable information on plume level wind and temperature structure.

This study focussed on the unique meteorological problems faced by power generating facilities located in coastal environments. The information and findings are applicable to facilities which must make estimates of the downwind dispersion of air pollutants in a coastal environment.

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EXECUTIVE SUMMARY

The Eastern Lake Ontario On-Shore Flow Field Study (ELOOFFS) was designed to study unique meteorological conditions near the southeastern shore of Lake Ontario. The primary objective of the study was to collect meteorological data within 10 km of the coastal transition zone in order to characterize meteorological parameters related to the transport and diffusion from power generating facilities during on-shore flow conditions.

In compliance with Federal Regulations regarding emergency planning, nuclear power generating facilities in the United States are required to have "adequate methods, systems, and equipment for assessing and monitoring of the actual or potential offsite consequences of a radiological emergency condition." In order to meet the meteorological aspects of this regulation, nuclear power generators must have the capability of making near real-time predictions of the transport and diffusion of effluent from their facilities. In order to make such predictions, meteorological data capable of describing the state of the atmosphere is vital.

The ESEERCO sponsored Eastern Lake Ontario Meteorological Study (ELOMS) was recently conducted to investigate mesoscale (ie. from 2 to 200 km) complexities in the vicinity of the lake. Nuclear facilities are concerned with conditions over even shorter distances (0 to 80 km). ELOOFFS was designed to enhance the ELOMS results by addressing several nuclear-specific issues over shorter distances. Specifically, this study investigated the following problems and issues:

- Location and height of elevated stability layers
- Stability classification problems
- Vertical variation of wind speed
- Data bases for ELOMS and related model validation studies
- Suitability of new remote sensing technology

Five specific objectives were identified in order to target the research of this project:

I. Determine the most appropriate location for a meteorological tower to satisfy Nuclear Regulatory Commission (NRC) guidance through measurements of the height of the thermal internal boundary layer (TIBL). Knowledge of the TIBL height assists in better assessing the stability of air into which specific plumes are released.

II. Address problems related to stability classification using shoreline meteorological towers. Further investigation leads to recommendations on what methods should be used for assessing stability.

III. Measure winds at release and plume heights and compare with other, standard measurement elevations. Determine if empirical expressions provide reliable, instantaneous wind speed estimates at different elevations.

IV. Make observations at Nine Mile Point (NMP) Nuclear Station and Ginna Nuclear Station in order to determine the comparability of results and collect detailed data in support of validation studies for the ongoing mesoscale meteorological modeling portion of the Eastern Lake Ontario Meteorological Study.

V. Evaluate the potential of next generation atmospheric profiling technology using a Microwave wind profiler and radio acoustic sounding system as an alternative to tall meteorological towers and Doppler Acoustic Sounders (SODAR) for measuring wind and temperature parameters in the boundary layer.

These objectives were addressed through one–year of continuous site-specific meteorological monitoring using monostatic acoustic sounders, meteorological towers, a microwave profiler, and Radio Acoustic Sounding System. Continuous monitoring data was supplemented with short–term, intensive observations with field teams collecting detailed information during targeted meteorological conditions using tethered and free–flying instrumentation (Tethersondes and Radiosondes).

The following summarizes the approach, conclusions and recommendations for each of the objectives identified above:

Objective I: In order to obtain data regarding the variation of the boundary layer with inland distance from shore, three monostatic acoustic sounders were placed a locations progressively inland. The acoustic sounder is capable of identifying elevated mixed layers by sensing acoustic backscatter characteristics of the atmosphere. Backscatter intensity is a function of thermal and velocity gradients. Inspection of the backscatter data allowed identification and interpretation of elevated mixing layers and related stability gradients.

The one year of monitoring failed to identify a statistically significant number of TIBLs over Nine Mile Point. A few hours of internal boundary layers were identified and showed reasonable agreement with the theoretical expressions for TIBL height as a function of inland distance. The limited data set was insufficient to develop or verify a site-specific TIBL height expression. Due to the limited TIBL data set, no justification can be made regarding the location of the meteorological tower. The sounder data did, however, clearly show evidence of more than one elevated mixing height approximately 25% of the time.

Further analysis of the data is recommended. It is also recommended that the current practice of estimating TIBL height using robust empirical expressions such as those suggested during ELOMS, be continued. No justification for relocating the tall meteorological tower was determined. The research suggests that the tall tower should be maintained at its current location in order to provide the best estimate of release height winds. In addition, a 10m tower located approximately 1 km inland is recommended in order to provide a measurement of the stability inside the TIBL.

Due to the apparent frequency of complex mixing layer patterns observed in the one-year of sounder data, it is recommended that an acoustic sounder be made routinely available to operators at the facility in order to facilitate assessment of vertical stability variation on an operational basis.

Objective II: To address problems related to the classification of atmospheric stability in the coastal zone, a 10 meter micrometeorological tower was installed and operated for a one-year period. Instrumentation was installed to measure stability using seven commonly accepted techniques, and the stability classes determined from each technique compared with those calculated using routine data from the NMP main meteorological tower.

The results showed that local conditions must be factored into a determination of the most appropriate stability class and, therefore, the selection of appropriate dispersion coefficients. In cases involving complex meteorology (i.e. coastal zones), consideration should be given to the collection of stability data at heights close to release elevation. Dispersion predictions for ground level releases should employ near surface stability classifications such as those obtained using the micrometeorological tower. Predictions for elevated releases should employ stability classes representative of the height of release such as those obtained from the 200 ft meteorological tower at NMP.

Specifically, for elevated releases, use of the 30 to 200 ft delta-temperature is recommended to account for the broad vertical variation in stability resulting from near-surface thermal fluxes and mechanical effects and smoother elevated flow. For near-surface releases, use of the sigma-theta method from either the 10 m tower or the 30 ft level of the NMP tower are recommended. The sigma-theta method should include a site-specific surface roughness correction.

Objective III: The representativeness of empirical extrapolation of wind speed to elevations above the highest measured elevation was investigated by obtaining wind speed measurements at potential release elevations using a tethersonde atmospheric profiling system, and concurrent measurements from the existing 200 ft meteorological tower. A comparison was conducted between the 200 ft measurement level and the release elevations.

Based upon the limited data set collected during this study, the current power law exponents employed to correct 200 ft wind speed to release heights at 350, 385 and 430 ft tend to over predict the actual wind speed on an observation-specific basis. The application of a wind profile exponent becomes less reliable as the difference between the reference and predicted elevations increases. The occurrence of mesoscale phenomena such as lake breezes, land breezes, and nocturnal low-level wind speed maximums are problematic for the application of wind profile exponents due to the large vertical variations in meteorological parameters observed with these phenomena.

With respect to the current meteorological observing system, direct use of the 200 ft wind speed provides a better estimate of release height wind speed on an observation-specific basis than use of the power law. It is recommended that further measurements using a combination of tower, tethersonde and remote sensing instruments be performed on a regular basis (e.g. annually). Continuous measurements at release elevations are recommended by either employing a tall meteorological tower or reliable remote sensing system, depending on the data recovery objective required.

Use of established wind speed profile exponents to determine average winds at release elevations is most likely appropriate for routine release calculations. However, the profiles should be refined with actual measurements between the tower and release elevations.

Objective IV: Detailed measurements of specific meteorological regimes were collected in order to develop a detailed data base for use in the development and validation of models for predicting the transport and dispersion of pollutants from power generating facilities located in shoreline environments. Difficulty in obtaining concurrent measurements at Ginna and NMP in similar weather conditions made direct comparison between the two sites impossible.

In general quality, high resolution data was obtained during weather conditions favorable for each of the targeted meteorological regimes. The data, combined with other measurements taken during the Eastern Lake Ontario On-shore Flow Field Study as well as routine meteorological measurements in the area should provide researchers with a data set suitable for developing and validating conceptual and numerical models of the dispersion meteorology along the southern shore of Lake Ontario.

Obtaining measurements of meteorological phenomena of concern to utilities is valuable and recommended as a suitable course of action to obtain detailed boundary layer profiles whenever possible. Use of the monitoring data by researchers involved in the development and validation of models over southern Lake Ontario should be actively encouraged.

Objective V: A 915 MHz Radar Profiler and Radio Acoustic Sounding System (RASS) were operated for a period of one year in the vicinity of NMP. The purpose of the monitoring was to evaluate the performance of these new monitoring systems as possible replacements for existing tall meteorological towers and provide enhanced data at levels well above that typically observed by the tall towers. The profiler is capable of providing supplemental information on wind direction and speed at heights ranging from 400 to 12,000 ft above the surface, and the RASS can provide information between 400 and 500 ft..

Operational reliability of the systems was quite high during this study even though the profiler system operated was a developmental version and not the current commercial version available. The system was available approximately 96 percent of the time. Data recovery, however, is dependent on operational status, weather, and siting conditions. This particular site suffered from ground clutter problems which limited data recovery. A data recover rate of 83 percent was the best achieved.

A short test of the radar profiler at another location at the end of the monitoring program showed significantly improved data recovery and reduced ground clutter effects. However, this short test did not demonstrate the full data recovery potential of the system since the antenna were not pointed over the lake where ground clutter would have been minimized.

Based upon this experience, the project team concluded that Radar profilers and RASS are not a replacement for tall towers. They are, however, capable of supplementing the tower-based measurements with detailed observations between the boundary layer and the middle troposphere. Combined with the existing NMP 200 ft meteorological tower and sodar for profiling in the lowest portion of the boundary layer, the profiler and

RASS can provide valuable information on plume level wind and temperature structure, particularly in lake breeze return flow, and onshore flow conditions. Great care must be taken in siting equipment to avoid sources of ground clutter. A thorough siting study which includes testing the profiler at candidate locations prior to permanent installation at the selected site is highly recommended.

In summary, the field monitoring and data analysis conducted during ELOOFFS met most of the objectives set forward at the beginning of the project. In general, all the equipment operated well throughout the monitoring program, although significant effort on the part of the site operator and equipment manufacturer was necessary in order to achieve this level of success.Poor weather conditions led to missing some of the desired measurements (Objective I), and some equipment siting problems led to lower than expected data recovery (Objective V).

This study provides a detailed data set which focusses on the unique meteorological problems faced by nuclear power generating facilities located in coastal environments. The information and findings resulting from this study are, in general, applicable to any facility which must make estimates of the downwind transport and diffusion of hazardous air pollutants in a coastal environment.

Introduction

The transition between land and water can complicate attempts to quantify atmospheric conditions found in the coastal zone. This is true at any shoreline location, including along the southern shore of Lake Ontario where a number of nuclear-, coal-, and gas-fueled power plants are operated. The Eastern Lake Ontario On-shore Flow Field Study (ELOOFFS) was established to address problems related to dispersion meteorology in the coastal transition zone. Of primary concern are: Thermal Internal Boundary Layers (TIBL), stability classification methods, and vertical wind speed profiles. Additional issues relate to the application of new remote sensing equipment to monitor the coastal zone meteorology and the availability of site-specific data for use in verifying mesoscale models.

Summary of Problems and Objectives

The primary objective of ELOOFFS was to collect meteorological data within 10 km of the coastal transition zone in order to characterize transport and diffusion from power generating facilities during on-shore flow conditions. Five specific tasks were identified in order to target the research of this project.

Task -1: Monitor Coastal Transition Zone Internal Boundary Layer

Guidance documents issued by the Nuclear Regulatory Commission (NRC) recommend that the main meteorological tower at any coastal nuclear power facility be located within the TIBL at all times in order to properly characterize dispersion conditions over land. The first specific objective of this study was to make measurements of TIBL height and elevated mixing layers in order to determine the most appropriate location for a meteorological tower to satisfy NRC guidance. Knowledge of elevated mixing layers is expected to assist in assessing the stability of the atmosphere into which specific plumes are released.

Task - 2: Evaluation of Stability Classification Schemes

A recent study commissioned by the Empire State Electric Energy Research Corporation (ESEERCO) looked at methods of classifying stability at Nine Mile Nuclear Power Station. Five methods were employed to classify stability into one of seven stability classes using data collected with existing monitoring systems. The study found that stability classification varied from scheme to scheme and that each of the methods suffered from various problems. Because most air pollution models allow specification of only one stability class, this presents a problem to specifying stability in the coastal transition zone. Therefore, the second objective of the project was to address stability classification problems associated with shoreline meteorological towers.

Task - 3: Monitor Vertical Wind Profile

NRC guidance recommends that measurements taken on the primary meteorological tower should be representative of the conditions at potential release elevations. If the highest measurement level on the tower is not at the same elevation as the highest release point, the measurements may not be adequate. At Nine Mile Point, the primary meteorological tower is 200 ft while the highest release point is 430 ft. Therefore, the third specific objective of this study was to measure winds at release and plume elevations and perform an intercomparison between other measurements in order to justify sensing levels.

Task - 4: Detailed Regime Measurements

Specific and detailed measurements of the unique meteorological regimes experienced over the southeastern Lake Ontario shore are lacking. To address this short-coming, the fourth specific objective was to make detailed observations of specific meteorological regimes in support of validation studies related to separate numerical modeling studies.

Task - 5: Evaluation of Wind and Remote Sensing Technology

The final objective of the study was to evaluate the potential for wind profiling technology as an alternative to tall meteorological towers and/or Doppler Acoustic Sounders (Sodar) for measuring wind speed and direction in the boundary layer.

Project Summary

Task 1 involved the installation and operation of three monostatic acoustic sounders for a period of one year in order to collect information on the boundary layer over Nine Mile Point. The three sounders were placed at locations progressively inland from the shoreline. In this way, the height of the boundary layer as a function of distance from shore was monitored. From this information, quantification of the TIBL and elevated mixing layers was developed.

In Task 2, stability classification schemes were evaluated using existing data sources as well as a specially designed 2- to 10-meter meteorological tower for making enhanced micrometeorological measurements. The data collected from this tower allowed the calculation of stability using a variety of methods and comparison with other, routinely used, techniques. An intercomparison of all methods leads to recommendations for site-specific stability classification.

In order to assess the appropriateness of the Nine Mile Point Primary Meteorological Tower for estimating wind speed at the release height, a field study was conducted as part of Task 3 in order to measure the vertical wind profile at the site. The field study employed a tethersonde boundary layer profiling system to develop a comparative data set. The tethersonde was flown at release heights and under a variety of meteorological conditions. The data set produced was used to compare with the 200 ft primary tower routinely used at the site. A data base of all measurements was produced allowing a comparative analysis between tethersonde and tower data.

Task 4 involved the collection of detailed information during meteorological regimes of specific concern in the coastal zone: on-shore flow fumigation, lake breezes, land breeze, and nocturnal low-level jets. This data is designed for use as verification data for numerical modelers and researchers.

Finally, Task 5 evaluated the applicability of the new wind and temperature profiling technology for use as a potential replacement for tall towers at Nine Mile Point and other nuclear facilities where elevated wind, stability, and temperature data is required. A 915 MHz profiler and Radio Acoustic Sounding System (RASS) were installed and operated concurrently with overall project monitoring. The performance of the profiler was evaluated in terms of data recovery, system reliability, and performance as compared to other monitoring systems. A final recommendation was made as to whether the technology is viable as a replacement for a tall tower.

Benefits of Research

Research results presented in this report are beneficial to power generating facilities located in the coastal transition zone where dispersion meteorology is complicated by unique phenomena resulting from the land/water interface. The primary objective of this research was to collect meteorological data within the coastal transition zone in order to better characterize transport and diffusion from power generating facilities located in these areas. The study addresses regulatory issues related to the siting of facilities in shoreline areas.

The results of this field project are recommendations on where to site a meteorological tower in order to best assess stability within the TIBL; what stability classification technique(s) are best suited for determining stability in the coastal transition zone for dispersion modeling purposes; what, if any, extrapolations are necessary to estimate the wind speeds at various release points; whether results of field studies at Nine Mile Point are applicable to other facilities; and, whether microwave wind profilers are a viable technology for determining the vertical wind profile in support of nuclear facility operations.

Report Organization

This report is separated into two Volumes. Volume I contains the final report text. Each section of the final project report describes one of the five tasks in detail. The sections are organized to be independent reports summarizing the background, research applications, approach, results, conclusions, and recommendations for each of the tasks outlined above. The reader may skip to that task report which addresses their particular concerns. Taken as a whole however, the report provides important details and insights to many of the meteorological issues which are relevant to nuclear facilities located in the coastal zone. Volume II provides the appendices which support the conclusions and recommendations outlined in Volume I.

Section 1.0

Monitor Coastal Transition Zone Internal Boundary Layer

This Section summarizes the results of a monitoring program to detect the existence of coastal internal boundary layers along the southeastern shore of Lake Ontario and make recommendations as to the placement of a meteorological tower at the Nine Mile Point Nuclear Station (NMP). A brief background description of the coastal internal boundary layer phenomena investigated during this study is presented in Section 1.1 and the study goals presented in Section 1.2. Descriptions of the equipment, monitoring program, and data analysis approach are provided in Section 1.3, with the data analysis results summarized in Section 1.4. Section 1.5 presents some conclusions and recommendations resulting from this portion of the study.

1.1 Background

1.1.1 Meteorology of the Coastal Transition Zone

At the coastal land/water interface, there is a unique step-change in the surface characteristics over which air flows. The water is characterized by high heat capacity and low surface roughness; thus, the temperature of the air over water is slow to change and flow is relatively smooth. On the other hand, land surfaces are distinguished by large temperature changes and high surface roughness: thus, air over land experiences large temperature variations and flow is more turbulent.

As air flows from one surface type to the other, it is modified at the bottom, gradually taking on the characteristics typical of air resident over the new surface. The depth of the modified surface layer increases with distance over the "new" surface type. The layer of modified air near the surface is referred to as an Internal Boundary Layer (IBL) because it grows within another boundary layer associated with the approach flow or the unmodified air. Two types of IBLs have been identified: the aerodynamic internal boundary layer (AIBL) resulting from changes in surface roughness, and the thermal internal boundary layer (TIBL) resulting from changes in surface temperature.

The AIBL and TIBL each have important implications for the assessment of stability in the coastal zone and, therefore, the transport and diffusion of pollutants. A step change in surface roughness, such as going from relatively smooth flow over water to more turbulent flow over land develops an AIBL, producing a wind profile modification (Figure 1-1) and a change in stability. A step change in surface temperature results in an adjustment in the vertical temperature profile (Figure 1-2) and likewise, a change in stability. The change in stability from inside to outside of the TIBL can be measured in terms of the standard deviation of vertical velocity (Figure 1-3).

To consider the AIBL and TIBL separately in the coastal zone is not really appropriate since both are occurring simultaneously. However, the surface roughness change is essentially constant over most temporal scales while the surface temperature (land and water) has dramatic variations on time scales ranging from several hours to one year. As a result, the TIBL is substantially more difficult to quantify since it depends on a number of continually changing meteorological parameters.

The most dramatic IBLs occur when cold stable air over a lake or ocean surface moves onshore over land heated by the daytime sun. This condition develops a TIBL. In order for a TIBL to develop, the following conditions must exist:

- Wind direction onshore (ie. air flow from water to land).
- Stable vertical temperature gradient over water.
- Neutral or unstable vertical temperature gradient over land.

True TIBL conditions occur only with unstable vertical temperature gradients over land. Shoreline fumigation under neutral stability classifications is possible, but most often results from mechanical mixing rather than thermal imbalances.

The TIBL is important to dispersion meteorology since a phenomena known as *shoreline fumigation* can occur when a pollutant plume intersects the boundary between an elevated stable layer and a surface-based unstable layer. When an elevated point source exists near the shoreline, the resultant plume would initially be emitted into the stable layers above the TIBL provided the wind is directed on-shore. However, the plume may eventually intersect the growing TIBL, where downward mixing of the plume occurs in the unstable air of the TIBL. The sudden downward mixing of the pollutant plume is referred to as shoreline fumigation. The occurrence of shoreline fumigation leads to sudden increases in ground-level pollutant concentrations closer to the source than would be expected if the phenomena was not occurring.

The NMP facility is located on the southeastern shore of Lake Ontario near Oswego in New York State, and is therefore subject to the potential of a TIBL meteorological regime. A previous frequency analysis using two years of site-specific meteorological data determined that on-shore flow occurs approximately 50-percent of the time in the vicinity of the NMP facility (Galson, 1990). The analysis also showed that on-shore flow with meteorological conditions appropriate for the development of a TIBL occur approximately 5 percent of the time on an annual basis, and over 15 percent of the time during the months of May, June, and July. It was concluded that the occurrence of TIBLs and associated shoreline fumigation conditions is potentially important when describing the transport and diffusion of pollutants in the vicinity of NMP and other power generating facilities with coastal locations.

As part of the Eastern Lake Ontario Meteorological Study-Phase III, a literature review of observations and TIBL formulations was conducted (Hanna, 1991). The review found that no studies of TIBLs have been made specific to the Lake Ontario shore. However, several studies have been conducted on some of the other Great Lakes, including Lake Michigan (Lyons, 1975), and Lake Erie (Portelli, et.al., 1982). Hanna (1991) compared previously developed formulas to describe the TIBL height as a function of inland distance with observed TIBL heights from several field studies. Empirical TIBL height equations were also compared to the observations.

Hanna (1991) identified the following difficulties with theoretical expressions for TIBL height when compared to the existing condition:

1) The vertical position of the TIBL is difficult to verify, since it can be defined as a temperature, wind speed, and/or turbulence discontinuity.

2) Some observation studies have shown that there may actually be two TIBLs, the top of the layer modified by the surface and the top of a second inner layer in which the boundary layer has reached an equilibrium with the underlying surface. This situation is further complicated by TIBLs which form inside sea (lake) breeze circulations.

3) The wind speed profile (an important input to some TIBL height expressions) is not spatially consistent, and can be different over water, at the coastline, and over land.

4) Sensible heat flux is not constant with distance from the shoreline. It is expected that boundary layer feedback will cause the heat flux to increase as the boundary layer deepens.

5) The over-water temperature gradient is not likely to be constant with height. Most boundary layer theories and observations suggest that the potential temperature gradient is greatest near the surface.

6) Water and surface temperatures are poorly defined. Temperature shows its largest variation near the surface, and can vary by several degrees between surface skin temperature (ie. air temperature 0.1 m above the surface) and the standard temperature measurement level.

To describe the TIBL height on the southeastern shore of Lake Ontario, Hanna indicated that theoretical equations would be preferable to empirical equations. However, in real-world applications, the values of some of the parameters necessary to solve theoretical equations are difficult to define. In addition, the equations may give unrealistic answers for certain combinations of parameter values. Therefore, Hanna recommends using "robust" empirical equations to estimate TIBL height. Such equations are stable with respect to input data, and agree reasonably well with the results of field experiments.

Specifically, Hanna (1991) recommends using one of the following empirical expressions developed to approximate the TIBL height (H_{TIBL}, in meters) as a function of inland distance (x, in meters):

- OCD (1985): $H_{TIBL} = 0.1x$ when $x \leq 2000m$
  $H_{TIBL} = 200m + 0.03(x-2000)$ when $x > 2000m$

- Hsu (1988): $H_{TIBL} = Ax^{1/2}$ where A = 1.9, 2.7, 1.7, and 1.2 for over-land stability classes A, B, C, and D, respectively

The TIBL heights predicted by these expressions are shown in Figure 1-4. The TIBL height equations all show a similar pattern, with the steepest slope near the shore, and decreasing slope farther inland. The deepest TIBLs are expected when instability is greatest (ie. Pasquill Stability Class A). This makes intuitive sense since the convective currents are most intense under high thermal instability, thus mixing through a deeper lay is supported thermodynamically. As mentioned previously, TIBL existence under neutral boundary layer conditions (ie. Pasquill Stability Class D) is mainly a result of mechanical mixing, and the TIBL is weaker and more difficult to define. The OCD TIBL height model is the most conservative of the approaches, and requires the user to determine only if appropriate conditions for TIBL development exist. The Hsu model is slightly less conservative, and requires a slightly more detailed assessment of the overland stability.

As compared to the unstable TIBL, the reverse situation of warm air advection over a colder surface has received very little attention. This situation may exist in winter along the southeast shore of Lake Ontario when warm lake air moves on-shore over cold, often snow covered land. Raynor et. al. (1979) reported on the stable IBL on the southern shore of Long Island, and developed an empirical relationship to predict growth of this type of IBL. Like the TIBL, the stable IBL also presents a problem when it is necessary to estimate the proper stability. In general, a plume release into or intersecting the stable IBL will remain in the stable layer where more traditional methods are adequate for estimating dispersion. Therefore, this study was intended to focus on the more volatile conditions presented by an unstable TIBL, and cold air advection over a warm surface.

1.1.2 Applications to Nuclear Facilities

The meteorological program at Nine Mile Point Nuclear Power Station and all other power generating facilities employing nuclear technology in the United States is subject to Federal Regulation 10CFR50.47. The regulation is in place to provide protection for the general public by requiring nuclear power generating facilities to have adequate facilities to allow the" assessment and monitoring of actual or potential offsite consequences of a radiological emergency." The Nuclear Regulatory Commission has issued the following documentation to provide guidance to nuclear facilities in meeting the requirements of the regulations:

- "Recommendations for Meteorological Measurement Programs and Atmospheric Diffusion Prediction Methods for Use at Coastal Nuclear Reactor Sites" (NUREG/CR-0936)
- "Meteorological Programs in Support of Nuclear Power Plants" (NRC Safety Guide 1.23 Revision 1*)

Meteorological data collected in support of the meteorological programs are used for short- and long-term dose calculations, and emergency response plume trajectory and arrival times. Regulations and guidance make specific statements regarding the need, location, availability, quality, and type of meteorological measurements.

The guidance documents listed above specifically identify coastal internal boundary layers (ie. TIBLs) as a "problem area" with respect to determining transport and diffusion from nuclear facilities located in coastal areas. Currently, the dispersion models employ robust, transportable methods for simulating the effect of shoreline fumigation on downwind impacts for pollutant plumes. In order to support dispersion estimates in areas where coastal internal boundary layers may be a factor, the above guidance documentation makes the following recommendations with respect to monitoring the TIBL:

1) The primary meteorological tower should be located so that the upper measuring level is always within the internal boundary layer.

2) A secondary meteorological tower should be placed at a location where measurements representative of the unmodified marine air can be obtained.

3) Instrumentation heights on the primary meteorological tower should be representative of conditions within the internal boundary layer while maintaining adequate separation between levels so that likely differences measured are greater than the uncertainty of the instrumentation.

This task is designed to further investigate the TIBL, and provide recommendations for assessing the significance to the problem, specifically to nuclear facilities located in shoreline areas.

1.2 Study Objective

The objective of this study is to make measurements of the TIBL in order to determine the most appropriate location for a meteorological tower to satisfy NRC guidance. Knowledge of the TIBL height will assist in assessing the stability of the air into which specific plumes are released, and provide required information for the modeling of transport and diffusion of releases from coastal nuclear facilities, specifically the Nine Mile Point Nuclear Station and J.A. Fitzpatrick Nuclear Power Plant.

1.2.1 Study Goal

The following specific goals were identified as necessary to address the task objective:

1) Successfully operate three monostatic acoustic sounders in order to collect information on the vertical profile of atmospheric turbulence.

2) Develop software to read and interpret the backscatter data from the sounders.

3) Identify the location of elevated mixing layers using automated techniques supplemented with manual inspection by a meteorologist familiar with the operation of the site.

4) Determine the elevation of the TIBL at various inland distances through interpretation of the sounder backscatter data during meteorological conditions favorable for TIBL development.

1.2.2 Potential Applications for Research

Any utility with a source of atmospheric pollution located in a coastal or shoreline area may potentially benefit from improved understanding of the dispersion meteorology in the coastal zone. Detailed observations of the internal boundary layer as a function of inland distance provides information on the vertical variability of stability parameters as a plume travels inland. This information may allow development of improved models to better predict the importance and location of vertical stability layers and the potential for plume trapping or fumigation.

This research provides information of interest to utilities wishing to investigate the potential for better predicting the dispersion meteorology associated with vertical variations in stability.

1.3 Approach

The Nine Mile Point Nuclear Power Station is located on the southeastern shore of Lake Ontario in upstate New York as shown in Figure 1-5. The shoreline runs essentially west to east at the site, however a bend to a southwest to northeast orientation is located immediately west of the facility. The terrain slopes upward from the lake, inland, through a series of rolling hills and valleys. The base elevation of the facility is approximately 270 ft above mean sea level (MSL). Terrain rises to approximately 480 ft MSL within 5 km south of the facility.

Because of its coastal location, NMP is subject to meteorological conditions favorable for the development of TIBLs. Throughout much of the spring and summer months, the land area surrounding Lake Ontario is often warmer than the lake due to daytime solar heating. As a result, relatively unstable temperature profiles develop during the daytime over the land while relatively stable profiles exist over the cooler water. When onshore winds carry the stable lake air onshore, there is a potential for a TIBL to develop and grow with inland distance as the stable lake air is modified from below by the warmer land surface.

1.3.1 Description of the Monitoring Instrumentation

In order to measure the boundary layer and identify elevated mixing layer (such as the TIBL), the single-axis monostatic acoustic sounder was selected. Acoustic sounding equipment is based upon the principle that a volume of air scatters incident acoustic energy. Scattering is due to wind speed and temperature discontinuities in the sampled volume of air. Most of the scattering occurs in the direction of propagation, but a small percentage of the energy is scattered back to the source. An acoustic sounder transmits a strong acoustic pulse (typically around 100 watts) vertically into the atmosphere and listens for that portion of the transmitted pulse that is scattered back to the transmitter. The monostatic sounder uses the same acoustic driver to both transmit and receive the signal with a single vertically pointed antenna. Bistatic sounding systems employ separate transmitting and receiving antennae.

Theoretical equations which relate the amount of return signal to the velocity and thermal structure functions have been developed. The existence of a temperature gradient and small-scale turbulence create local instantaneous temperature differences greater than the mean vertical temperature gradient. A strong return signal can be produced either by an unstable temperature gradient and little wind shear (convective boundary layer) or by a stable potential temperature gradient and large wind shear (stable boundary layer). As a result, qualitative atmospheric stability and temperature profiles can be developed. This strength allows the monstatic acoustic sounder to be used for sampling the boundary between marine and non-marine air during onshore flow.

Monostatic sounders can produce both facsimile and digital outputs of return signal strength for analysis. The facsimile output is essentially a strip chart recording of the strength of return signal versus height for each acoustic pulse. Dark shading indicates strong signal return while light shading indicates weak. Often, strong returns are associated with boundaries, such as the boundary between modified surface air in a TIBL and unmodified air above the TIBL in on-shore flow. In this way, the height of such mixing layers can be determined. Backscatter intensity data obtained using a monostatic sounder is converted from an analog signal to digital representation and stored in a computer for each of a user specified set of range gates or height increments.

In addition to the qualitative results, one strength of sounders is their ability to detect shifts in the frequency of the transmitted acoustic pulse. Frequency shifts are caused by the doppler effect and are directly proportional to the speed of an air parcel moving away from or towards the transmitter. In this way, vertical velocity (W) and standard deviation of vertical velocity (σW) can be calculated in each of the range gates. Atmospheric stability can be classified according to σW.

Acoustic sounders can reach heights as great as 1000 meters, depending on the atmospheric conditions. However, this range is often limited in high winds, precipitation, and high ambient noise level environments. In addition, fixed echo sources such as buildings and trees must also be avoided. The limitations in siting acoustic equipment are numerous, and all must be taken into account when determining an appropriate location for the system.

1.3.2 Sampling Approach

Three acoustic sounders were deployed at positions progressively inland from the shore. The purpose of this arrangement was to allow measurement of the height variation of the boundary layer with distance from shore. Spatial boundary layer height data is critical to satisfying the siting criteria for the primary meteorological tower as outline in NRC guidance documents. The sounders were located at approximately 1, 2.25 and 5.5 km inland along a line nearly perpendicular to the shoreline (Figure 1-5). The ground elevation at each of the sounders sites, 290, 312, and 485 ft MSL, respectively, reflects the gradually increasing terrain inland from shore.

The three sounders deployed for this study were the Radian Corporation Echosonde®. Each unit consisted of the following:

- single, vertically pointing antenna operating at 1850 Hz,
- IBM PS/2 Model 30-286 host computer with Echosonde® controller for signal processing and data storage on magnetic media,
- monochrome graphics monitor for onsite data display and operator use,
- printer for data backup,
- surge protector and uninterruptable power supply, and
- telephone modem for remote data checks.

The sounders each transmitted 75 Watts of acoustic power using a 150 msec pulse length which repeated every 5 minutes. The returned pulse (backscatter), was received and converted from an analog signal to a digital signal intensity in terms of power units. Digital backscatter returns were classified into altitude intervals or gates, determined by relating the response time to the transmission time, and calculating the distance traveled based upon a function of the speed of sound. The sounders each had 200 altitude gates, each gate approximately 4.5 m deep, extending from 30 to 940 m above the ground elevation. The total signal power in each gate was averaged over a 10 to 15 minute period, and then stored digitally on the host computer disk drive. The data was further edited using a background noise estimate made automatically during periodic non-transmitting times. Upon completion of the averaging, the power contribution due to this background noise estimate is subtracted from each backscatter power estimate. In addition, pulse cycles with noise estimates above a specified threshold (typical maximum background noise level), were excluded from the averaging process.

In addition to recording of backscatter data from which thermal structure may be inferred, vertical profiles of the vertical wind (W) were derived by measuring the Doppler shift of energy reflected back to the sounder within each range gate. Doppler measurements in each altitude gate are time-averaged over 30 minute periods from which a vertical wind speed is derived (Initially, the sounders recorded W over 15-minute periods, however, this was changed mid-way through the monitoring program in order to improve data recovery rates). Data availability, including range, is dictated by atmospheric siting conditions. As the sounder records the vertical wind speed for each altitude gate and time-averaging interval, the standard deviation of the vertical wind speed (σW) is also computed and recorded. The σW value from the lowest altitude gate is also converted to an estimate of the atmospheric stability class.

In addition to measuring atmospheric parameters such as backscatter, vertical wind speed, and stability, the Echosonde automatically employed a backscatter pattern recogniti on scheme which, in conjunction with the stability estimate, provided an estimate of the mixing height. The automated mixing height calculation scheme has been shown to be accurate within ±50% as much as 80-90% of the time. The automated mixing height was recorded to disk along with the other parameters.

The sounders were installed in late October, 1991, by Radian and Galson technicians and began routine recording on November 1, 1991. The systems operated continuously for a period of twelve months. A Galson technician made twice weekly site visits to perform routine maintenance operations such as data backup, operational checks, printer paper pickup/replacement, and snow, ice, and insect removal. Periodic remote interrogation of the sites was performed by Galson and Radian in order to assure continuous operation and identify/diagnose potential problems. Radian performed two maintenance visits during the project in order to determine the satisfactory operating status of the acoustic sounder systems.

The stored digital backscatter, vertical velocity, stability, and mixing height data was collected by Galson monthly, and sent to Radian for validation and reporting. All data was quality reviewed by an experienced meteorologist familiar with the project and the operation of the sounders. Mixing height data was provided monthly to Galson for inclusion in the monthly project progress reports.

Overall data recovery for the network was excellent. The overall system availability was greater than 99% of the total possible hours throughout the one year monitoring period. Data capture statistics for mixing height, vertical velocity and standard deviation of vertical velocity parameters are provided in Table 1-1. The major cause for lost data was the system down-time for routine maintenance and data backup, and atmospheric conditions unfavorable for return echoes. Note that during February, 1992, operating system parameter changes were implemented which improved data recovery for the measured parameters. Backscatter data recovery remained unaffected.

1.3.3 Data Analysis

Extensive data analysis was necessary to address the objectives of this task. The limited capability of the automated mixing height identification algorithm required an alternative approach to assessing the height of elevated mixing layers and the TIBL. In addition, the sounders produced an extraordinary amount of data requiring sorting, averaging, and reduction in order to produce a data record of manageable size. Nearly 220MB of digital sounder data was created as a result of the monitoring. The majority (over 90%) of this information was backscatter data.

The data analysis in support of this task focussed on two areas: Determination of multiple elevated mixing layers and identification of TIBLs. The following sub-sections discuss the data analysis associated with these areas.

1.3.3.1 Determination of Elevated Mixing Layers

Elevated mixing layers within the acoustic sounder data were determined by using significant vertical gradients in the backscatter data to identify mixing layer boundaries. Following averaging and smoothing of the detailed backscatter data, each of the vertical backscatter data records was processed from the bottom up (ie. beginning at 30 m and ending at 940 m). Increases in backscatter (following correction for acoustic attenuation) were interpreted as mixing layer boundaries. The strength of the backscatter gradient (Δb, where b is the backscatter power at any elevation z) and depth of the backscatter increase (Δz) were also noted. A Δb value greater than 25 was selected as representing a layer of significant scattering and flagged as a probable mixing layer boundary. Further, $\Delta b/\Delta z$ greater than zero was defined as the mixing layer boundary base, and $\Delta b/\Delta z$ less than zero was defined as the mixing layer boundary top. In order for multiple mixing layers to be defined, two separate layers where Δb is greater than 25 are required.

A frequency of occurrence analysis of multiple elevated mixing layers was performed following the progressive use of four separate post-processing programs for each day in the sounder records. Multiple elevated backscatter layers identify a vertical stability gradient. The existence of a vertical stability gradient can lead to erroneous estimates of pollutant dispersion since current dispersion models do not allow for vertical stability variations. The four programs used to identify multiple elevated mixing layers are described as follows:

- PROC.FOR - Convert Echosonde® raw data archive files to ASCII format
  - Reformat data in preparation for decoding and averaging

- BSTR2.FOR - Decode raw backscatter data
  - Calculate average backscatter data

- MIXDET.FOR - Bin data and smooth (33 bins with 27 m increments)
  - Identify scattering layers
  - Output number, depth, and strength of scattering layers

- MIXFREQ.FOR - From MIXDET.FOR output, determines the occurrence and frequency of multiple mixing layers by identifying layers with $\Delta b>25$

In addition to the robust automated procedure outlined above, mixing height data was reviewed by a meteorologist familiar with the project to verify the results. The results of the multiple mixing height frequency analysis are presented in Section 1.4.

1.3.3.2 Identification of TIBLS

The identification of TIBLS proved to be extremely difficult due to the apparent dominance of synoptic scale mixing layers, the variable nature of onshore flow conditions, and the complexity of performing detailed review of the digital backscatter data files.

The first step to identifying TIBLs, was to identify hours of onshore flow at NMP. This was performed using available meteorological data from the NMP main meteorological tower (9MP) and the ELOOFFS micro-meteorological tower (MMT). For the purposes of this analysis, periods of onshore flow were identified using the following criteria:

1) Wind direction at 9MP 30 ft level between 270 and 40 degrees
2) Wind direction at MMT 10 m level between 270 and 40 degrees
3) Wind direction criteria must be met at both 9MP and MMT for at least 2 consecutive hours

Over 2,300 hours were selected as meeting the onshore flow criteria. In order to identify potential onshore flow cases which were more likely to support a TIBL across the acoustic sounder "network", the wind direction criteria were further refined to better distinguish periods with onshore flow perpendicular to the shoreline at NMP. In addition, a wind speed criteria was added to eliminate consideration of light and variable wind conditions. Night-time hours were also eliminated from consideration. The potential TIBL criteria are as follows:

1) Wind direction at 9MP 30 ft level between 325 and 15 degrees
2) Wind direction at MMT 10 m level between 325 and 15 degrees
3) Wind speed at 9MP 30 ft level greater than 1.5 m/s
4) Wind speed at MMT 10 m level greater than 1.0 m/s
5) Solar radiation at MMT greater than 0.02 Langleys/min

Approximately 231 hours were identified as potential TIBL hours using this selection criteria. It should be noted that the actual number of potential TIBL hours at NMP during the one year monitoring period is higher, however, the wind directions for the eliminated hours would not have been favorable for investigating TIBLs over the sounder network.

Finally, the best time periods for potential TIBL development were identified using the following additional data reduction criteria in order to assure that conditions sufficient for the development of unstable lapse rates over the land existed:

1) Solar radiation measured at MMT greater than or equal to 75% of total possible.
2) No snow cover reported on ground at the National Weather Service Office in Syracuse, New York (nearest inland snow cover reporting station).
3) Air temperature measured at the 2 m elevation of the MMT tower should be greater than the climatological lake temperature (no reliable observed lake temperature data was available for the period of record).

Following this final stratification of the data, approximately 84 hours remained for detailed TIBL investigation. The specific time periods identified as potential TIBL hours are detailed in Table 1-2.

Each of the 84 hours of potential TIBL data was manually inspected by a meteorologist familiar with the project. The hourly averaged backscatter data produced from the routine BSTR2. FOR described above were used rather than the 10-minute data since the format of the higher resolution data was very cumbersome and tended to be extremely variable.

The results of the TIBL identification and height analysis are presented in Section 1.4.

1.4 Data Analysis Results

1.4.1 Multiple Mixing Layer Analysis

The existence of multiple elevated backscatter layers (mixing layers) is a potential problem for the reliable prediction of plume transport and diffusion. Multiple mixing layers identify a vertical stability gradient which can lead to erroneous estimates of pollutant dispersion since most dispersion models do not allow for vertical stability variations. Multiple mixing heights are analogous to TIBLs in that plumes undergo changing dispersion conditions when intersecting the boundaries between mixing layers. Since measurements of stability are generally confined to below 200 ft at NMP, elevated releases may be made into mixing layers above the height detected by the standard monitoring system. Therefore, the occurrence of vertical variations in stability may result in poor dispersion predictions using the existing monitoring system at NMP.

This analysis attempted to conservatively estimate the frequency of the multiple mixing heights over NMP. As outlined in Section 1.3.3.1, at least two positive vertical backscatter gradients were required in the sounder record to define an hour as having multiple mixing heights. The results of the analysis are shown in Table 1-3 and graphically depicted in Figures 1-6 and 1-7. The results indicate that multiple mixing heights as defined for this study occurred approximately 25% of the time on an annual basis during the November 1991 through October 1992 monitoring period. This relatively high frequency of occurrence is potentially significant from a dispersion modeling standpoint for releases from the NMP facility.

The period of record showed that multiple mixing heights are most common in early spring, and least common during late summer and early fall. This distribution is believed to be related to the following causes:

- Intensity of the nocturnal inversion
- Snow cover (March)
- Proximity of a cold air source (ie. Lake Ontario)

In terms of the occurrence of multiple mixing heights as a function of the hour of the day, the phenomena appears to be most common during the early morning period just following sunrise. This is probably related to the breakup of the nocturnal inversion, when heating near the surface lifts the nighttime radiation inversion aloft. Multiple mixing layers are less frequent during the late morning through afternoon hours when convective mixing is most intense, thus allowing mixing through a layer which is probably deep enough to prevent multiple mixing layers within sounder range.

The existence of multiple mixing layers at NMP warrants further investigation and monitoring due to the critical nature of assessing stability for dispersion predictions of elevated releases. Continuous monitoring of the boundary layer using a sounder which reports detailed backscatter profiles is recommended as one approach to observing and identifying elevated mixing layers for operational purposes.

1.4.2 TIBL Height Analysis

The observed meteorological data available from the 9MP and MMT towers was processed to select time periods for TIBL height analysis in the method outlined in subsection 1.3.3.2, above. As stated above, approximately 84 hours were identified as potential TIBL hours using the selection criteria. A listing of the time periods selected and their durations (≥ 2 hours) is provided in Table 1-2.

The total number of hours (84) selected was rather disappointing and somewhat below what was expected. This result is believed to be a reflection of the relatively cool and wet summer experienced in 1992 compared to the 30-year mean. Table 1-4 shows the temperature, precipitation, and sunshine departures from the 30-year mean as measured at the Syracuse National Weather Service (nearest long-term meteorological station) for the expected peak TIBL occurrence period (March through August, 1992). The table shows that temperatures averaged below the 30-year mean for all months but May, and were significantly below the mean during March, June, and July. In addition, the precipitation and sunshine data indicate that solar input for warming of the land was well below the mean, resulting in less frequent conditions favorable for unstable conditions over the land, consequently reducing the occurrence of lake breezes which may have supported TIBL development. As a result of the cool/wet/cloudy conditions prevalent during the peak TIBL season of this monitoring study, the number of cases available for study was less than expected.

Following the selection process, the high resolution backscatter data from each sounder for each of the identified time periods was manually inspected by a meteorologist familiar with coastal internal boundary layer phenomena and the acoustic sounders. The purpose of the manual inspection was to identify all potential backscatter boundaries in the data records having the TIBL signature of cool, stable lake air overlying warm, unstable land air. The backscatter signature typically shows high backscatter power values in the lowest range gates, decreasing up to some elevation, followed by a region of steady and/or increasing backscatter, with again decreasing values above. The elevated layer of increased acoustic backscatter has been shown to mark the boundary of the cooler, more stable lake air aloft.

The process of reviewing the digital backscatter data manually was extremely tedious, and required many hours of the analyst's time. Table 1-2 shows the TIBL events studied and a summary of the findings for each event. Of the 19 events studied in detail, only 5 revealed boundary layers which are believed to be TIBLs with high confidence. The 5 TIBLs identified provided estimated TIBL height information for just 11 hours of the total record. A total of 6 events had suspected TIBLs, however the analyst could not verify with high confidence the TIBL height or backscatter intensity. The remaining events were eliminated either because no evidence of the TIBL could be found or the event was marginal.

The TIBL height as a function of inland distance for each of the identified events is presented in Figures 1-8 through 1-12. The estimated TIBL elevations at each of the monitoring sites have been corrected for the ground elevation of the sounder (ie. the effects of terrain are eliminated). In all cases, the profiles show the expected pattern of increasing TIBL height with inland distance, with a rapid increase near the shore (assuming the TIBL height at the shoreline is zero) and a slower increase with height further inland. The exception to this finding is the TIBL which was observed on April 10, 1992, when an almost linear increase with inland distance was observed.

In comparison with the empirical TIBL height equations outlined in Section 1.0, the few observed TIBLs appear to follow these equations closely. Of particular note is the April 10, 1992 case, when

TIBL height showed a gradual decrease through the afternoon. This corresponded to increasing cloud cover and increasing stability in the surface layer over the land. This decrease in TIBL height with increasing stability is predicted by the Hsu model. However, caution is recommended in drawing conclusions from this single case since this data set is extremely limited.

1.5 Conclusions and Recommendations

Regulation and guidance applicable to the siting and operation of meteorological instrumentation at nuclear power generating facilities are clear regarding the need to consider the influences of coastal internal boundary layers. Internal boundary layers can have a significant impact on the dispersion of pollutants from facilities located in coastal locations, and should be considered whenever making estimates of air quality and dose impacts for releases in the coastal zone.

However, observation and tracking of the location and height of the TIBL is difficult. For a TIBL height study on Lake Michigan, Lyons (1975) conceded that "... the TIBL depth as a function of distance from the shoreline is not easily predictable. Simple statistical analysis showed it [the TIBL] to be very poorly related to any single variable or collection of variables." Indeed Hanna (1991) further concedes the uncertainty in identifying the predicted TIBL height, saying "... the behavior of the TIBL near the shoreline is uncertain because of the fact that near-shore water temperatures are generally warmer than off-shore...", thus making the actual "shoreline" difficult to identify.

This study attempted to monitor and estimate the height of the TIBL along the southeastern shore of Lake Ontario using three acoustic sounding systems located at varying distances inland form the shore. The goal was to determine the site-specific characteristics if the TIBL in hopes of justifying the location of the primary meteorological tower at NMP.

Based upon the monitoring completed during this study, and the data analysis which followed, the following conclusions are made:

- The data collected failed to reveal enough verifiable TIBLs to determine whether or not use of the empirical TIBL height expressions recommended by Hanna (1991) is justified.

- The limited TIBLs identified did show the expected TIBL shape (ie. rapidly increasing TIBL near the shore, then slower increase farther inland). Use of hourly data help smooth the TIBL variations. Instantaneous TIBLs heights show much more variability.

- A frequency analysis showed that multiple mixing layers occurred over NMP nearly 25% of the time during the 1-year monitoring period. The use of acoustic sounders allowed the continuous monitoring of these mixing layers through measurement of acoustic backscatter. Gradients in the backscatter have been shown to be related to vertical gradients in atmospheric stability.

- The most complex vertical distributions of stability occur at NMP during early spring on a seasonal basis, and just following sunrise on a daily basis.

Based upon the conclusions outlined, the following recommendations are made:

- Due to the limited observations of TIBLs at NMP, no justification can be made regarding the location of the meteorological tower. The current tall tower should be maintained in order to provide the best estimate of release height winds. However, since multiple mixing layers are frequently observed, monitoring through a deep layer of the atmosphere is recommended by employing remote sensing technology.

- In order to insure measurement of the stability inside the TIBL, continued operation of the MMT tower at a location approximately 1 km inland is recommended. At this inland distance, 10 m level of the MMT tower is expected to always be within the TIBL.

- Use of the OCD TIBL model as a general guideline for determining the TIBL height is recommended since the formula is simple and believed robust enough to provide reasonable height estimates for most TIBL occurrences.

- Further study is recommended to identify the causes of multiple mixing layers over NMP. The occurrence and potential impact of multiple mixing layers on the prediction of transport and dispersion from NMP should be considered. Identification of the causes for multiple mixing layers will enhance prediction of the phenomena.

- Continued operation of the Sodar is recommended with the addition of a facsimile output display to allow operators the visual confirm the existence and elevation of mixing layers.

- Further analysis of the voluminous data collected from the acoustic sounders is recommended and encouraged. Further analysis in combination with other data collected during this study may broaden the scope of the TIBL investigation and help clarify marginal cases. It should be noted that studies involving the backscatter data will involve significant labor effort to implement appropriate processing and analysis programs.

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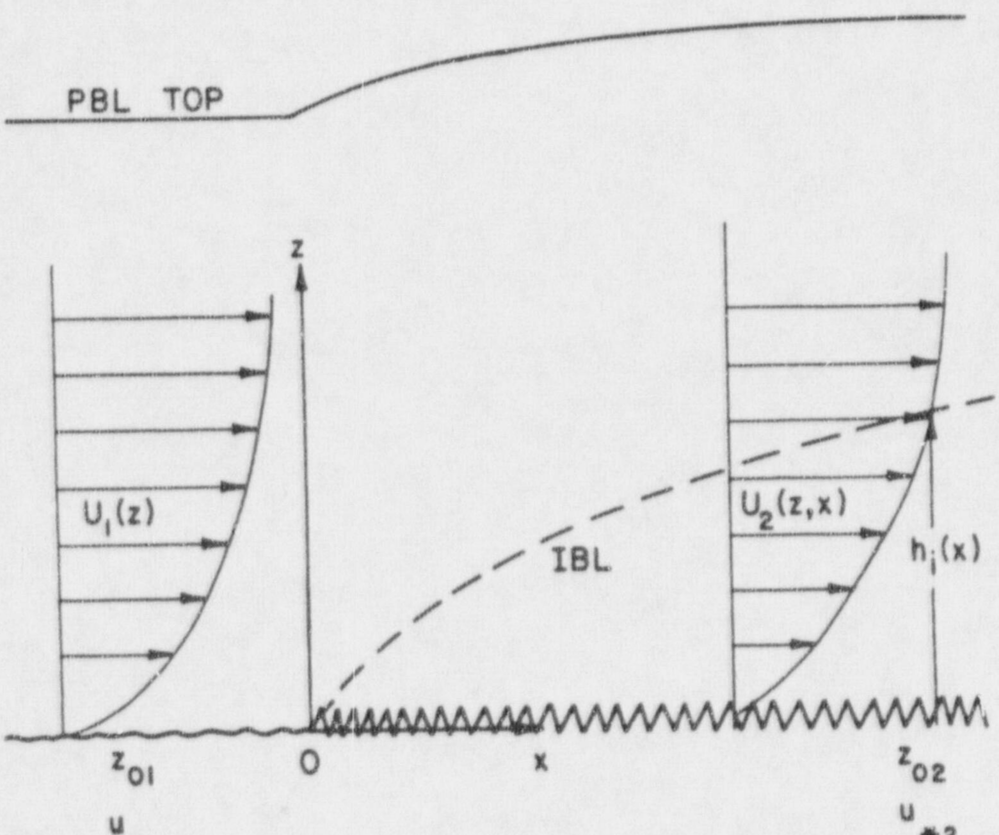


Figure 1-1
Schematic of Wind Profile Modification in an Aerodynamic Internal Boundary Layer
(From Arya, 1988)

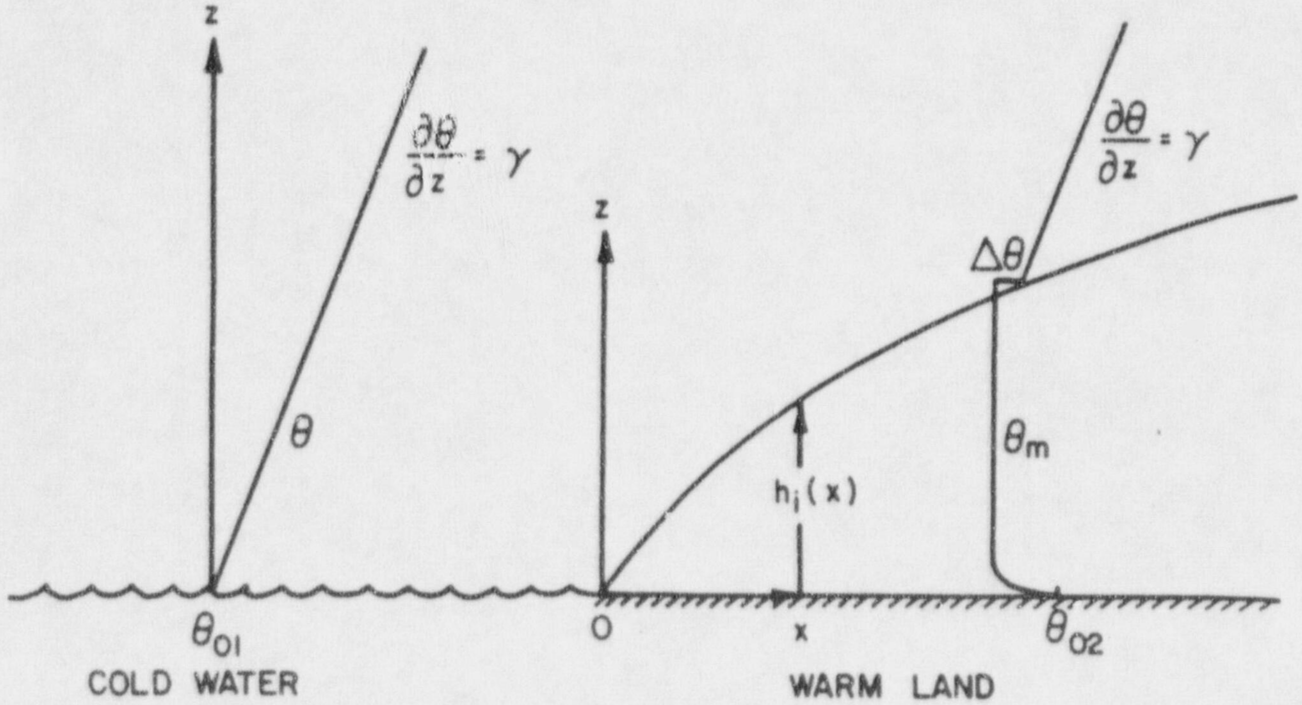


Figure 1-2
Schematic of Temperature Profile Modification in a Thermal Internal Boundary Layer
(From Ayra, 1988)

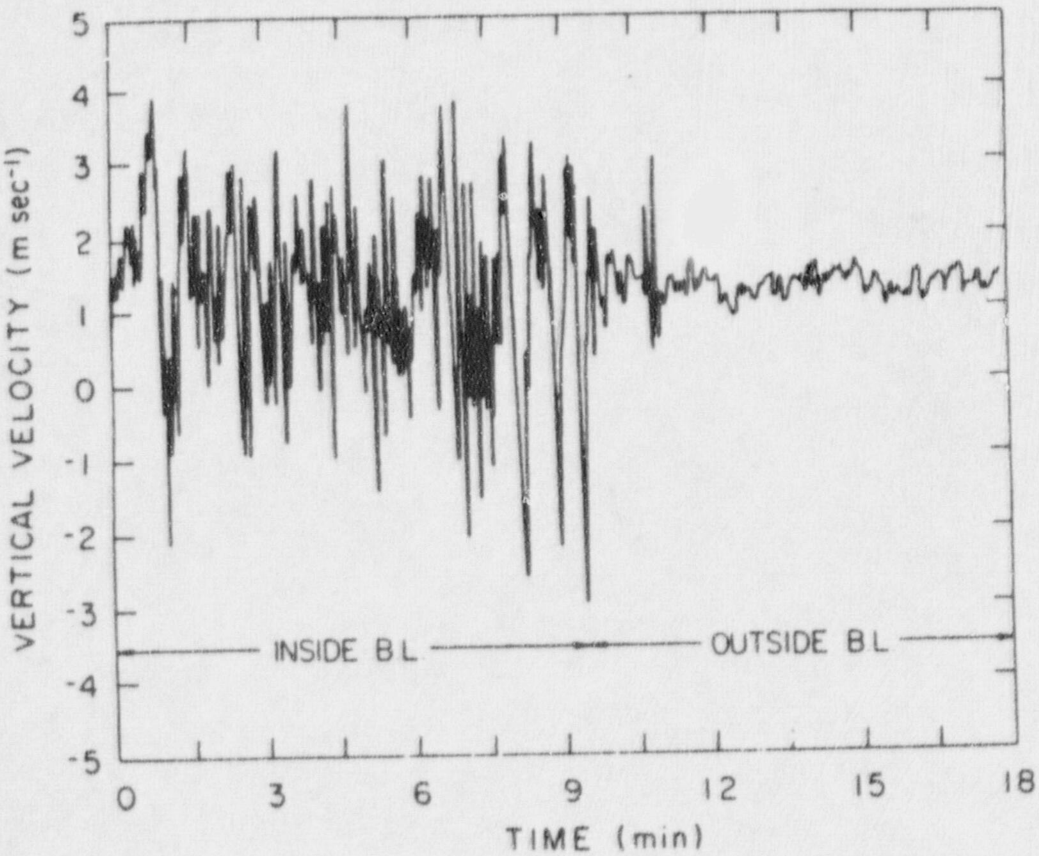
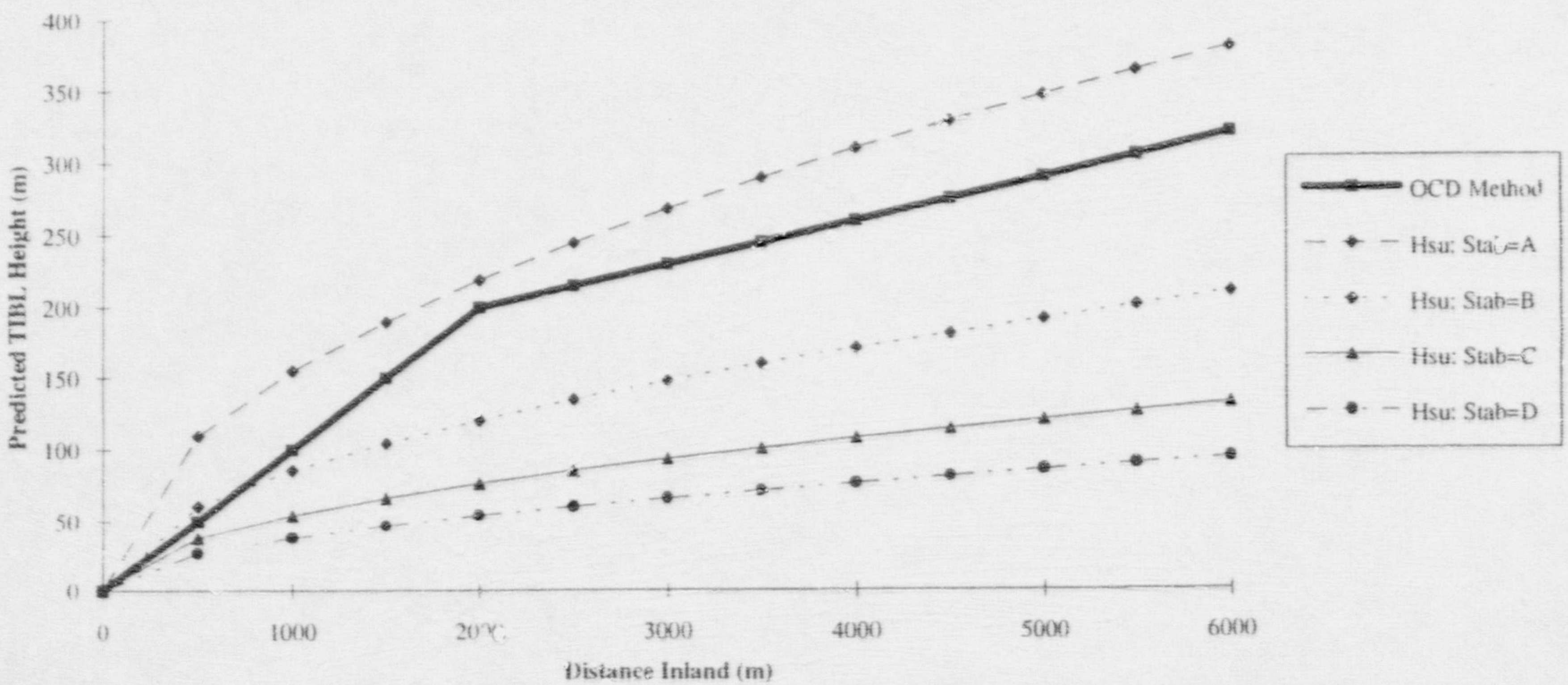


Figure 1-3
Vertical Velocity Obtained by an Aircraft Flying through the TIBL (left) into Stable Marine Air (Right)
(From Raynor, et.al., 1979)

Figure 1-4
TIBL Height vs Distance Inland Using Robust Formula (Hanna, 1991)



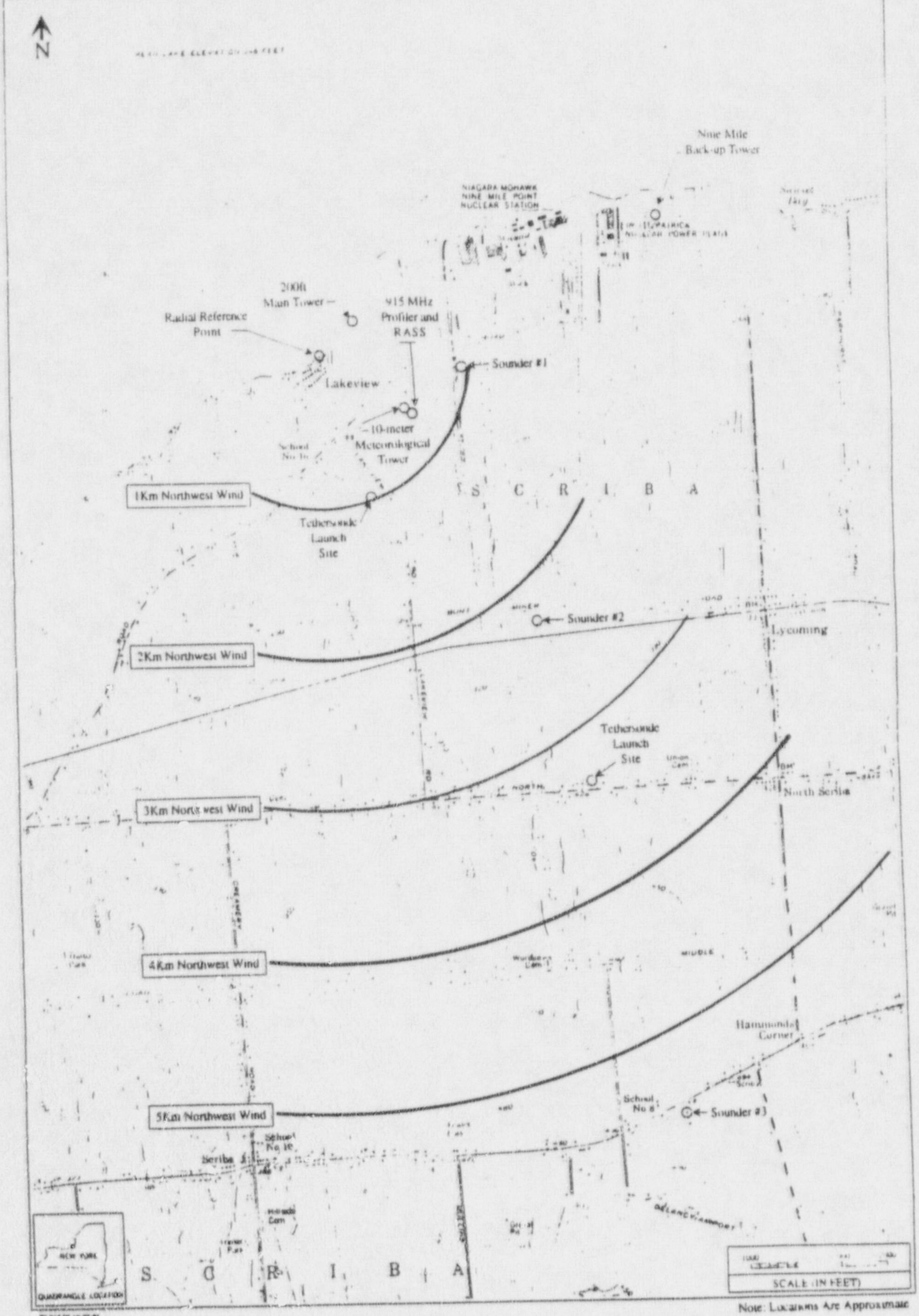


Figure 1-5
Field Monitoring Area
Eastern Lake Ontario Onshore Flow Field Study
(Locations of monitoring sites indicated)

Figure 1-6
Frequency of Multiple Mixing Heights at NMP by Month
November 1991 through October 1992

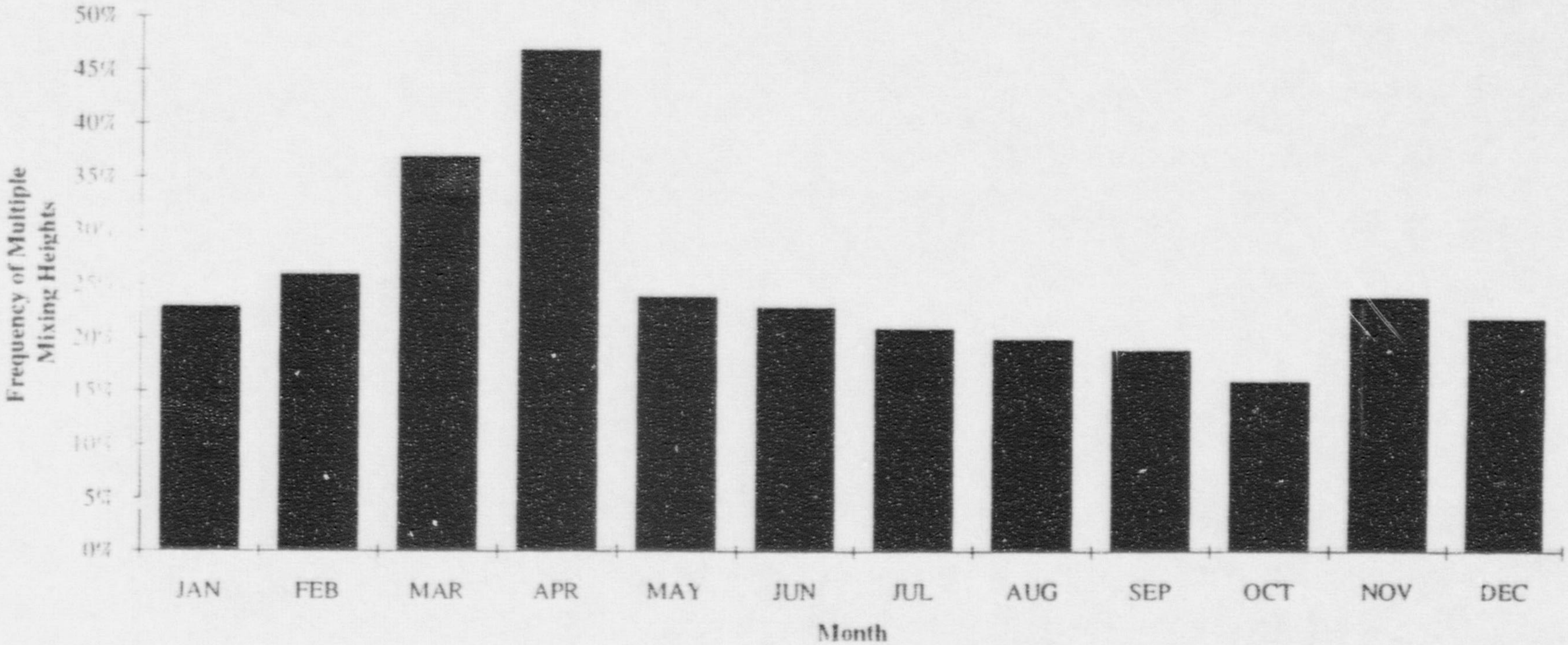


Figure 1-7
Frequency of Multiple Mixing Heights at NMP by Hour
November 1991 through October 1992

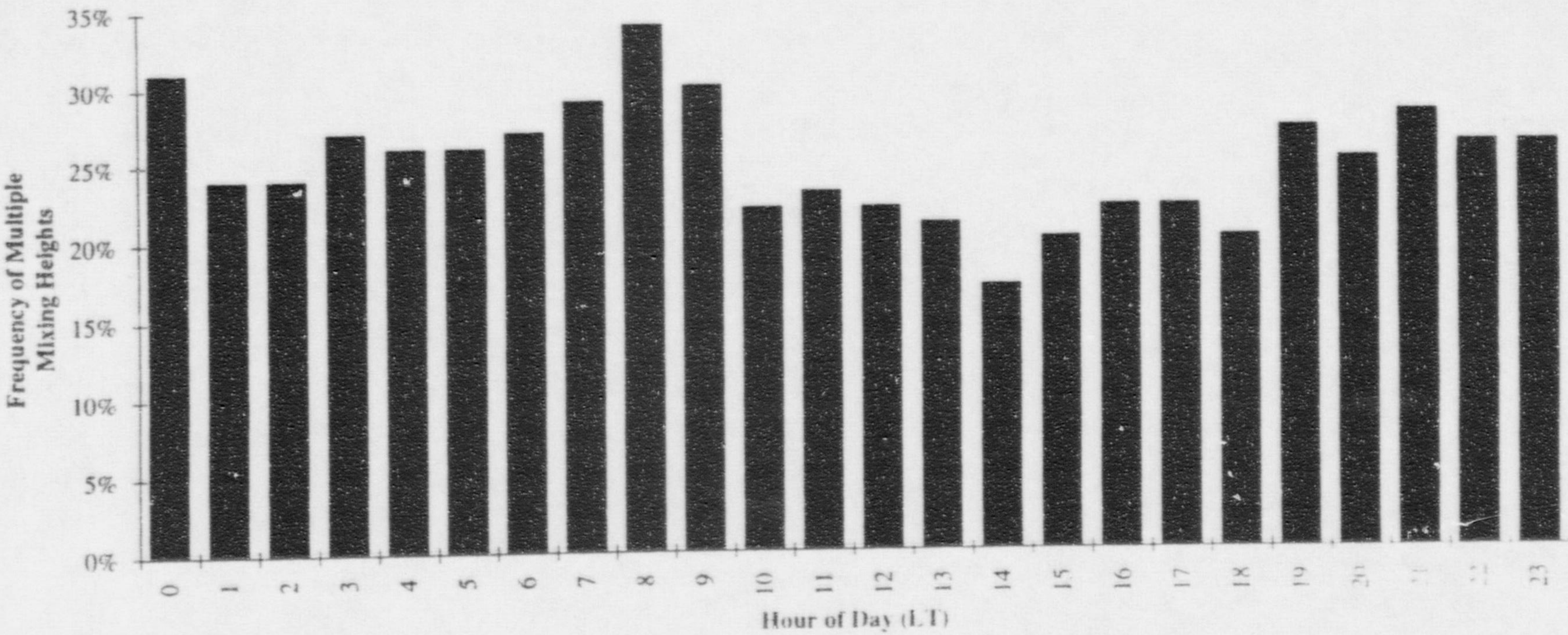


Figure 1-8
Estimated TIBL Height versus Distance from Shore: MAR-5-1992

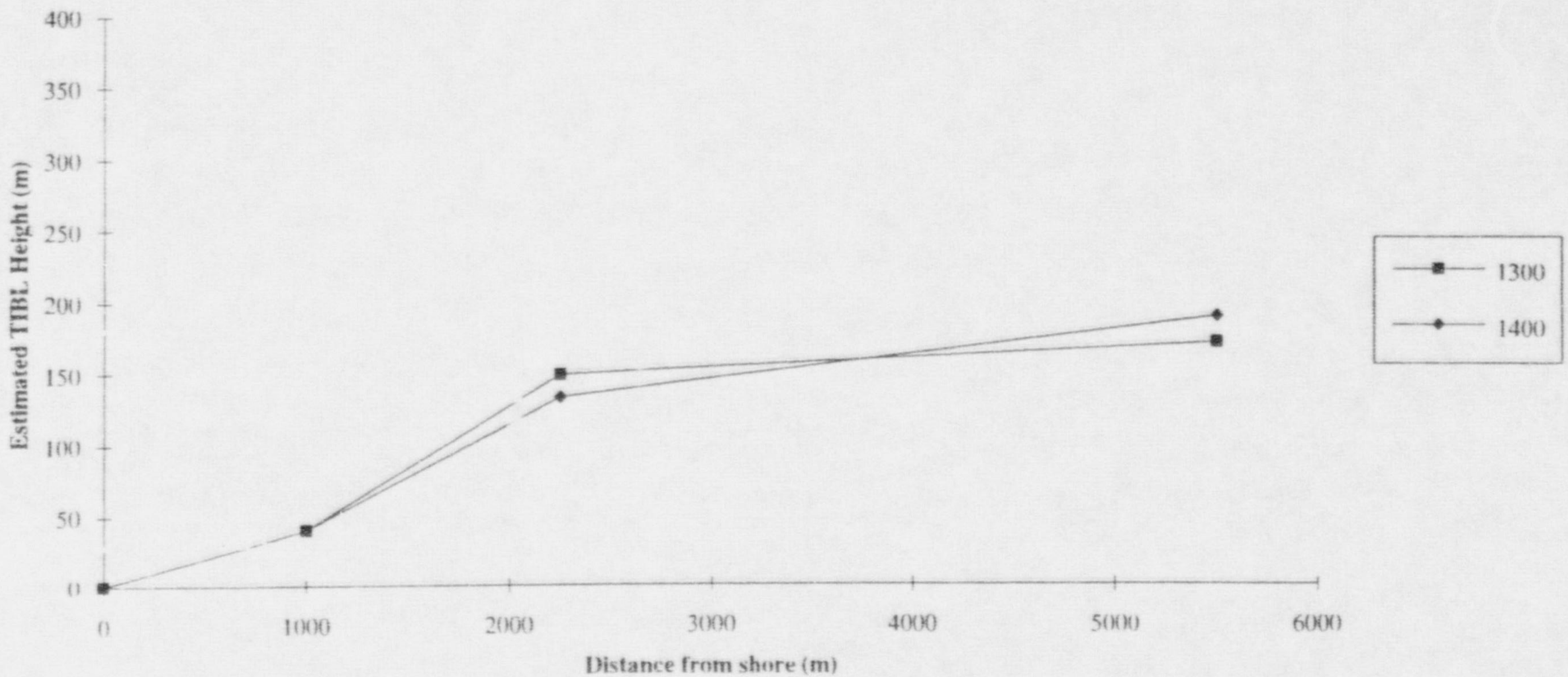


Figure 1-9
Estimated TIBL Height versus Distance from Shore: APR-10-1992

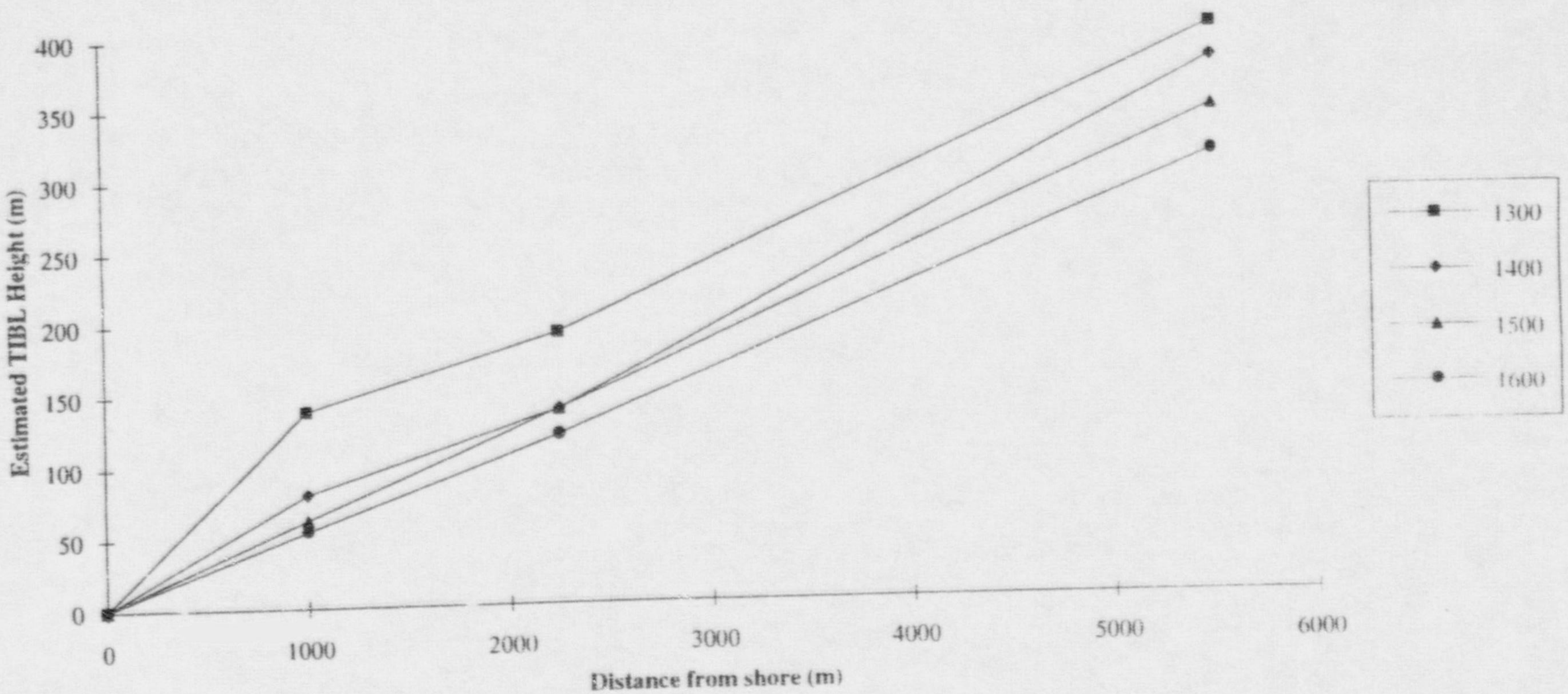


Figure 1-10
Estimated TIBL Height versus Distance from Shore: MAY-6-1992

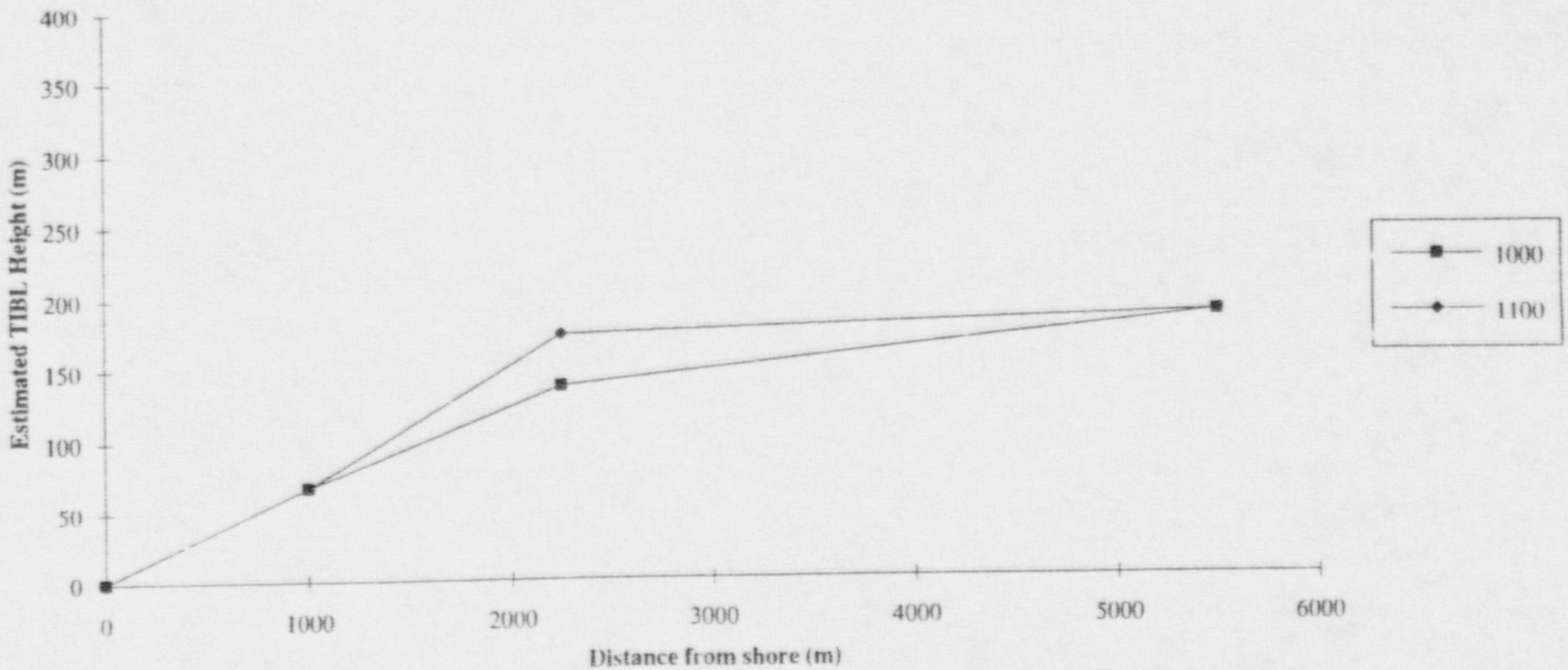


Figure 1-11
Estimated TIBL Height versus Distance from Shore: MAY-14-1992

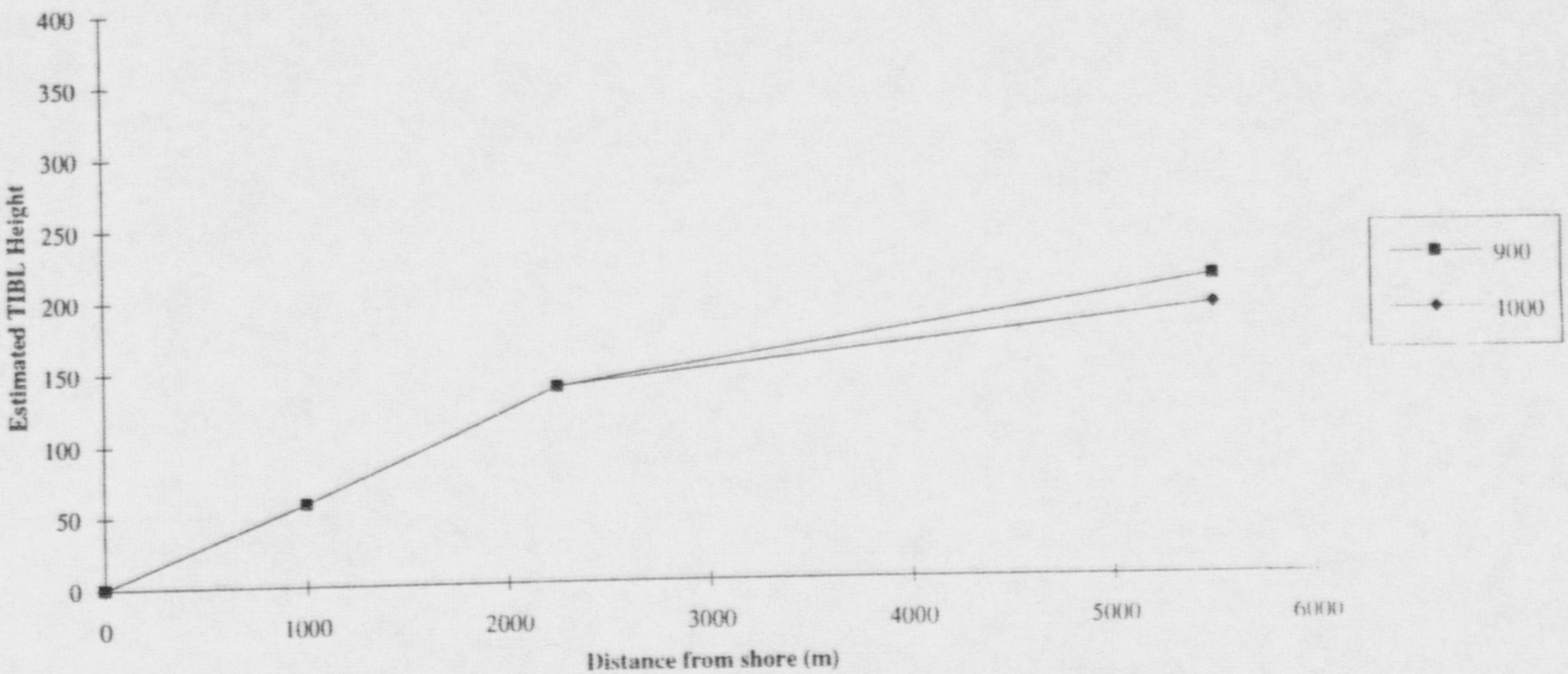


Figure 1-12
Estimated TIBL Height versus Distance from Shore: MAY-15-1992

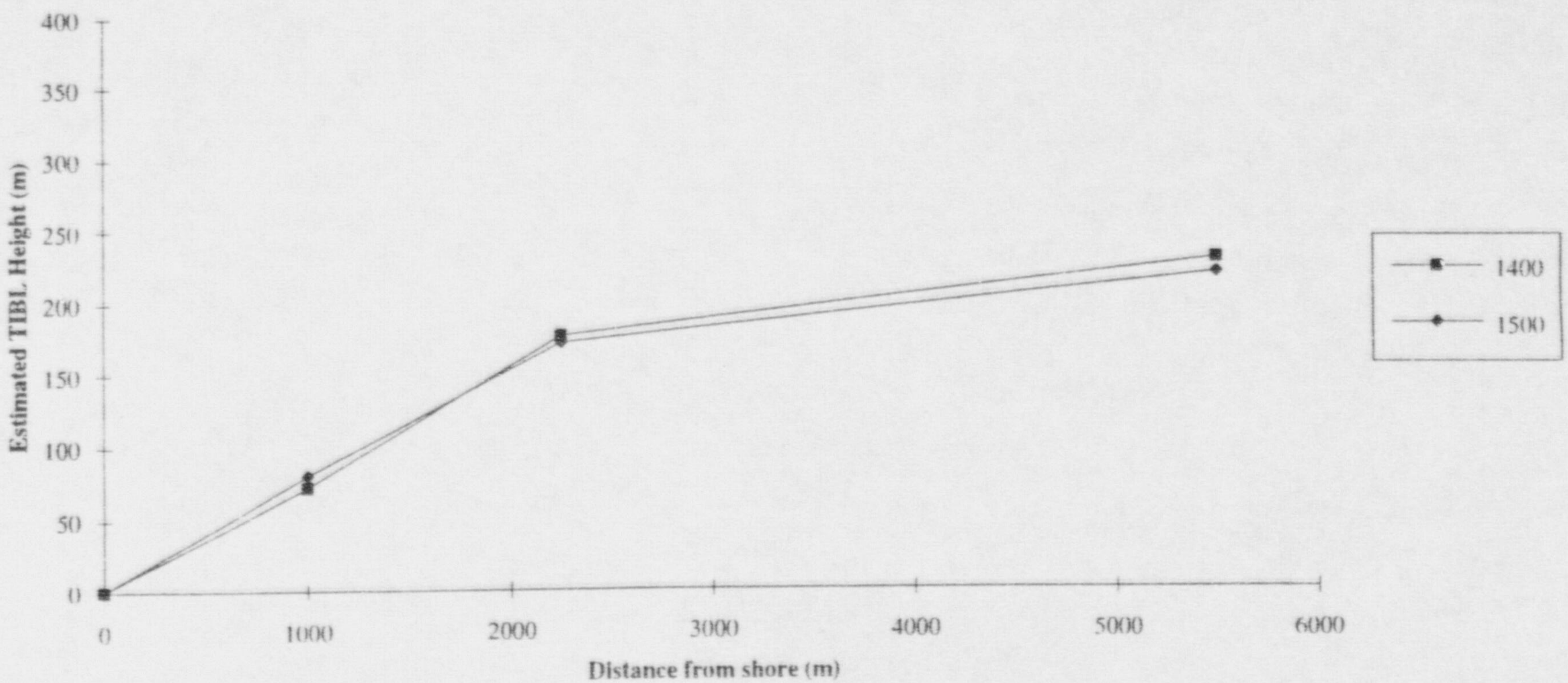


Table 1-1

Percent Data Capture—Monostatic Sounders

Site	Pmtr	1991 Nov	1992 Dec	1992 Jan	1992 Feb	1992 Mar	1992 Apr	1992 May	1992 Jun	1992 Jul	1992 Aug	1992 Sep	1992 Oct	Cumulative
1	ML	71%	70%	62%	96%	98%	99%	99%	99%	99%	99%	99%	99%	90.8%
	VV	99%	99%	76%	86%	99%	99%	99%	99%	99%	99%	99%	99%	96.0%
	VSD[1]	99%	99%	76%	--	99%	99%	98%	99%	99%	99%	99%	99%	96.8%
2	ML	70%	70%	76%	99%	98%	99%	99%	99%	99%	99%	99%	99%	92.2%
	VV	99%	99%	99%	86%	99%	99%	99%	99%	99%	99%	99%	99%	97.9%
	VSD[1]	99%	99%	99%	85%	99%	99%	99%	99%	99%	99%	99%	99%	97.8%
3	ML	71%	71%	73%	99%	97%	99%	99%	99%	99%	99%	99%	99%	92.0%
	VV	99%	99%	99%	99%	98%	99%	99%	99%	99%	99%	99%	99%	98.9%
	VSD[1]	99%	99%	99%	99%	61%	99%	99%	98%	99%	99%	99%	99%	95.8%

Parameter (Pmtr) Abbreviations

ML–Mixing Layer
VV–Vertical Velocity
VSD–Vertical Standard Deviation

Site Locations:

1. Niagara Mohawk Service Road (1 KM inland)
2. Miner Road (2.5 Km inland)
3. New York Route 104 (5 Km inland)

[1] Vertical standard deviation for all three sites did not write to the magnetic disk November 1991 through April 1992. Hard copy printout was not affected.

Table 1-2.
Time Periods Investigated for Potential TIBL Identification

Date	Start Time (EST)	End Time (EST)	Duration (hrs)	Notes (See Below)
11/1/91	1200	1445	2.75	(1)
3/5/92	1315	1530	2.25	(2)
4/8/92	0730	1100	3.50	(1)
4/10/92	1315	1745	4.50	(2)
4/15/92	1100	1330	2.50	(1)
4/24/92	1130	1445	3.25	(3)
5/6/92	0945	1245	3.00	(2)
5/14/92	0630	1100	4.50	(2)
5/15/92	1330	1600	2.25	(2)
5/18/92	0630	1930	12.50	(3)
5/20/92	1130	1630	5.00	(3)
5/25/92	0915	1830	9.25	(4)
5/29/92	1130	1345	2.25	(3)
6/15/92	0845	1315	4.50	(3)
6/16/92	0945	1515	5.50	(4)
7/2/92	0945	1415	4.50	(4)
9/9/92	1045	1400	3.25	(3)
9/13/92	1400	1600	2.00	(4)
10/7/92	1015	1630	6.25	(3)

Notes: (1) Land/Water temperature difference marginal (ie. within 1°C). No TIBL identified.

(2) TIBL identified with high confidence in acoustic sounder data. Detailed in report.

(3) TIBL suspected in acoustic sounder data, but confidence low.

(4) No TIBL identified in acoustic sounder data.

Table 1-3
Frequency (%) of Multiple Mixing Layers
November 1991 through October 1992

	Month												
HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
0	16	36	42	40	29	27	45	42	23	17	30	29	31
1	23	28	23	43	29	20	23	26	30	20	13	16	24
2	26	28	29	43	29	17	23	29	17	20	17	16	24
3	26	28	29	33	36	40	23	32	20	17	23	16	27
4	10	32	29	47	26	30	32	23	23	20	17	29	26
5	19	32	39	50	36	20	29	16	20	3	27	19	26
6	29	20	32	57	32	20	19	16	17	23	27	26	27
7	23	16	42	53	32	47	23	19	20	13	30	32	29
8	26	32	45	47	45	37	36	39	40	13	23	26	34
9	23	36	45	60	26	17	29	26	30	17	33	26	30
10	23	36	32	47	10	27	10	16	30	13	20	10	22
11	26	20	52	50	19	10	10	10	20	10	23	23	23
12	26	36	52	43	29	0	7	16	3	13	27	16	22
13	23	12	55	60	10	7	19	7	10	13	27	10	21
14	16	8	34	43	10	10	10	7	13	13	27	7	17
15	23	24	39	53	13	10	7	19	7	3	20	19	20
16	26	20	39	40	23	13	10	10	10	17	33	26	22
17	42	16	42	53	7	27	13	0	7	10	23	26	22
18	23	24	29	43	10	10	19	0	13	17	23	29	20
19	19	24	29	50	29	33	23	3	23	30	33	26	27
20	19	24	29	37	29	33	16	26	23	23	20	26	25
21	32	24	45	33	32	30	23	45	13	23	17	19	28
22	19	28	29	47	29	30	26	26	23	23	17	16	26
23	10	32	29	47	20	37	23	32	20	20	17	32	26
TOTAL	23	26	37	47	24	23	21	20	19	16	24	22	25

Note: Shading highlights occurrances greater than 50%.

Table 1-4
Observed Temperature, Precipitation and Sunshine Conditions
Syracuse, NY
1992

Month	Temperature Departure (°F)	Precipitation Departure (in)	Percent of Possible Sunshine	
			1992	30-year Mean
March	-4.0	+0.69	42	46
April	-1.7	+0.20	46	50
May	+0.5	+2.05	58	55
June	-2.3	-1.85	63	59
July	-3.6	+4.24	44	64
August	-1.8	-1.13	57	59

Section 2.0

Evaluation of Stability Classification Schemes

This section presents the results of a one-year evaluation of various atmospheric stability classification schemes in the shoreline zone near the vicinity of the Nine Mile Point Nuclear Facility (NMP). Classification of stability is an important input parameter to models which describe the transport and dispersion of effluent from the facility. A variety of techniques exist for defining the atmospheric stability. A special micrometeorological tower was installed near NMP to collect data allowing the calculation of stability using a variety of techniques. These calculations were compared with stability classifications from an existing 200 ft meteorological tower. A background description of stability classification is provided in Section 2.1 and the study objective presenting in Section 2.2. A summary of the monitoring equipment and the various stability classification schemes calculated is provided in Section 2.3, and the data analysis results in Section 2.4. Conclusions and recommendations are provided in Section 2.5.

2.1 Background

Knowledge of the atmospheric stability is critical in most applications involving prediction of pollutant dispersion since the stability defines the degree to which the effluent will spread in both the vertical and horizontal dimensions as it travels away from the point of emission. Most pollutant impact and dispersion predictions are performed with models employing the Gaussian plume approach. Gaussian plume Models employ a three-dimensional axis system of downwind, crosswind and vertical components; assume that the concentrations from a continuously emitting plume are proportional to the emission rate; and that these concentrations are diluted by the wind at the point of emission at a rate inversely proportional to the wind speed; and that the time-averaged (generally about 1-hour) pollutant concentrations crosswind and vertically near the source are well described by gaussian or normal distributions (Turner, 1984).

The degree of spreading is a function of the atmospheric stability. The standard deviations of plume concentration in the vertical (σ_y) and horizontal (σ_z) dimensions are empirically related to the level of atmospheric turbulence (stability) with distance from the source. One inherent uncertainty in Gaussian

Plume Modeling results from the complex and random nature of the atmospheric turbulence which controls dispersion. Models must parameterize this random complexity but, by definition, cannot describe it completely.

2.1.1 Stability Classification Schemes

Atmospheric stability is a function of both thermal and mechanical interactions between the surface and air overlying the surface. In the case of thermally-based interactions, during the day, solar heating of the ground in turn heats the air in contact with the ground, resulting in warmer, less dense air underneath cooler, dense air. This results in an "over turning" of the atmosphere with warmer air rising and being "replaced" by cooler air. This thermal turbulence describes an *unstable* atmosphere. Alternatively, at night, radiative cooling of the ground cools the air in contact with it, leaving cooler, dense air underneath warmer, less dense air. The result is a thermally *stable* condition. In the case of mechanical atmospherics turbulence, the interaction of horizontally transported air with the ground surface is the basis for the production of turbulence. In other words, air traveling over a rough surface (e.g. forests, hills, mountains, buildings, etc.) is relatively unstable compared to air traveling over smooth surfaces (e.g. water, mown fields, snow, etc.).

Once the characteristic air motions of stable and unstable atmospheric conditions are understood, the implications to the dispersion and spreading of pollution plumes become clear. Under unstable conditions, a high level of turbulence results in rapid mixing and dispersion of the pollutant in both the vertical and horizontal dimensions. In a stable atmosphere, turbulence is suppressed, leading to slow dispersion of pollutant plumes.

Atmospheric stability can vary significantly on a daily basis, ranging from an extremely stable atmosphere during a clear, cool, calm night, to a very unstable atmosphere during a warm, sunny day. In general, thermally-based causes result in the wide variations over the course of a day, while mechanically-based causes are slower to change. The situation is complicated somewhat, particularly in the vicinity of a large water body due to the differing heat capacity of water relative to the land. At night, the water can be a heat source, resulting in unstable conditions even though night is typically considered relatively stable due to the lack of solar influence.

Parameterization of stability for the purposes of dispersion modeling has been investigated by a number scientists since gaussian plume models first came into wide use. The infinite combination of atmospheric stability and dispersion characteristics necessitated stability parameterization (classification) in order to account for the random nature of atmospheric turbulence while providing a computationally straight forward method of predicting dispersion. Classification of the degree of stability (Extremely stable, slightly stable, neutral, slightly unstable, extremely unstable) has been performed for many decades. The common practice of defining stability into one of six (A through F) or seven (A through G) stability classes was introduced by Pasquill, where A is least stable, F (or G) is most stable, and D is neutrally stable. These stability classes are then used to determine dispersion coefficients for use in the Gaussian plume equation using empirically derived relationship.

Stability classification techniques employing routinely available meteorological data (such as that obtainable from National Weather Service observations) have been developed which use observations of wind speed and cloud cover. Alternative techniques using combinations of various measurements of solar radiation, net radiation, standard deviation of wind direction, and vertical wind and temperature profiles have also been applied.

2.1.2 Applications to Nuclear Facilities

In compliance with Federal Regulation 10CFR50.47 regarding emergency planning, nuclear power generating facilities in the United States are required to have "adequate methods, systems, and equipment for assessing and monitoring of actual or potential offsite consequences of a radiological emergency condition." In order to meet the meteorological aspects of this regulation, nuclear power generators must have the capability of making near real-time predictions of the transport and diffusion of effluent from their facilities. In order to make such predictions, meteorological data capable of describing the atmospheric stability is vital.

As introduced above and described in greater detail in Section 2.3, many different approaches have been applied to calculate the stability class. However agreement between the various techniques has been shown to be poor, making selection of the appropriate technique in an operational setting difficult. This situation is complicated further in coastal areas, where inhomogeneities in surface characteristics result in spatially varying stability classes near the surface. As a consequence, comparisons of the various stability classification schemes is necessary to determine which techniques most reasonably represent the stability and dispersive characteristics of the atmosphere within the mixed layer.

2.2 Study Objective

The objective of this task was to install and operate a 10 m micrometeorological tower for a period of one year in the vicinity of NMP for the purpose of evaluating various atmospheric stability classification techniques.

2.2.1 Study Goal

The goal of this task was to successfully operate the 10 m micrometeorological tower for a period of one year, develop software to calculate stability class from the data using seven different stability classification methods, intercompare the stability calculations from the micrometeorological tower data and existing 200 ft meteorological tower, and evaluate the various stability classes for use in the shoreline environment of NMP.

2.2.2 Potential Applications for research

As indicated in the task objectives, the evaluation of various stability classification schemes will serve as the basis for identifying those schemes which are appropriate for use as input parameters to models predicting the transport and diffusion of pollutants in a shoreline location. This research provides information of interest to utilities that must perform dispersion modeling in coastal zones where use of various schemes can result incorrect stability classification for the observed meteorological condition.

2.3 Approach

In order to collect data for evaluating the various stability classification techniques, a 10-meter meteorological tower was installed approximately 1 km southwest of NMP for a period of 12-months.

The following describes the monitoring system including the instrumentations installed, the sampling, data validation and calibration methods, and a description of the various stability classification schemes using the data.

2.3.1 Description of Monitoring System

A 10-meter meteorological tower (MMT) was located in an open area approximately 0.75 km from Lake Ontario on the southeastern shore (See Table 1-x and Figure 1-x). Instrumentation on this tower measured the following parameters:

- Wind speed at 2 and 10 m,
- Wind direction at 10 m,
- Standard deviation of wind direction at 10 m,
- Temperature at 2 m,
- Temperature difference between 2 and 10 m,
- Solar radiation, and
- Net-radiation.

A schematic representation of the installed tower is shown in Figure 2-1.

Since the height difference of temperature and wind speed measurements was so small, differences in the wind speed and temperature were also small. This necessitated careful selection of the sensors used to make the measurements. All instrumention selected met or exceeded the precision and accuracy requirements outlined in the USEPA On-site Meteorological Monitoring Program Guidance for Regulatory Modeling Applications (USEPA, 1987). In addition, a strict quality control program including six full systems calibrations and twice weekly site visits by the site operator assured high quality data with a very high data recovery rate. The final data recovery statistics for the MMT parameters are provide in Table 2-1.

2.3.2 Sampling Technique and Data Validation

Data was stored digitally on a data logger, and averaged for later analysis. Averages were obtained for all parameters at 15-minute intervals. Data was routinely downloaded to a central computer twice per week. Raw data files were merged with the complete data base, then passed through a screening program designed to note and flag questionable data. Flagged data were reviewed by a meteorologist familiar with the operation of the site. Discrepancies were resolved where possible and corrective action taken when necessary. Data validation procedures were in compliance with USEPA recommended techniques, and questionable data was removed from further analysis. All stability classifications discussed in the next section were calculated during post-processing of the validated data file.

2.3.3 Data Analysis

Using the data from the micrometeorological tower, a variety of stability classifications were calculated for a period of 1-year. Stability data were available every fifteen minutes. Following is a brief overview of the seven stability classification techniques used to analyze the unique situation observed at a Lake Ontario site.

2.3.3.1 Objective Technique

In order to provide a baseline stability class against which to judge the performance of the other stability classification techniques, an objective scheme was employed to determine baseline Pasquill stability classes (Pasquill 1961). The technique uses the 10 meter wind speed, time of day, change in temperature between 2 and 10 meters, and the cloud cover (through solar radiation) to classify stability for 15-minute periods. Day and night were determined using the USEPA recommended approach (night = one hour before sunset to one hour after sunrise). The technique is summarized in Table 2-2.

2.3.3.2 Sigma-theta

The sigma-theta stability classification technique uses the standard deviation of horizontal wind direction as an indicator of atmospheric stability. The most commonly applied technique is that recommended by the USEPA (1987), where high values of sigma-theta are associated with unstable stability classes, and lower values with stable conditions. Wind speeds are also incorporated into the method, by restricting the stability class to neutral anytime winds are above 6 m/s.

This technique is relatively easy to apply in practice, however it is limited to actual measurement of horizontal stability, while failing to explicitly measure vertical stability. Stabilities are restricted to unstable and neutral classes during the day, and neutral and stable classes during the night. This latter adjustment is suggested in order to account for reduced thermal fluxes between the ground and atmosphere at night (no solar heating), and the increased fluxes during the day (solar heating).

In addition to the adjustment of stability class based upon the wind speed, adjustments have been suggested to account for site-specific influences which may create localized mechanical turbulence. The base category boundaries were established for sites with a roughness length (z_o) of 15 cm. However, if the monitoring site has a roughness length other than 15 cm, a category adjustment technique was proposed by Irwin (1980). The technique employs a correction to the stability boundaries based upon the following:

$$\sigma_\theta(z_o)=\sigma_\theta(15cm)\times(\frac{z_o}{15})^{0.2}$$

For the micrometeorological tower, the average surface roughness was determined for each of eight wind direction sectors (N, NE, E, ..., etc.), and the stability categories adjusted by the appropriate amount. The average surface roughness for each sector was determined using the following equation developed from the neutral wind profile and proposed by Schulman and Haga (1991):

$$z_o=z\exp(\frac{-0.68}{\sigma_\theta(z)})$$

Table 2-3 details the boundaries of standard and site-specific sigma-theta techniques employed in the analysis of the data. Note that the data from the 9MP tower used the NRC approach which does not employ a correction to the sigma-theta category values for surface roughness or to stability categories for day or night. Stability calculated using data from the 10 m tower was determined using the standard USEPA techniques, both with and without corrections to the sigma-theta categories to account for surface roughness and with adjustments to stability class for day and night, as detailed in Table 2-3.

2.3.3.3 Delta-temperature

Direct measurement of the vertical temperature gradient (delta-temperature) between two specific elevations is another technique for classifying stability. Lapse rates less than neutral are considered unstable, while conditions are classified as stable when the lapse rate is greater than neutral. The

NRC recommends measurement of delta-temperature between 10 and 60 meters, as well as between 10 meters and a higher elevation representative of the stack release height. This technique is independent of wind speed, however no modification is performed to protect against stable classes occurring during the day or unstable conditions being selected at night. Table 2-4 provides the NRC delta-temperature stability classification criteria.

Alternatively, the USEPA (1993) has suggested measurements of delta-temperature at lower elevations (between 2- and 10- meters), which is likely to produce observations more sensitive to thermal fluxes between the atmosphere and the ground. However, USEPA suggests using the technique as a substitute for sigma-theta at night when wind speeds are frequently light and sigma-theta measurements can indicate unstable conditions even though the lapse rate is stable. The USEPA delta-temperature method includes an adjustment to the stability class depending on the wind speed.

2.3.3.4 Solar Radiation/Delta-Temperature

In order to better justify the effects of solar heating on stability, USEPA (1993) suggested that stability classification using a combination between the delta-temperature method and actual measurements of incoming solar radiation at the surface might be appropriate. The delta temperature method is recommended for determining stability classes during the night hours, while during the day, solar radiation measurements are used. High values of incoming solar radiation indicate significant solar heating and unstable conditions, while low values demonstrate limited solar heating and more stable conditions.

Again, the stability classes are adjusted to account for the effects of mechanical mixing using wind speed data for both day and night. Stabilities are restricted to unstable and neutral classes during the day, and neutral and stable classes during the night. The classification criteria are presented in Table 2-5.

2.3.3.5 Net Radiation and Wind Speed

Another stability classification method makes use of net radiation measurements and wind speed as proposed by Williamson and Krenmayer (1980). The concept of this technique is to better account for the interaction of thermal fluxes between the atmosphere and the ground. Conditions are said to be unstable with low wind speed and high net radiation values, and more stable with high wind speed and low net radiation.

Again, as with other techniques, stabilities are restricted to unstable and neutral classes during the day, and neutral and stable classes during the night. In addition, net radiation limits used in identifying stability classes vary to account for order of magnitude changes in net radiation values between day and night. The stability classification criteria are presented in Table 2-6.

2.3.3.6 Solar Radiation and Wind Speed (Day)/Net Radiation and Wind Speed (Night)

An alternative to using net radiation and wind speed for the entire day is to use solar radiation measurements instead of net radiation during the day (Williamson and Krenmayer, 1980). This technique is similar to the net radiation method described above, with unstable classifications during low wind speed and high solar radiation, and more neutral stabilities with high wind speed and low solar radiation values. Again, stable classes are not allowed during the day. The night-time stability criteria are the same as those determined Section 2.3.3.5, above, while the daytime stability criteria are shown in Table 2-7.

2.3.3.7 Richardson's and Bulk Richardson's Numbers

Recently, improved accuracy of commercial meteorological instrumentation has allowed the measurement of more detailed meteorological quantities, and thus stability classifications that better account for both thermal and mechanical turbulence. Both the Richardson's and Bulk Richardson's numbers are closer to an actual measurement of stability, since they use both lapse rate and vertical wind speed gradient as measures of the production of convective and mechanical turbulence (Schulman and Haga, 1991).

The Richardson's number is defined by the following equation:

$$Ri=\frac{g}{T}\left(\frac{\delta\theta/\delta z}{(\delta u/\delta z)^2}\right)$$

where $g \equiv$ gravitational acceleration,
$T \equiv$ surface temperature,
$\delta\theta/\delta z \equiv$ vertical change in potential temperature, and
$\delta u/\delta z \equiv$ vertical change in wind speed.

Negative Richardson's numbers are classified as unstable because convective turbulence is indicated by the negative $\delta\theta/\delta z$ term. Positive Richardson's numbers are stable since the positive $\delta\theta/\delta z$ term indicates that convective turbulence is suppressed. Under neutral conditions, the Richardson's number approaches zero, indicating that convective and mechanical turbulence are equally important. No adjustments to the observed stability are made for day or night conditions, thus unstable stabilities can occur at night and stable conditions during the day.

The Richardson's number limits used to categorize Pasquill stabilities were determined using the technique described by Schulman and Haga (1991) where

$$Ri = \frac{(z/L)\phi_h}{\phi_M^2}$$

L is defined as the Monin-Obukov length and is the depth of the surface layer dominated by mechanical turbulence. The z term is the geometric mean height of the two measurement levels. The terms ϕh and ϕm represent the temperature and wind speed profiles for non-neutral conditions and are a function of z and L. As described by Schulman and Haga, the values of L as a function of roughness length (z_o) using a series of equations fit the a graph developed by Golder (1972) relating stability class to L.

The Bulk Richardson's number is given by the following expression:

$$Ri_b = \frac{g}{T}\left(\frac{\delta\theta/\delta z}{u^2}\right)z^2$$

The parameters are defined as previously except u is the 10m wind speed. From an operational standpoint, this technique is simpler to apply than the Richardson's number in that wind speed need only be measured at one level. The response of the Bulk Richardson's number is essentially the same as with the Richardson's number.

The stability limits of the Bulk Richardson's number can be calculated from the Richardson's number limits by

$$Ri_b = \frac{Ri\phi_m^2}{[\ln(z/z_o) - \psi]^2}$$

where the terms are as described previously except for ψ which is a correction to the logarithmic wind profile and is a function of ϕ_m, z, and L.

2.3.4 Data Analysis

In addition to calculating various stability classes using the MMT data, data from the 30 ft, 100 ft, and 200 ft levels of the NMP 9MP tower were also treated. Stability classes were determined using the techniques applied currently applied at NMP, namely sigma-theta (without correction for wind speed and surface roughness) and delta-temperature (200-30 ft and 100-30 ft). The stability classification criteria for sigma-theta and delta-temperature were defined as in Tables 2-3 and 2-4, respectively.

2.4 Data Analysis Results

Validated fifteen-minute stability classifications for each of the methods described in Section 2.3 are provided separately on computer disk. Frequency distributions of all stability classification techniques developed using the MMT and 9MP data are provided in Appendix A. The frequency distributions are provided for all hours combined, as well as separated by various site-specific criteria (Season, Flow Direction, and Time of Day).

The stability frequency tables show wide variation between the various stability classification techniques. The widely used and tested sigma-theta technique shows the expected tendency to a normal distribution centered around neutral stability. The delta-temperature technique also shows some trend toward a normal distribution, however, some radical departure is noted. The 30 to 200 ft 9MP delta-temperature distribution appears to be more appropriate than the 2 to 10 m or 30 to 100 ft approaches. The MMT solar radiation (day), delta-temperature (night) also appears to show the expected distribution of stabilities. The less used and tested Richardson's number and Williamson and Krenmayer techniques are more radical in there stability distributions, tending to predict either stable or unstable conditions and minimal neutral flow.

Separation of the data by onshore flow (wind directions between 245° and 25°) and offshore flow (wind directions between 85° and 230°) show that most techniques have the expected responses to the differing flow conditions. In general, more unstable classes were observed during onshore flow when compared to offshore. This is likely due to the effect of onshore advection of unstable lake air, particularly in winter, and the prevalence of a stable, offshore flowing land breeze at night. The significant exception to this result is observed in the sigma-theta results, particularly at the 9MP 100 and 200 ft levels. Since the sigma-theta technique was designed using 10 m data, responses at 100 and 200 ft elevations are not appropriate.

The results of a joint frequency analysis of the stability classification techniques as compared to the baseline objective stability determination are presented in Tables 2-8 through 2-19. These tables emphasize the variability obtained between the various stability classification techniques, and highlight the difficulty in selecting an appropriate stability classification technique.

As shown in Table 2-8, the 2 to 10 m delta-temperature technique tends to be more stable than the objective method at night and slightly less stable during the day. This a result of the use of 2 to 10 m delta-temperature which responds more dramatically to the surface heating during the day, resulting in the development of a super-adiabatic lapse rate near the surface, and significant surface cooling at night and the development of a strong surface based inversion, particularly under clear sky conditions. Typically, one would expect delta-temperature measurements taken over a higher elevation (e.g. 30 to 200 ft) to show less dramatic variation and possibly closer correlation with stability classes developed from the objective technique.

In general, the sigma-theta method of stability classification showed generally good agreement with the objective method, but tended to be less stable at night (Table 2-9). This results in an over prediction of neutral stability (D). It is believed that this results from meander of the night-time wind direction even though the technique employs a nighttime wind speed correction. Perhaps the development and variation of land breeze and drainage winds at this particular site require a modified wind speed correction scheme at night. Alternatively, some of the increase in neutral stabilities may be accounted for by unstable day-time conditions being classified as neutral. This could result from an over-estimation of the site-specific surface roughness correction.

Since the objective scheme and the solar radiation/delta-temperature method are closely related, little difference is noted in the predicted stability classes between the two techniques. The results of this joint frequency analysis are shown in Table 2-10.

Both the Williamson and Krenmayer methods (wind speed corrected net-radiation and solar radiation/net-radiation) show significant differences from the objective scheme and require additional analysis (Table 2-11 and Table 2-12, respectively). In both cases, the methods predicted less stable conditions during the day and more stable conditions at night. It is believed that this is due to the inclusion of net-radiation, which is sensitive to local ground cover conditions. Subjective observations over the course of monitoring indicated that the MMT site ground cover had, on average, a slightly higher albedo than the surroundings within 1 km since the immediate location around the tower was mown grass while much of the area is thickly green with bushes and trees. Another interesting observation is the lack of "E" stability classes at the site predicted by the Williamson and Krenmayer methods. This is believed to be a site specific feature, but is deserving of further investigation.

Both the Richardson's Number and the Bulk Richardson's Number were expected to provide the most realistic assessment of stability due to the methods' accounting of both thermal and mechanical stability (Schulman and Haga, 1991). However, as shown in Tables 2-13 and 2-14, the techniques tend to be more radical than any of the other methods in that they tend to predict either very unstable or very stable conditions with little consideration for neutral conditions. This is a little surprising since the monitoring location tended to be fairly windy, resulting in greater mechanical mixing which should lead to frequent observations of neutral stability. These techniques are rather complex due to the "dynamic" measurements required. Further investigation beyond the scope of this study would be appropriate, perhaps to further adjust the stability class ranges on a site-specific basis.

Comparison of the 9MP tower stabiltiy classifications with the objective scheme from the 2 to 10 m tower are provided in Table 2-15 through 2-19. Tables 2-15, 2-16, and 2-17 show the results for sigma-theta measurements at the 30, 100, and 200 ft levels, respectively.

2.5 Conclusions and Recommendations

Regulatory schemes for stability classification have been developed to be easily transportable to a variety of locations. The results of this study show that indiscriminate use of any given stability classification technique can lead to estimates of stability that are widely different from that expected using traditional methods. In selecting a stability classification technique, it is important to carefully consider the siting and vertical extent of tower-based measurements. From this analysis, the following conclusions can be drawn:

- Local conditions must be factored into a determination of the most appropriate stability class and, therefore, the selection of appropriate dispersion coefficients. In cases involving complex meteorology (i.e. coastal zones), consideration should be given to the collection of stability data at heights close to release elevation. Ground level releases should employ near surface stability classifications such as those obtained using the 2 to 10 m micrometeorological tower, while elevated releases should emply stability classes representative of the height of release such as those obtained from the 200 ft meteorological tower (9MP).

- In addition to considering siting and measurement protocol, the boundaries used to define specific stability classes may require adjustment on a case-by-case basis. This is particularly true of the sigma-theta, Richardson's and Bulk Richardson's Number, and Williamson and Krenmayer techniques.

- When employing the sigma-theta method for specifying stability from the 30 ft level of the 9MP tower, a site-specific correction for surface roughness is suggested to account for localized mechanical effects.

- 100 and 200 ft sigma-theta should not be used to determine stability class using exisiting classification criteria since these were developed using 10 m data. If 100 and 200 ft classification are used, the stability classification criteria should be revised to reflect the different mechanical and thermal stability conditions found at higher elevations.

- For elevated releases, use of the 30 to 200 ft delta-temperature is recommended to account for the broad vertical variation in stability resulting form near-surface thermal fluxes and mechanical effects and smoother elevated flow.

- For near-surface releases, use of the sigma-theta method from either the 2 to 10 m tower or the 30 ft level of the 9MP tower are recommended. The sigma-theta method should include a site-specific surface roughness correction developed similarly to that described above.

Further analysis of the data collected is recommended. A review of the tendency for some techniques to predict stability extremes rather than a distribution as is typically observed using traditional stability classification techniques is necessary. Further analysis may allow definition of site specific stability class boundaries for the Richardson's Number and Bulk Richardson's number criteria.

In summary, generalized limitations on stability classifications may be inappropriate for use at shoreline locations where complex meteorological phenomena result in varying stability in both the horizontal and vertical dimensions. In particular, stability classification methods which assume that the only source of thermal heating is solar radiation may be inappropriate in environments where the advection of unstable air may be important, such as that encountered in a coastal environment.

2.6 References

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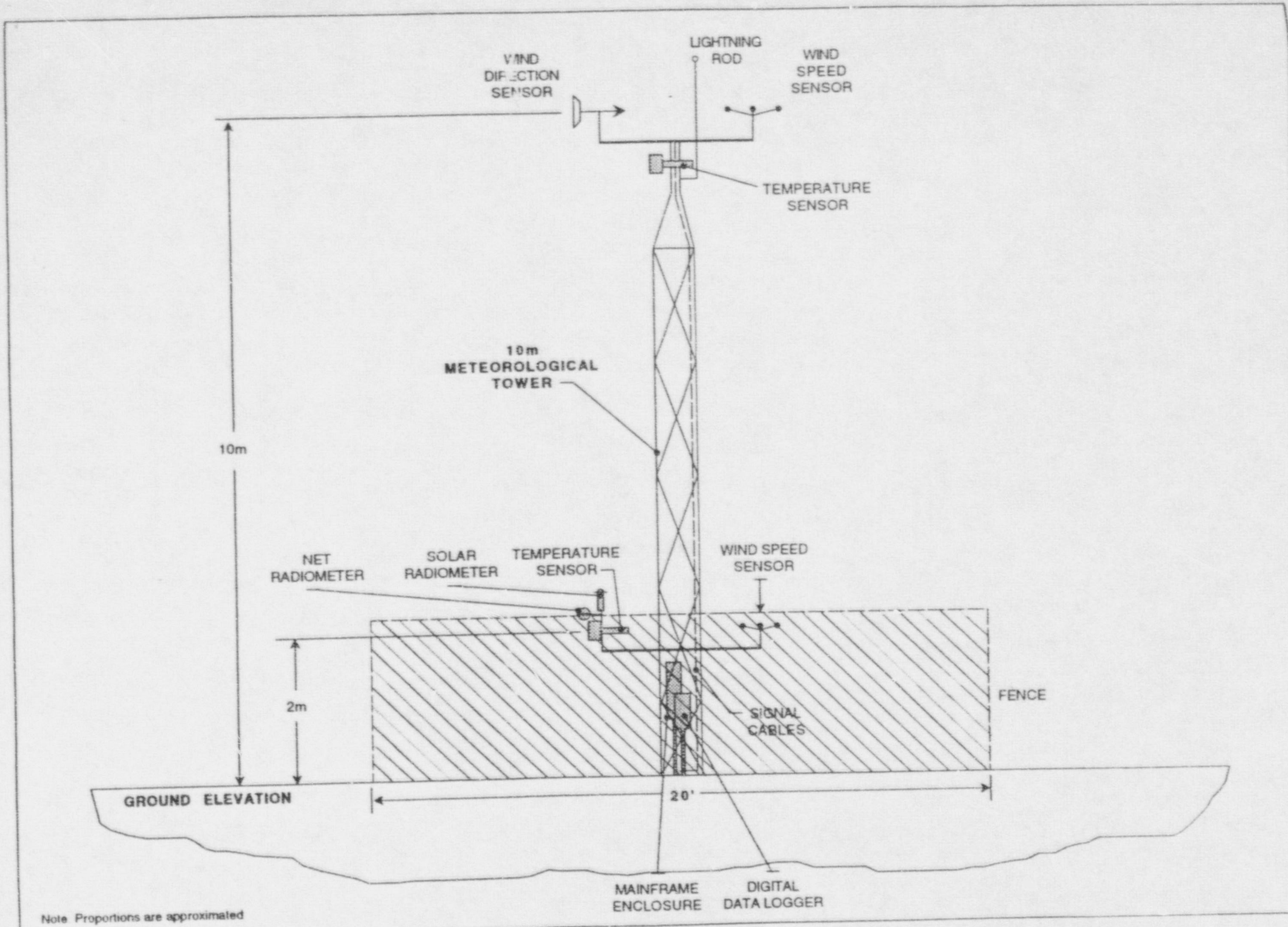

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Figure 2-1. Micrometeorological tower installation schematic.

Table 2-1
Percent Data Capture[1]—Micrometeorological Tower, All Hours
October 1991 through September 1992

Site	Pmtr	1991 Oct	1991 Nov	1991 Dec	1992 Jan	1992 Feb	1992 Mar	1992 Apr	1992 May	1992 Jun	1992 Jul	1992 Aug	1992 Sep	1992 Oct	Total
MMT	2MWS	99.8%	100.0%	99.6%	99.4%	100.0%	100.0%	99.1%	100.0%	99.9%	99.6%	100.0%	100.0%	99.6%	99.8%
	10MWD	99.7%	100.0%	99.5%	99.5%	100.0%	100.0%	99.1%	100.0%	99.9%	99.6%	99.9%	100.0%	99.6%	99.8%
	10MWS	99.6%	100.0%	99.5%	99.5%	100.0%	100.0%	99.1%	100.0%	99.9%	99.6%	100.0%	100.0%	99.6%	99.8%
	2MTP	99.7%	100.0%	99.7%	99.5%	100.0%	100.0%	99.1%	100.0%	99.9%	99.6%	100.0%	100.0%	99.6%	99.8%
	DELT	99.6%	100.0%	99.7%	99.5%	100.0%	100.0%	99.1%	100.0%	99.9%	99.6%	100.0%	100.0%	99.6%	99.8%
	SR	99.9%	100.0%	99.7%	99.5%	100.0%	100.0%	99.1%	100.0%	99.9%	99.6%	100.0%	100.0%	99.6%	99.8%
	NR	99.9%	67.3%	99.7%	99.5%	100.0%	100.0%	99.1%	100.0%	99.9%	99.6%	100.0%	100.0%	99.6%	97.3%
	SIGT	98.7%	99.5%	99.0%	99.8%	99.7%	94.2%	93.7%	99.4%	99.4%	97.8%	99.2%	99.2%	99.0%	98.4%

Parameter (PMTR) Abbreviations:

MMT—Micrometeorological Tower
10MWD—10 Meter Wind Direction
2MTP—2 Meter Temperature
SR—Solar Radiation
SIGT—Sigma Theta
2MWS—2 Meter Wind Speed
10MWS—10 Meter Wind Speed
DELT—Delta Temperature (10m—2m)
NR—Net Radiation

[1] Percent Data Capture is based on data collection beginning October 18, 1991, at 12:00 EST.

Table 2-2. Summary of the Objective Stability Classification Scheme used as the baseline for comparison to alternative schemes.

	Day			Night	
	Incoming Solar Radiation (ly/min)			Delta Temperature	
Wind Speed	> 1.0	0.5 to 1.0	< 0.5	(T_{2m} - T_{10m})	
m/s	Strong	Medium	Slight	Negative	Positive
≤ 2	A	A	B	E	F
2 to 3	A	B	C	E	F
3 to 5	B	B	C	D	E
5 to 6	C	C	D	D	D
≥ 6	C	D	D	D	D

Table 2-3. Stablity Classification Criteria based on the Sigma-theta Method.

Stability Class	Standard Classification Criteria	Site-specific sector-based turbulance criteria for determining stability class using Sigma-Theta (σ_θ) Method							
		N	NE	E	SE	S	SW	W	NW
	(z_o = 15 cm)	(z_o = 18 cm)	(z_o = 22 cm)	(z_o = 25 cm)	(z_o = 22 cm)	(z_o = 27 cm)	(z_o = 70 cm)	(z_o = 41 cm	(z_o = 31 cm
A	$\sigma_\theta \geq 22.5°$	$\sigma_\theta \geq 23.3°$	$\sigma_\theta \geq 24.3°$	$\sigma_\theta \geq 24.9°$	$\sigma_\theta \geq 24.3°$	$\sigma_\theta \geq 25.3°$	$\sigma_\theta \geq 30.6°$	$\sigma_\theta \geq 27.5°$	$\sigma_\theta \geq 26.0°$
B	$17.5° \leq \sigma_\theta < 22.5°$	$18.1° \leq \sigma_\theta < 23.3°$	$18.9° \leq \sigma_\theta < 24.3°$	$19.4° \leq \sigma_\theta < 24.9°$	$18.9° \leq \sigma_\theta < 24.3°$	$19.7° \leq \sigma_\theta < 25.3°$	$23.8° \leq \sigma_\theta < 30.6°$	$21.4° \leq \sigma_\theta < 27.5°$	$20.2° \leq \sigma_\theta$ 26.0°
C	$12.5° \leq \sigma_\theta < 17.5°$	$13.0° \leq \sigma_\theta < 18.1°$	$13.5° \leq \sigma_\theta < 18.9°$	$13.8° \leq \sigma_\theta < 19.4°$	$13.5° \leq \sigma_\theta < 18.9°$	$14.1° \leq \sigma_\theta < 19.7°$	$17.0° \leq \sigma_\theta < 23.8°$	$15.3° \leq \sigma_\theta < 21.4°$	$14.5° \leq \sigma_\theta < 20.2°$
D	$7.5° \leq \sigma_\theta < 12.5°$	$7.8° \leq \sigma_\theta < 13.0°$	$8.1° \leq \sigma_\theta < 13.5°$	$8.3° \leq \sigma_\theta < 13.8°$	$8.1° \leq \sigma_\theta < 13.5°$	$8.4° \leq \sigma_\theta < 14.1°$	$10.2° \leq \sigma_\theta < 17.0°$	$9.2° \leq \sigma_\theta < 15.3°$	$8.7° \leq \sigma_\theta < 14.5°$
E	$3.8° \leq \sigma_\theta < 7.5°$	$3.9° \leq \sigma_\theta < 7.8°$	$4.1° \leq \sigma_\theta < 4.1°$	$4.2° \leq \sigma_\theta < 8.3°$	$4.1° \leq \sigma_\theta < 8.1°$	$4.1° \leq \sigma_\theta < 8.4°$	$5.2° \leq \sigma_\theta < 10.2°$	$4.6° \leq \sigma_\theta < 9.2°$	$4.4° \leq \sigma_\theta < 8.7°$
F	$\sigma_\theta \leq 3.8°$	$\sigma_\theta \leq 3.9°$	$\sigma_\theta \leq 4.1°$	$\sigma_\theta \leq 4.2°$	$\sigma_\theta \leq 3.1°$	$\sigma_\theta \leq 4.1°$	$\sigma_\theta \leq 5.2°$	$\sigma_\theta \leq 4.6°$	$\sigma_\theta \leq 4.4°$

Wind Speed Adjustments to Stability Class Determined using Site-specific Sigma-theta Method

	Initial Class	Wind Speed (m/s)	Adjusted Class
Daytime	A	ws < 3	A
		3 ≤ ws < 4	B
		4 ≤ ws < 6	C
		ws ≥ 6	D
	B	ws < 4	B
		4 ≤ ws < 6	C
		ws ≥ 6	D
	C	ws < 6	C
		ws ≥ 6	D
	D,E,F	Any	D

	Initial Class	Wind Speed (m/s)	Adjusted Class
Nighttime	A	ws < 2.9	F
		2.9 ≤ ws < 3.6	E
		ws ≥ 3.6	D
	B	ws < 2.4	F
		2.4 ≤ ws <3.0	E
		ws ≥ 3.0	D
	C	ws < 2.4	E
		ws ≥ 2.4	D
	D	Any	D
	E	ws < 5.0	E
		ws ≥ 5.0	D
	F	ws < 3.0	F
		3.0 ≤ ws < 5.0	E
		ws ≥ 5.0	D

Table 2-4. Delta Temperature Criteria

Stability Class	Delta-Temperature (°C/100m)
A	< -1.9
B	-1.9 to -1.7
C	-1.7 to -1.5
D	-1.5 to -0.5
E	-0.5 to 1.5
F	1.5 to 4.0
G	> 4.0

Table 2-5. Solar Radiation (Day)/Sigma-theta (Night) Stability Classification Method.

Wind	Day				Night		
	Incoming Solar Radiation (W/m^2)				Delta Temperature (T_{2m} - T_{10m}) (°C/m)		
(m/s)	> 700	350 to	50 to 350	< 50	< -0.01	-0.01 to	>+0.01
≤ 2	A	A	B	D	D	E	F
2 to 3	A	B	C	D	D	E	F
3 to 5	B	B	C	D	D	D	E
5 to 6	C	C	D	D	D	D	D
≥ 6	C	D	D	D	D	D	D

Table 2-6a. Daytime Williamson and Krenmayer Wind Speed Corrected Net Radiation

Wind Speed (m/s)	Net Radiation (ly/min)								
	< 0.05	0.05-0.15	0.15-0.25	0.25-0.35	0.35-0.45	0.45-0.55	0.55-0.65	0.65-0.70	>0.75
0.0-2.3	D	C	B	B	A	A	A	A	A
2.3-2.8	D	C	C	B	B	A	A	A	A
2.8-3.3	D	D	C	C	B	B	B	B	A
3.3-3.9	D	D	C	C	C	B	B	B	B
3.9-4.4	D	D	D	C	C	C	B	B	B
4.4-5.0	D	D	D	C	C	C	C	B	B
5.0-5.4	D	D	D	D	C	C	C	C	B
5.4-5.9	D	D	D	D	C	C	C	C	C
≥5.9	D	D	D	D	D	C	C	C	C

Table 2-6b. Nighttime Williamson and Krenmayer Wind Speed Corrected Net Radiation

Wind Speed (m/s)	Net Radiation (ly/min)				
	≤-0.10	-0.09 to -0.07	-0.07 to -0.05	-0.05 to -0.03	≥-0.03
0.0 - 1.8	F	F	F	F	F
1.8 - 2.8	F	F	F	F	F
2.8 - 3.3	F	F	E	E	E
3.3 - 3.9	E	E	E	E	E
3.9 - 4.4	E	E	E	E	D
4.4 - 4.9	E	E	E	D	D
4.9 - 5.4	E	E	D	D	D
> 5.4	E	D	D	D	D

Table 2-7. Williamson and Krenmayer Wind Speed Correction Solar Radiation (day) / Net Radiation (night).

WindSpeed (m/s)	Solar Radiation (ly/min)							
	< 0.15	0.15-0.35	0.35-0.45	0.45-0.55	0.55-0.75	0.75 0.95	0.95-1.15	> 1.15
0.0-1.8	D	B	B	B	B	A	A	A
1.8-2.8	D	C	C	B	B	B	A	A
2.8-3.3	D	D	C	C	C	B	B	B
3.3-3.9	D	D	C	C	C	C	B	B
3.9-4.4	D	D	D	C	C	C	B	B
4.4-4.9	D	D	D	C	C	C	C	B
4.9-5.9	D	D	D	D	C	C	C	C
> 5.9	D	D	D	D	D	C	C	C

Table 2-8. Joint frequency table (Percent) of objectively determined stability class versus the delta-temperature method for the 2-10 meter tower.

Objectively Determined Stability Class	Delta-Temperature Stability Class: A	B	C	D	E	F
A	4.2	0.0	0.0	0.0	0.0	0.0
B	13.9	0.6	0.5	1.3	0.5	0.2
C	7.6	1.3	1.4	4.5	1.8	0.1
D	1.3	0.4	0.9	11.8	7.5	0.1
E	0.4	0.2	0.6	5.9	8.8	2.1
F	0.0	0.0	0.0	0.0	6.5	15.3

Table 2-9. Joint frequency table (Percent) of objectively determined stability class versus the sigma-theta method for the 2-10 meter tower.

Objectively Determined Stability Class	Sigma-Theta Stability Class: A	B	C	D	E	F
A	1.1	0.9	1.4	0.6	0.0	0.0
B	1.4	2.0	6.9	5.9	0.0	0.0
C	0.1	0.4	5.1	10.5	0.0	0.0
D	0.0	0.0	0.2	21.5	0.4	0.0
E	0.0	0.0	0.0	13.7	3.0	1.1
F	0.0	0.0	0.0	10.9	7.4	3.2

Table 2-10. Joint frequency table (Percent) of objectively determined stability class versus the solar radiation (day)/delta-temperature (night) method for the 2-10 meter tower.

Objectively Determined Stability Class	Solar Radiation/Delta-Temperature Stability Class: A	B	C	D	E	F
A	4.1	0.0	0.0	0.0	0.0	0.0
B	0.0	15.4	0.0	1.3	0.0	0.0
C	0.0	0.0	13.6	3.0	0.0	0.0
D	0.0	0.0	0.0	22.2	0.0	0.0
E	0.0	0.0	0.0	0.0	18.1	0.0
F	0.0	0.0	0.0	0.0	0.0	21.8

Table 2-11. Joint frequency table (Percent) of objectively determined stability class versus the net-radiation method for the 2-10 meter tower.

Objectively Determined Stability Class	Net Radiation Stability Class: A	B	C	D	E	F
A	3.6	0.6	0.0	0.0	0.0	0.0
B	9.1	3.3	2.5	1.9	0.0	0.0
C	0.9	4.8	5.9	4.4	0.0	0.0
D	0.2	0.7	1.2	1.7	0.0	17.5
E	0.0	0.0	0.0	0.0	0.0	17.4
F	0.0	0.0	0.0	0.0	0.0	21.3

Table 2-12. Joint frequency table (Percent) of objectively determined stability class versus the solar radiation (day)/net-radiation (night) method for the 2-10 meter tower.

Objectively Determined Stability Class	Solar Radiation/Net-Radiation Stability Class: A	B	C	D	E	F
A	3.3	0.9	0.0	0.0	0.0	0.0
B	7.4	7.0	0.0	2.4	0.0	0.0
C	0.8	9.4	0.0	5.9	0.0	0.0
D	0.1	1.5	0.2	2.0	0.0	17.5
E	0.0	0.0	0.0	0.0	0.0	17.4
F	0.0	0.0	0.0	0.0	0.0	21.3

Table 2-13. Joint frequency table (Percent) of objectively determined stability class versus the Richardson's Number method for the 2-10 meter tower.

Objectively Determined Stability Class	Richardson's Number Stability Class: A	B	C	D	E	F
A	4.2	0.0	0.0	0.0	0.0	0.0
B	15.5	0.1	0.1	0.1	0.0	1.1
C	11.8	0.4	0.5	0.1	0.0	3.8
D	3.9	0.9	1.2	0.6	0.4	15.2
E	3.4	0.3	0.3	0.0	0.0	14.1
F	0.0	0.0	0.0	0.1	0.0	21.7

Table 2-14. Joint frequency table (Percent) of objectively determined stability class versus the Bulk Richardson's Number method for the 2-10 meter tower.

Objectively Determined Stability Class	Bulk Richardson's Number Stability Class A	B	C	D	E	F
A	4.2	0.0	0.0	0.0	0.0	0.0
B	15.3	0.2	0.2	0.1	0.1	1.1
C	9.4	1.7	1.1	0.8	1.3	2.4
D	1.0	1.4	2.2	4.0	8.0	5.5
E	2.6	0.5	0.4	0.4	0.6	13.5
F	0.0	0.0	0.0	0.0	0.0	21.8

Table 2-15. Joint frequency table (Percent) of objectively determined stability class versus the Sigma-Theta method for 9MP at the 30 ft level.

Objectively Determined Stability Class	9MP 30ft Sigma-Theta Stability Class A	B	C	D	E	F
A	0.3	0.6	1.2	1.3	0.7	0.1
B	0.6	2.4	6.0	4.3	2.5	0.8
C	0.2	1.9	7.5	3.2	3.1	0.9
D	0.1	1.3	7.5	3.6	8.3	1.2
E	0.4	1.8	7.8	5.1	2.2	0.7
F	0.7	1.2	5.2	10.1	3.4	0.7

Table 2-16. Joint frequency table (Percent) of objectively determined stability class versus the Sigma-Theta method for 9MP at the 100 ft level.

Objectively Determined Stability Class	9MP 100ft Sigma-Theta Stability Class A	B	C	D	E	F
A	0.2	0.3	0.7	1.1	1.1	0.8
B	0.3	0.5	2.6	4.8	4.4	4.1
C	0.0	0.1	2.1	7.1	3.9	3.4
D	0.0	0.0	1.1	7.9	8.1	5.0
E	0.1	0.2	1.5	9.1	4.6	2.5
F	0.2	0.2	1.1	5.5	8.7	5.8

Table 2-17. Joint frequency table (Percent) of objectively determined stability class versus the Sigma-Theta method for 9MP at the 200 ft level.

Objectively Determined Stability Class	9MP 200ft Sigma-Theta Stability Class: A	B	C	D	E	F
A	0.2	0.2	0.4	1.1	1.1	1.2
B	0.2	0.2	0.9	4.3	5.3	5.8
C	0.0	0.0	0.2	4.1	7.0	4.9
D	0.0	0.0	0.1	3.1	10.7	7.8
E	0.1	0.0	0.3	3.1	9.4	4.7
F	0.1	0.1	0.4	2.2	7.4	10.8

Table 2-18. Joint frequency table (Percent) of objectively determined stability class versus the Delta-Temperature method for 9MP between the 30 ft and 100 ft level.

Objectively Determined Stability Class	9MP 30 to 100ft Delta-Temperature Stability Class: A	B	C	D	E	F
A	3.1	0.2	0.1	0.4	0.3	0.2
B	9.3	1.2	0.9	3.2	1.6	0.7
C	4.7	1.3	1.5	6.6	2.3	0.3
D	7.9	1.2	1.1	8.4	3.2	0.2
E	0.9	0.5	0.8	7.2	8.1	0.5
F	0.1	0.1	0.1	2.2	8.2	10.7

Table 2-19. Joint frequency table (Percent) of objectively determined stability class versus the Delta-Temperature method for 9MP between the 30 ft and 200 ft level.

Objectively Determined Stability Class	9MP 30 to 200ft Delta-Temperature Stability Class: A	B	C	D	E	F
A	1.2	0.5	0.4	1.0	0.7	0.4
B	3.4	1.5	1.8	6.4	2.4	1.1
C	0.9	0.8	1.2	10.2	2.9	0.5
D	2.9	1.6	1.9	11.5	4.0	0.1
E	0.1	0.1	0.3	7.8	8.7	0.8
F	0.0	0.0	0.0	2.5	7.9	11.0

Section 3.0

Monitor Vertical Wind Profiles

Knowledge of the vertical variation of wind speed with height is important in studying the transport and dispersion of air pollutants. In most instances, the vertical resolution of wind speed measurements are limited for physical reasons such as the extent of a vertical tower or proximity of flow obstructions. To overcome these limitations, techniques have been developed to extrapolate wind speed measurements from one elevation to another, applying both physical models of fluid dynamics and empirical relationships from laboratory or controlled field experiments. However, there is concern over the transportablility of these techniques to specific applications in the field. This study is designed to specifically investigate the appropriateness of applying an empirical wind profile extrapolation technique known as the power law to operational use at nuclear power generating stations located in a coastal location. A background description of wind profile extrapolation is provided in Section 3.1 and the study objective and goal in Section 3.2. A summary of the monitoring equipment and data analysis methodology is provided in Section 3.3, with the results of the analysis presented in Section 3.4. Conclusions and recommendations are provided in Section 3.5.

3.1 Background

The vertical wind profile (defined as the change in wind speed with height) is not constant in time due to surface friction effects (surface roughness), the vertical temperature profile (stability), and the natural variability of the atmosphere. There are many applications in which the change of wind speed with height is an important parameter. For instance, the concentration of a pollutant measured downwind from a source is found to be inversely proportional to the wind speed at the elevation of the release. This effect refers to the dilution of continuously released pollutants at the point of emission. In, addition, wind speed effects the plume rise and the travel time between source and receptor. Since these effects are most prominent at the point and elevation of release, measurements of wind speeds at the release height are suggested for most applications involving the prediction of pollutant transport and diffusion.

3.1.1 Vertical Wind Profile Estimates

Wind profiles in an operational setting are most easily obtained by taking measurements of wind speed at several different elevations. However, in most operational cases, only one or two measurement levels are available. In these situations, theoretical estimates of the vertical wind profile must be used. The two most widely employed techniques are the Logarithmic Law:

$$U(z) = \frac{U_*}{\kappa} \ln \frac{z}{z_0}$$

and the Power Law:

$$\frac{U(z)}{U_r} = \left(\frac{z}{z_r}\right)^P$$

The difficulty with using the Logarithmic Law or the Power Law method is determining the various variables needed to evaluate the expressions. Use of the Log Law involves knowing or estimating the values of the similarity parameters (u_*, z_o and κ), while the Power Law requires applying the correct exponent (P) to the surface roughness and stability conditions.

To determine which method is the most appropriate for describing a wind profile, the first step is to find the difference which will result from using one method as opposed to another. Figure 3-1 shows the results provided by the Power Law and the Log Law as compared to a reference height (z_r) and wind speed (u_r). The comparison shows the difference between the methods for two types of "roughness" conditions (m=0.1 and m=0.3, where m=0.1 is a relatively smooth surface and m=0.3 is a relatively rough surface). The variable m is analogous to the power law exponent. It can be shown that

$$m = \frac{1}{\ln \frac{z}{z_0}}$$

and the Log Law can be re-written as

$$\frac{U}{U_r} = 1 + m\left(\ln\left(\frac{z}{z_r}\right)\right)$$

and the Power Law written as

$$\frac{U}{U_r} = \left(\frac{z}{z_r}\right)^m$$

Solving these equations for the two "roughness" conditions (m=0.1 and m=0.3), we obtain the curves presented in Figure 3-1.

If we consider a change in height one order of magnitude from the reference height, z_r, and a high surface roughness or extremely stable environment (m=0.3), the difference in the wind speed calculated between the two methods is 15.1%. However, over smooth surfaces with neutral lapse rates (such as that commonly found in the marine boundary layer, m=0.1), the difference between methods is much smaller, around 2.3%.

Clearly, for the marine boundary layer (onshore flow), where surface roughness is small, the difference between the estimated wind speed profile obtained using the Log Law and that using the Power Law method is almost negligible. However, over land, where temperature profiles can be significantly different than neutral and surface roughness is often high, the choice of an appropriate extrapolation method becomes more difficult. In order to avoid the difficulty involved in determining which method is appropriate and what coefficients are correct for a given set of meteorological conditions, site-specific measurements of the wind profiles are often recommended for applications involving dispersion of pollutants released from elevated sources.

For most applications involving dispersion modeling, wind speeds at elevations above a reference height are frequently determined using the power law exponent. As suggested above, the actual power law exponent can vary significantly from application to application depending on the stability of the atmosphere and the roughness of the surface over which the air is traveling. The most commonly used power law exponent is applied through the so-called "1/7 power law" or P=0.14. This value is said to be appropriate for neutral flow over relatively flat, open terrain (Sutton, 1953). Similarly, the United States Environmental Protection Agency (USEPA) suggests a value of P=0.15 for neutral stability flow in a rural environment. However, due to the variability of siting and exposure of meteorological instrumentation at any given location, it is often appropriate to develop site-specific wind profile exponents.

3.1.2 Applications to Nuclear Facilities

In compliance with Federal Regulation 10CFR50.47 regarding emergency planning, nuclear power generating facilities in the United States are required to have "adequate methods, systems, and equipment for assessing and monitoring actual or potential offsite consequences of a radiological emergency condition." In order to meet the meteorological aspects of this regulation, nuclear power generators must have the capability of making near real-time predictions of the transport and diffusion of effluent from their facilities. In order to make such predictions, measurements or reliable estimates of the wind speed at the height of the effluent release are necessary. Such measurements are used to determine the dilution rate of the emission as well as the transport time to receptors downwind.

Presently, the Nine Mile Point Nuclear Generating Station (NMP) maintains a 200 ft meteorological monitoring tower (9MP) with equipment which continuously measures wind speed at elevations of 30, 100, and 200 ft. Estimates of wind speed at higher elevations are developed by using a power law relationship which employs the 200 ft wind speed. Table 3-1 outlines the wind profile exponents which are currently in use at NMP. The exponents differ depending upon the height range used to calculate them, and are a function of stability. Also shown in Table 3-1 are power law exponent values typically applied for dispersion modeling applications (USEPA, 1987). This project will provide information regarding the reliability of using such power law exponents (P) as a method for extrapolating tower observed wind speeds to the release heights at the NMP site, as well as other, similarly located, nuclear generating stations.

3.2 Study Objective

The objective of this study is to measure wind speeds at elevations corresponding to potential release elevations at the Nine Mile Point Nuclear Power Station Units 1 and 2 and the J.A. Fitzpatrick Nuclear Station. These elevations correspond to 350, 385, and 430 ft above ground level. The measurements will be used for comparison to wind speeds predicted at the those elevations using observed wind speeds at 200 ft and a power law extrapolation technique.

3.2.1 Study Goal

The goal of this study is to determine the appropriateness of extrapolating wind speeds measured at the 200 ft level of the NMP 200 ft meteorological tower (9MP). This technique is currently used at NMP and other nuclear power generating stations for estimating wind speeds at release elevations for calculations involving plume dilution and transport.

3.2.2 Potential Applications for Research

The results of this research are expected to be of interest to any utilities that must perform dispersion modeling using wind speed data that is collected at elevations different from the release and/or plume elevation. The conclusions will assist in making decisions related to the need for collecting wind speed information at release and/or plume elevations.

3.3 Approach

3.3.1 Description of Monitoring System

The primary data set for evaluating the wind profile between the 9MP 200ft level and the potential release elevations was obtained with a tethersonde atmospheric profiling system. The tethersonde system consists of a large, blimp-shaped tethered balloon, tether winch, instrument package, and a ground station for receiving data telemetered from the instrument package. The instrument package provides measurements of air temperature, wet bulb temperature, pressure, wind speed and wind direction. The package is carried beneath the aerodynamic balloon which is connected to the winch by a tether line. The ascent or descent of the balloon is controlled by releasing or retrieving line from the winch. The balloon has a nominal inflated volume of 110 cubic feet which provides sufficient lift to operate to an altitude of over 3000 ft (approx. 1 km). The balloon is controllable by the winch for wind speeds of up to approximately 20 mph, above which the balloon becomes unstable. Figure 3-2 shows a schematic representation of the tethersonde system and the instrument package.

When in flight, measurements are made sequentially over a period of approximately 13 seconds and transmitted as audio tones over a 403 MHz FM transmitter. The ground station receives the signal, decodes the audio tones, scales the values in terms of standard units, and outputs the data reports as serial digital data. The data stream from the receiver is captured by a computer and stored for subsequent analysis.

Although the tethersonde instrument is capable of collecting dry and wet bulb temperature, the main focus for this task was data collected for tethersonde elevation and wind speed Elevation is determined by measurement of pressure. Pressure is measured using an aneroid capsule which acts as a variable capacitance transducer. Calibration errors are of the order of 0.2 mb with somewhat larger hysteresis errors which are corrected during data analysis. Temperature and humidity corrections are employed in the elevation calculation. Wind speed is sensed by a cup anemometer mounted on top of the instrument package. It has a linear response with a starting threshold of 2 mph. Static tests indicate a measurement error of less than 5%.

Use of the tethersonde allowed for the direct measurement of atmospheric conditions at the heights of the release points while the main meteorological tower collected data from the 200 ft level. The tethersonde ground station was installed at a site adjacent to the main meteorological tower and was operated by subcontractor AWS Scientific, Inc.

3.3.2 Sampling Technique

Seven test runs were proposed, each in different meteorological conditions as practical. This approach was to allow comparison of the winds in meteorological flows typical of the Nine Mile Point area. The flight procedure for each test consisted of positioning the tethersonde at each of the three release heights in order to record 5-minute average time periods. Concurrent 5-minute average data was obtained by averaging one-minute observations from the meteorological tower. Each measurement period included a set of flights at the 200 ft level, conducted both before and after the flights at the release point heights in order to define a benchmark of agreement between the different measurement systems. In total, a minimum of eight test sets were required to produce a minimum total of 84 five-minute average intercomparison values between each release point elevation and the main meteorological tower.

In cases when strong winds or excessive heights precluded the use of the tethersonde (wind speeds greater than 20 to 25 mph), it was originally proposed that free-flight radiosondes would be substituted. Radiosondes are capable of providing comparable vertical resolution of the wind and temperature field, but they provide only a single instantaneously measured value at any given height. In addition, the radiosondes are manually tracked using an optical theodolite, a method which has a relatively large error compared to the cup/vane method of measurement used by the tower and tethersonde instrumentation. Therefore, the project team concluded that comparable, statistically significant data between the main meteorological tower and radiosondes could not be obtained, and the alternative method was shelved.

3.3.3 Data Analysis

Data used to evaluate the wind profile and resulting power law exponents employed by NMP personnel underwent several data analysis levels: data validation, separation into test specific data sets, correction for 200 ft benchmark data for each test day, comparison of each level with 200 ft tower, calculation of observed power law exponents, and comparison of power law exponents to values currently used.

Data collected during the field experiment was validated by the tethersonde operators (AWS Scientific, Inc.). Validation of the data included inspection by a meteorologist for reasonable data values based upon conditions observed, removal of suspect data and bad data, and calibration adjustments. Data from the 9MP tower was provided by the operator, Niagara Mohawk Power Corporation, and was assumed to be [illegible]dy validated.

All data was binned into a specific test day. Calculation of 200 ft benchmarks and application of corrections was performed on a test specific basis. A total of eight test days were performed. Data from 9MP was extracted from the one-minute observations, matched to the tethersonde runs, and averaged to five minute values for comparison to the tethersonde five minute averages.

Each days collection of 200 ft tethersonde wind speed observations were compared directly to the 200 ft 9MP tower observations. A mean bias and standard deviation was calculated. The bias was interpreted as the test correction for the remaining tethersonde observations taken during the test day, and the correction was applied to each subsequent five-minute tethersonde average at 350, 385, and 430 ft elevations. The correction was intended to adjust for test-to-test (day-to-day) variations in the performance and horizontal location of the tethersonde.

Elevated data from the tower was matched to the corrected tethersonde data and compared. The comparison involved calculation of a power law exponent (P) for each observation pair. The P factor was calculated using the following equation:

$$P=\frac{\ln(U_1/U_2)}{\ln(z_1/z_2)}$$

In order to determine the impact of applying the 200 ft benchmark correction to the calculation of P, the exponent was determined for both uncorrected and corrected data.

The wind speed at the elevated levels was also compared to the expected value predicted using an average power law exponent from those currently employed at NMP and outline in Table 3-1. The average P exponent employed was for a 30 to 200 ft correction and D stability class (i.e. P=0.275). Scatter plots of the predicted versus observed wind speed were produced for each release height. The scatter plots show the relative comparability of the actual and predicted wind speed and the applicability of the existing power law exponents used at the site.

3.3.4 Limitations of Study

Every practical effort was made to minimize the limitations of this study. However, limits in the operation of the equipment and evaluation of the data existed that were beyond the control of the project team. First, the evaluation of measurements is limited due to the difficulty of matching the tower and comparison instrumentation in time and space. Following are the significant time and space limitations to the analysis:

- Every effort was made to keep the tower and tethersonde measurements within an accuracy of 30 seconds. This may be a source of error, especially in variable wind speed conditions.
- Tethersonde height was maintained within 10 feet of the desired measurement elevation during each test.
- The tethersonde launch site was located approximately 200 m from the tower. This horizontal separation was necessary to prevent the measurement systems from interfering with one another and to maintain a safe operating distance from the tower.

In addition to the measurement limitations, operational restrictions also limit the study as follows:

- Wind speed comparisons between the tower and tethersonde measurements are limited to light or moderate wind speeds (less than 20 mph) due to the operational limits of the tethersonde.
- Weather condition restrictions on the tethersonde system also limited the operations of the tethersonde. The system was not operated during periods of low ceiling, restricted visibility, or precipitation.
- Due to the intensive labor and resulting expense involved in operating the tethersonde system, the operational duration of the tethersonde and collection of comparative data was limited. Attempts were made to sample in a variety of stability and wind direction conditions.
- The tethersonde's battery operated instrument package and telemetry transmitter limited the time the tethersonde could spend aloft during any given test period, since the battery required replacement every 3 hours or so of operation.

3.4 Data Analysis Results

Data used in the analysis of wind profiles and calculation of power law exponents is provided in Appendix B. A total of eight test runs were performed on eight separate days. The test runs and counts of 5-minute averages obtained at each of the desired elevations is summarized in Table 3-2. Limitations in the weather conditions and other duties related to the project (i.e. Task 4), limited the tests during the initial four periods. Initially, only seven test days were projected. However, an error on the part of the subcontractor collecting the tethersonde data led to a shortfall in the number of averages expected compared to the goal of 84 at each elevation. To correct this shortfall, a make-up test day was scheduled. This accounts for the May 10, 1993 test day, as well as the significant number of observations taken at the 430 ft elevation on this day. It should be noted that this may bias the results for the 430 ft level when compared to the more even distribution of observations obtained at the 200, 350, and 385 ft heights.

The following sections provided a summary of the weather conditions during each test, analysis of the 200 ft benchmark data, presentation of the wind profile exponents determined using 9MP 200 ft data and tethersonde data at 350, 385, and 430 ft, and a comparison of the observed versus predicted wind at the potential release elevations.

3.4.1 Summary of Test Conditions

The following briefly summarizes the time of day the test runs took place, the weather conditions observed during each of the tests, and briefly any problems experienced during the test.

3.4.1.1 Test 1 - June 23, 1992

The first test of this task took place with two tethersonde flights during the early to mid-afternoon period of the day between 1300 and 1600 LST. Two flights were conducted during the period. The weather was mainly clear with wind onshore from the northwest. Wind speeds were generally below 10 mph throughout the afternoon. Stability, using the 30 ft to 200 ft delta-temperature measured at 9MP was classified as A (extremely unstable) throughout the afternoon.

3.4.1.2 Test 2 - August 6, 1992

Two flights took place on this day during the evening hours centered around sunset. The tests took place between approximately 1940 and 2240 LST. The evening was clear, with winds at flight elevation nearly parallel to the coast from the west-southwest at 5 to 10 mph early in the test period, backing to southwest at less than 5 mph by the end of the test period. Clear sky conditions and light winds resulted in F and G stability classes through the test. A land breeze developed during the test, appearing first at the 30 ft level of the tower early in the test and deepening to the 200 ft level by the end of the test. This type of mesoscale phenomena can account for significant differences between tower winds and those observed at release elevations.

3.4.1.3 Test 3 - August 24, 1992

A single flight took place during the late morning between 0900 and 1100 LST. The winds were light from the south-southwest to southwest during the test, with speeds between 5 and 10 mph during the first half of the test, decreasing to less than 5 mph during the second half. Between 1045 and 1100 LST, a lake breeze developed an onshore flow from the west and west-northwest. Stability through most of the test was slightly unstable to neutral (C to D), until the development of the lake breeze, when stability became stable (E). Like the land breeze, the lake breeze is a mesoscale phenomena which occurs along the lake shore area which can account for significant differences between the tower wind speed and direction measurements and those measured at release elevations.

3.4.1.4 Test 4 - September 13, 1992

As with Test 2, Test 4 took place in the evening hours around sunset, beginning around 1830 and ending at 2000 LST. Winds were offshore from the southeast throughout the test, and increased from 8 mph at the beginning of the test to near 20 at the end of the test. Due to the increasing winds and turbulent nature of the air, the test was cut short as the tethersonde was becoming unstable in the increasing wind speeds. Stability during the test was classified as G (extremely stable). The day had been mainly clear with a lake breeze during the late morning and afternoon, followed by a rapidly developing land breeze in the evening and an increasing southerly gradient wind as high pressure passed east of the area. A low level nocturnal wind speed maximum is also suspected based upon the high winds observed by the tethersonde and the 200 ft level of the tower, while surface winds remained relatively light. Again, these mesoscale features are cause for concern since they can create significant variations in wind speed and direction between the 200 ft level of the tower and the release elevations.

3.4.1.5 Test 5 - October 5, 1992

A moderate northeasterly gradient wind flow dominated the fifth test as high pressure was north of the area. The test took place during the late morning, from 0940 to 1135 LST. North-northeast to northeast winds at 10 to 15 mph lasted through the test. Stability in the cool air flow around the high was generally neutral to slightly stable (classified as D or E).

3.4.1.6 Test 6 - October 6, 1992

High pressure continued in the vicinity of NMP during an extended day of flight marking Test 6. Flights began before sunrise around 0515 LST, and lasted until late afternoon (1700). A weak land breeze from the southeast with wind speeds from 5 to 10 mph dominate until mid-morning, when a weak lake breeze developed and persisted through the afternoon. Stabilities were stable during the early portion of the test, then became unstable just prior to the development of the lake breeze during the mid to late morning. The onshore flow during the afternoon has mainly neutral to slightly stable stabilities.

3.4.1.7 Test 7 - October 7, 1992

High pressure and weak gradient allowed a lake breeze to develop during the seventh test day. Three flights were conducted during the period from 0910 until 1535 LST, with the lake breeze developing during the first flight. By 1100, the onshore lake breeze was well established, but wind speed remained quite light, remaining around 5 mph or less throughout the remainder of the test. Stability was extremely unstable (A) early in the first test as the lake breeze developed, then became neutral or slightly stable (D and E) once the onshore flow of the lake breeze was established. Significant variability occurred between the 200 ft tower level and the test elevations during the onset period of the lake breeze.

3.4.1.8 Test 8 - May 10, 1993

Weak high pressure with variable overcast conditions dominated the eighth and final test day. Flights were conducted between 0800 to 1730 LST, with winds generally 5 to 10 mph from the west southwest throughout the test day. The only exception was a period of very light and variable winds which occurred at the 200 ft level of the tower during the early afternoon. However, wind speeds remained between 5 and 8 mph at the 430 ft elevation during this time period. It is not clear what caused the different wind speed conditions, however the tethersonde operators confirmed the tethersonde data by observing the motions of the tethersonde balloon and the tether wire. As will be shown, this event led to significant differences in the P exponent calculations for the 430 ft level during this test.

3.4.2 Analysis of the 200 ft Benchmark Data

Figure 3-2 shows a scatter plot of the tower measured versus the tethersonde measured wind speed at 200 ft. This comparison was performed at the beginning and end of each test in order to develop a benchmark correction to be applied to the tethersonde observations (except Test 4 where high wind speeds resulted in a comparison only at the start of the flight). This benchmark was intended to take into account any changes in calibration between the instrumentation, as well as changes in the horizontal location of the tethersonde due to flight in varying wind directions. For each test, the 5-minute average 200 ft tower wind speed was compared to the 5-minute average 200 ft tethersonde wind speed, and an average bias calculated (9MP wind speed - Tethersonde wind speed). The average bias was then added to the tethersonde wind speed for all observations at alternate elevations during the test in an attempt to correct the tethersonde data for instrumentation error.

The average difference between the observed 200 ft wind speed on the 9MP tower and the tethersonde (benchmark correction) for each test is summarized in Table 3-3. As can be seen from Table 3-3 and Figure 3-2, the tethersonde tended to measure wind speeds less than those observed at the 200 ft level of the 9MP tower. Thus, in all but Test 2 (8/6/93), the tethersonde observed winds were increased for comparison at other elevations.

An independent analysis of the 200 ft tethersonde and tower data indicated that the wind speeds observed by the tethersonde and the tower are likely not the same (Caiazza, 1993). This conclusion was based upon conducting a student's t-distribution of the 200 ft wind speed data, which showed that the probability of the tethersonde-tower wind speed difference being due to random fluctuations (as is assumed in this analysis) is less than 0.001. However, in order to make the most of the data, the comparison at alternative levels was carried out using the described procedure. Hopefully, the comparison can still provide a useful indication of whether or not adjustment of instantaneous 200 ft measurement to alternative heights using a power law function is justified.

3.4.3 Observed Wind Profile Exponents

The calculation of wind profile exponents for each test elevation and each test are shown in Appendix

B and summarized for elevations 350, 385, and 430 ft in Tables 3-4 through 3-6, respectively. Tables 3-4 through 3-6 show variability in the average wind speed profile exponent when compared test-to-test. Power law exponents averaged between 0.07 and 0.05 for 350 and 385 ft, respectively, and increased to 0.40 for 430 ft. Individual test values ranged between -0.38 to 0.68. Note that a negative power law exponent is indicative of wind speed *decreasing* with height. Inspection of the individual power law exponents calculated for each five minute average as shown in Appendix B indicates even more dramatic variability, and highlights that the use of the power law exponent on an individual observation basis is not necessarily appropriate.

Care should be taken in comparing the power law exponents obtained for the various test elevations. While the tendency of the power law correction was similar within each test, the eight test average values differ significantly between 350 and 385 ft (0.05 and 0.07, respectively) and that obtained for 430 ft elevation (0.40). This difference is believed to be a result of the different sample distributions obtained between the elevations. For example, over half of the 430 ft samples were collected during a single test (5/10/93), while the 350 and 385 ft samples had a more even distribution.

It is interesting to note that the average values behave in a way similar to that expected from theory. For instance, power law exponents obtained for the 350 ft and 385 ft elevations over a variety of stability classes and wind directions are slightly less than the mean value of 0.14 frequently suggested (Panofsky and Dutton, 1984). Also, a value of 0.40 at 430 ft from samples collected during primarily stable conditions is also similar to expected values (USEPA, 1987). Also, the 350 ft and 385 ft values are similar to values outlined by Segal and Pielke (1988), where a power law exponent of 0.07 is suggested as reasonable in neutral stable marine environments.

Based upon this analysis, it is reasonable to conclude that, under light to moderate wind speed conditions, at a location with important mesoscale features, application of the wind speed profile on a case specific basis in not necessarily appropriate. However, on an average wind speed basis, the power law exponent appears to provide a reasonable estimate of winds speeds at elevations above the reference elevation.

3.4.4 Observed Wind Profiles Compared to Predicted

Using the observed 200 ft wind speed for the 9MP tower and the established wind profile exponents for the tower as outlined above and in Table 3-1, a predicted wind speed was calculated at each of the test elevations and compared to the tethersonde observed wind speeds. Since stability was variable during testing, an "average" wind profile exponent was used as a simplified approach to determining the predicted wind speed at the test elevations. The profile exponent selected was 0.275, which corresponds to the exponent for the 30 to 200 ft levels of the tower during a D stability. This exponent was applied to the 200 ft elevation (reference) to calculate the expected (predicted) value at each of the release elevations.

Scatter plots of the predicted versus observed wind speed at each of the test elevations for each sample are provided in Figures 3-4 through 3-6. As can be seen from the plots, there is a fair amount of scatter, particularly with increasing height, amplifying the difficulty in applying the power law on a case-specific basis rather than an average basis. In general, the wind speeds calculated from the current power law exponent values (predicted) are higher than the observed. Thus, the current exponents in use at NMP may tend to over predict wind speeds at release elevation. Also, the application of the power law becomes even less reliable as the height for which the wind speed is being calculated differs from the reference height.

3.5 Conclusions and Recommendations

Methods for extrapolating observed wind speeds to elevations different from the observed have been developed using both physical and empirical models. At NMP, a power law extrapolation technique is employed using a set of site-specific power law exponents to extrapolate wind speeds from the 200 ft level of the meteorological tower (9MP) to potential effluent release heights. In order to determine the appropriateness of applying this extrapolation technique at NMP, wind speed measurements were taken at 350, 385, and 430 ft using a tethersonde atmospheric profiling system, and concurrent measurements collected from the 9MP tower at the 200 ft elevation. A comparison was conducted between the 200 ft measurement level and the release elevations, from which the following conclusions are made:

- Based upon the limited data set collected during this study, the current power law exponents employed to correct 200 ft wind speed to release heights at 350, 385 and 430 ft tend to over predict the actual wind speed. This is particularly significant since the power law exponents can become quite large for both stable and extremely unstable conditions, resulting in even higher predicted wind speeds than those presented in Figures 3-4 through 3-6.
- The application of a wind profile exponent becomes less reliable as the difference between the reference and predicted elevations increases.
- Elevated wind speeds calculated using established wind power law exponents show poor correlation to observed wind speeds on a case-by-case basis. However, applied to wind speeds averaged over a long period under a variety of meteorological conditions, power law exponents perform well.
- The occurrence of mesoscale phenomena such as lake and land breezes, and nocturnal low-level wind speed maximums are problematic for the application of wind profile exponents. Due to the large variation in the vertical distribution of meteorological parameters found with these phenomena, simple, empirical relationships such as the power law fail to adequately describe the complexity of the physical processes involved.

Based upon the conclusions, the following recommendations are made:

- Due to the limited nature of this study and the discrepancy between 200 ft tethersonde and 200 ft tower measurements, further measurements using a combination of tower, tethersonde and remote sensing instruments is recommended on a regular basis (e.g. annually). Changes in the surrounding surface roughness on a seasonal basis should be measured.
- Routine measurement of wind at release elevations is recommended by either employing a tall meteorological tower or reliable remote sensing system, depending on the data recovery objective required.
- The practice of using established wind profile exponents to calculate wind speed at release elevation on an observation specific basis should be reconsidered. Such use can result in large errors between the predicted and observed wind speed. Consideration should be given to using observations of wind speed at the desired elevation as a first option, measurements of 200 ft wind as a second option, and extrapolated wind speed estimates third.
- Use of established wind profile exponents to determine average winds at release elevations is most likely appropriate, however the exponents should be further refined with measurements between the tower and release elevations rather than the tower alone.

3.6 References

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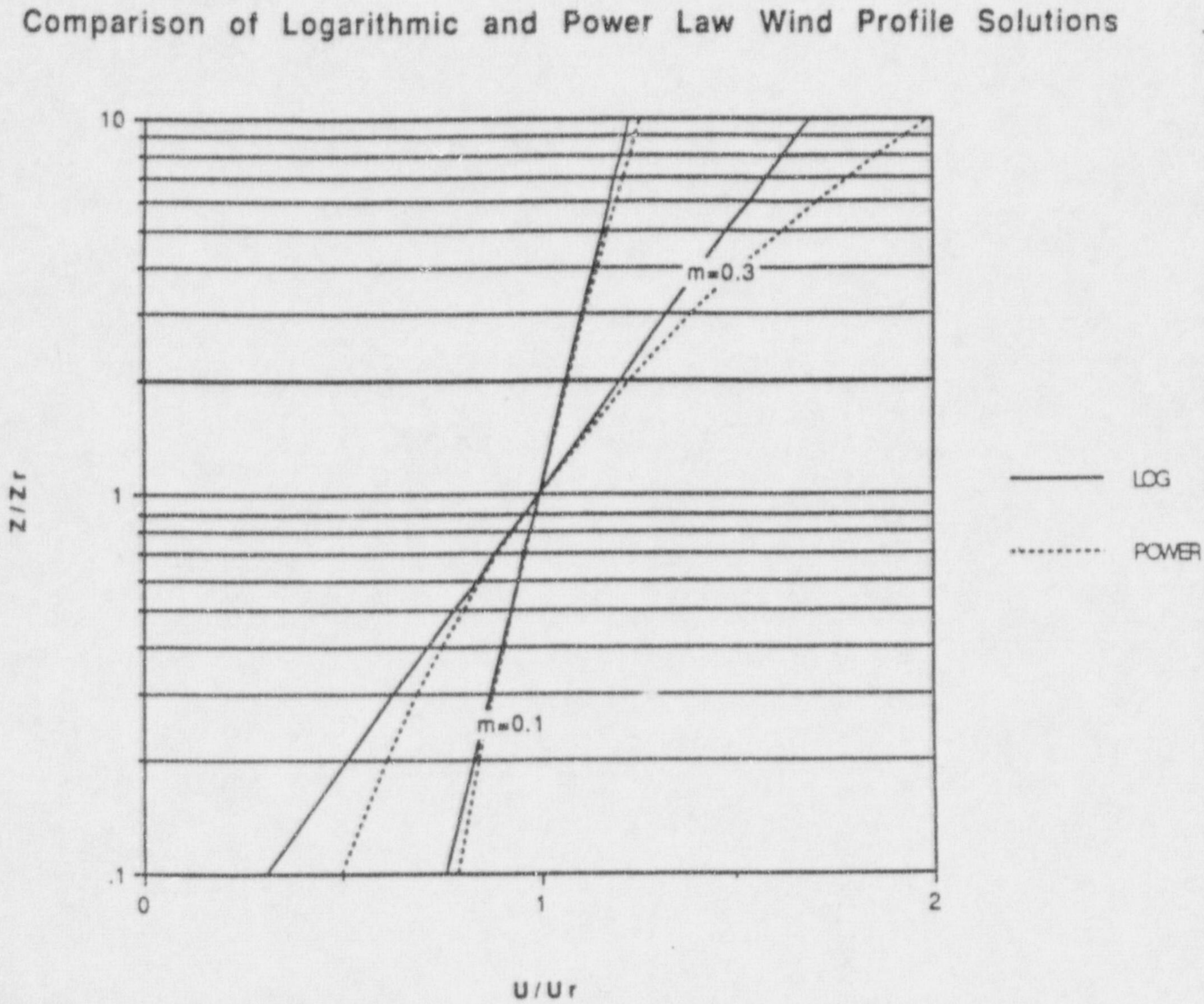

Figure 3-1. Plots of differences in estimating the wind profile using two different methods.

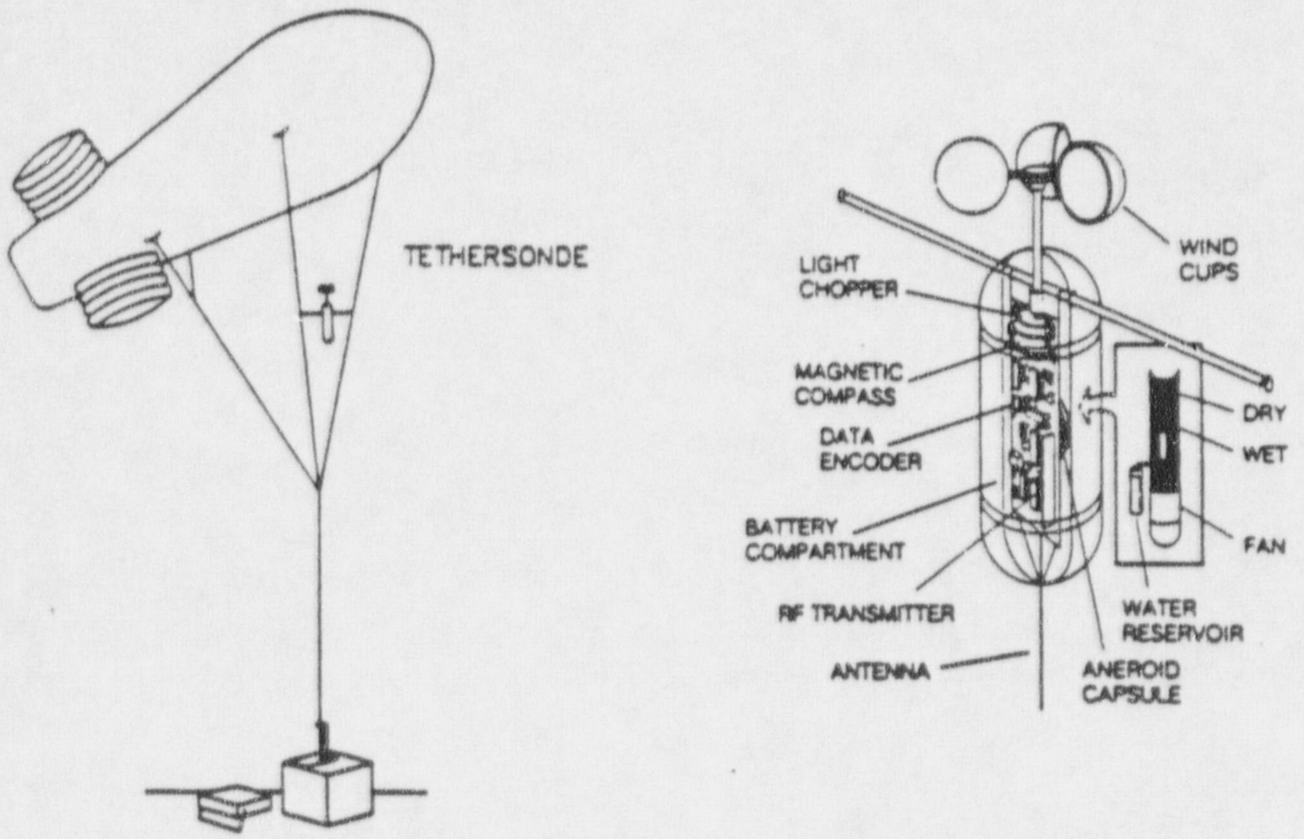

Figure 3-2. Schematic of the tethersonde boundary layer profiling system showing the balloon, winch, ground station, and attached instrument package (left); and the instrument package parts (right).

Figure 3-3
9MP vs Tethersonde 200 ft Wind Speed

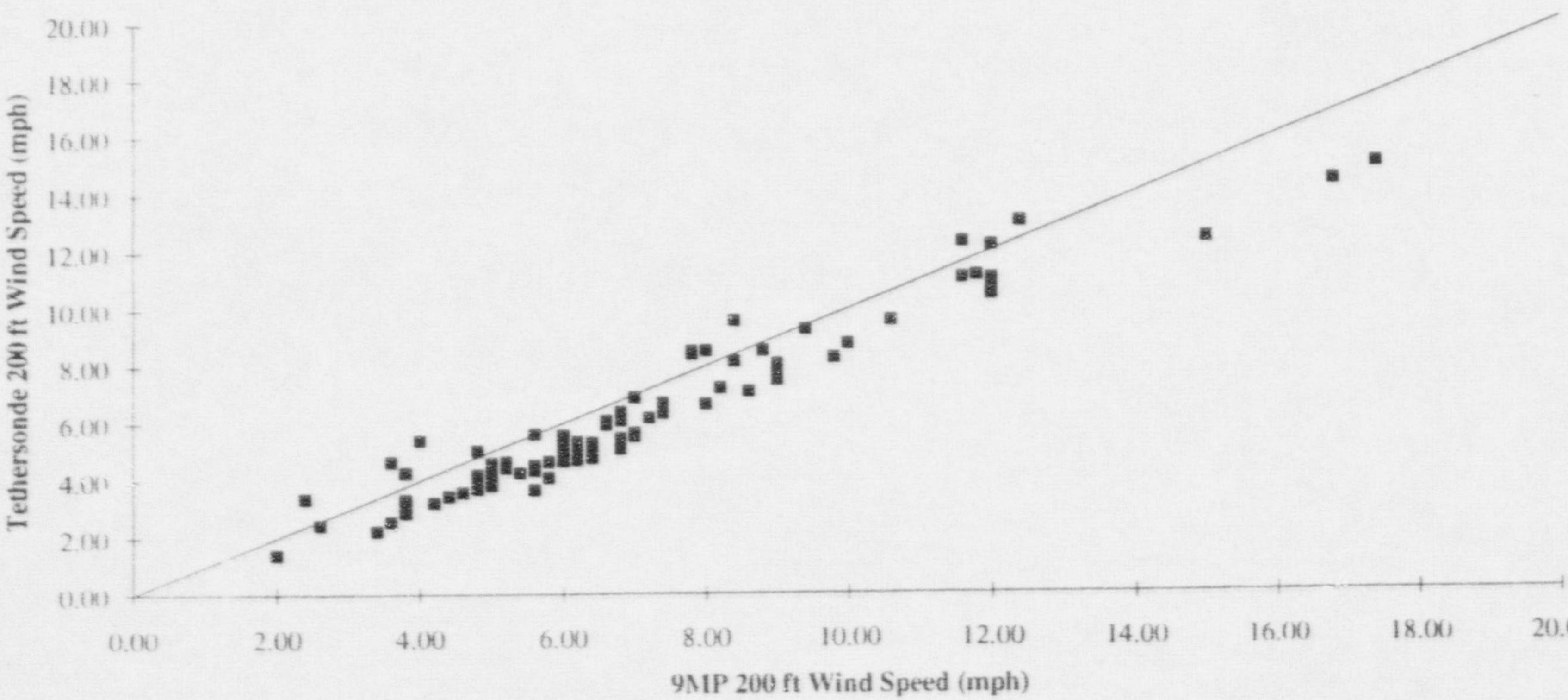

Figure 3-4
9MP 350 ft Predicted vs Tethersonde Observed 350 Ft Wind Speed

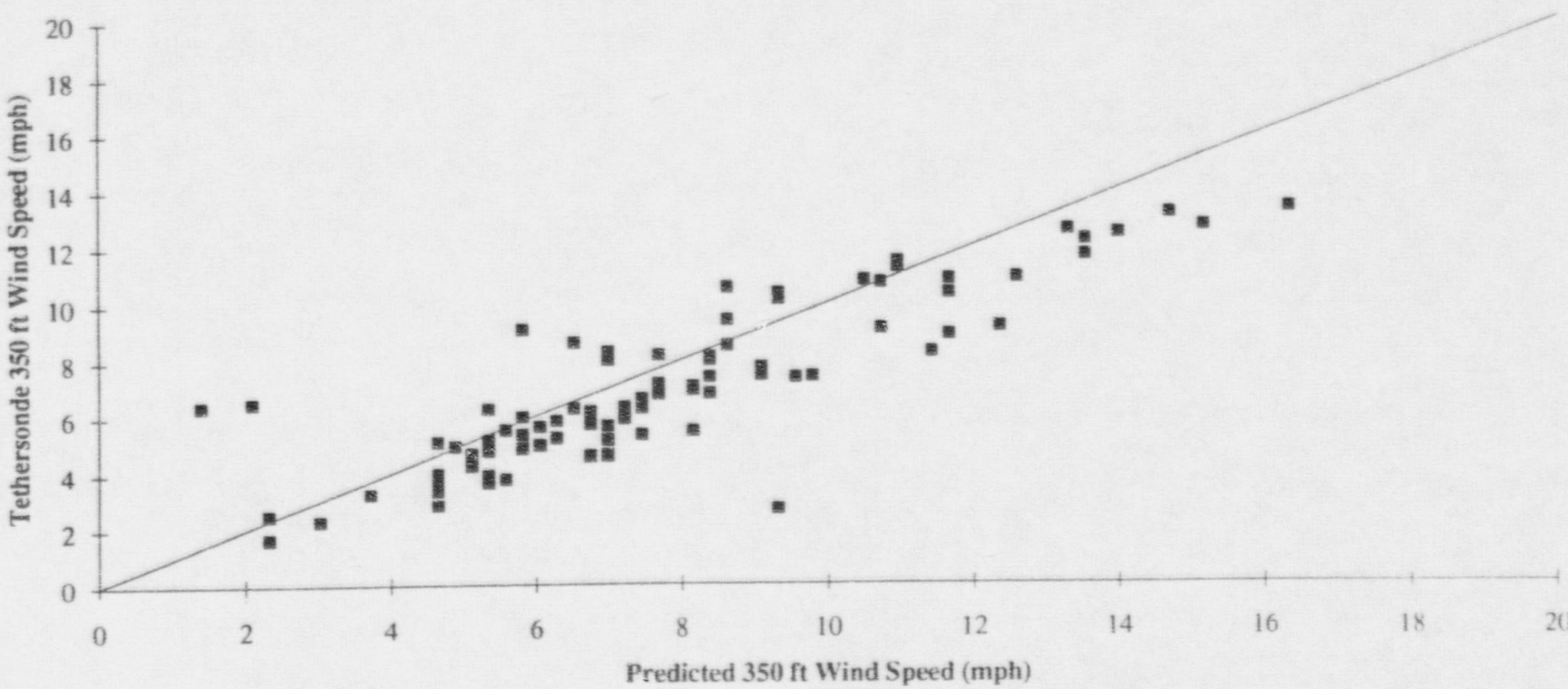

Figure 3-5
9MP 385 ft Predicted vs Tethersonde Observed 385 ft Wind Speed

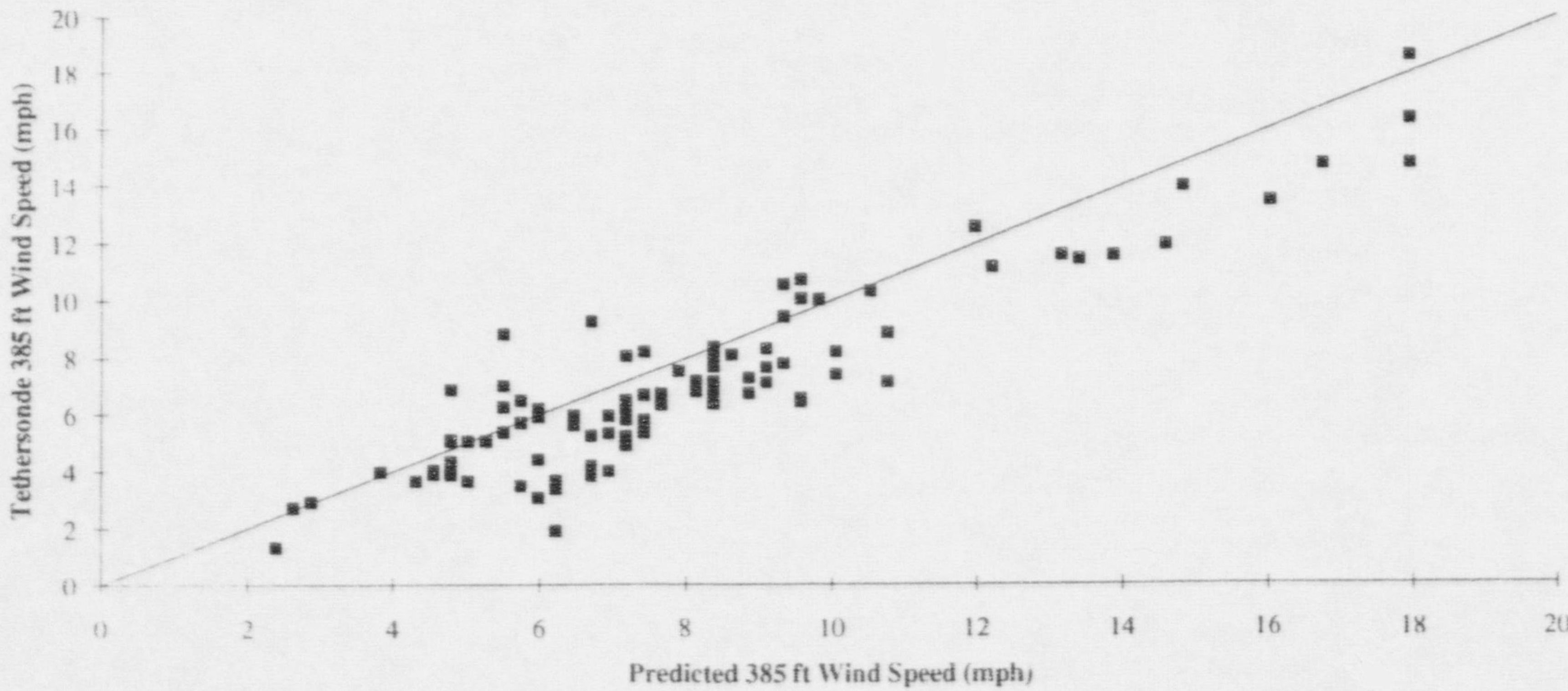

Figure 3-6
9MP 430 ft Predicted vs Tethersonde Observed 430 ft Wind Speed

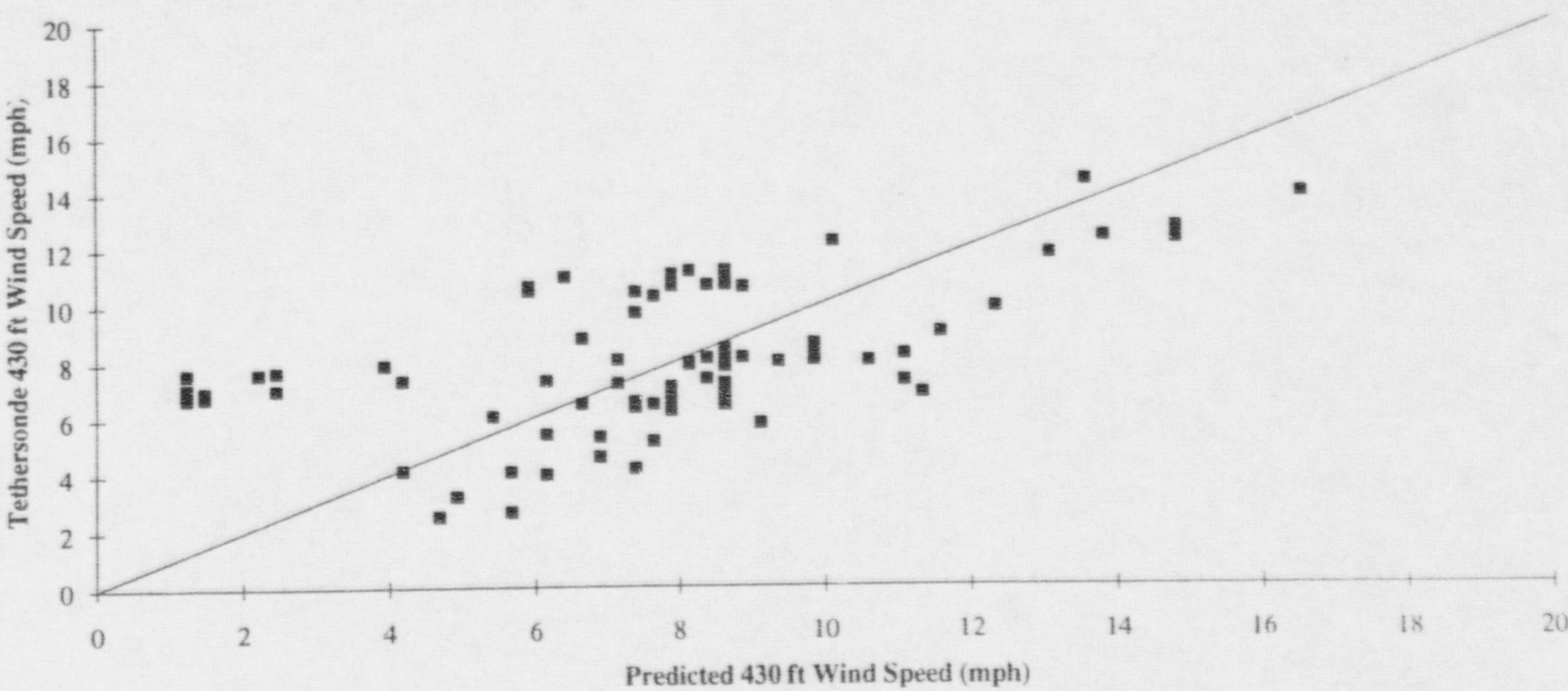

Table 3-1
Established Power Law P-factor Values

	USEPA[1]	9MP Site-Specific P-values[2]		
Stability	10 m Reference	30 ft to 100 ft	30 ft to 200 ft	100 ft to 200 ft
A	0.07	0.281	0.343	0.264
B	0.07	0.264	0.241	0.255
C	0.10	0.289	0.212	0.223
D	0.15	0.313	0.275	0.259
E	0.35	0.486	0.431	0.387
F	0.55	0.613	0.561	0.484
G	-[3]	0.707	0.564	0.493

[1] Values commonly used in regulatory modeling applications (USEPA, 1987).
[2] Values currently in use at NMP (EIA, 1984).
[3] G stability class not employed by EPA. Assumed same as F stability class.

Table 3-2
Summary of Field Monitoring Data

Date	Elevation			
	200 ft	350 ft	385 ft	430 ft
6/23/92	4	8	10	4
8/6/92	7	7	8	4
8/24/92	5	6	6	3
9/13/92	3	3	6	3
10/5/92	6	6	6	3
10/6/92	30	30	30	15
10/7/92	16	16	16	8
5/10/93	16	16	16	48
Total	87	92	98	88
Goal	84	84	84	84
Percent of Goal	104%	110%	117%	105%

Table 3-3. Summary of measured differences between 9MP and tethersonde 200 ft elevation.

Date	Stability (30 to 200 ft Delta-T)	9MP Average (200 ft)	Tethersonde Average (200 ft)	Average Difference	St. Dev. of Difference
6/23/92	A	6.75	6.44	0.31	1.41
8/6/92	F/G	5.91	6.47	-0.56	0.57
8/24/92	D (Variable)	6.27	5.50	0.77	0.45
9/13/92	F/G	9.60	8.20	1.40	0.14
10/5/92	A	14.20	13.21	0.99	1.65
10/6/92	A/C/D/F	7.29	6.39	0.90	0.40
10/7/92	B	4.78	3.94	0.84	0.63
5/10/93	F	7.11	6.04	1.07	0.42
Average (all observations)	-	7.11	6.32	0.79	0.78

Table 3-4. Summary of calculated power law coefficients (P) for 350 ft.

Date	Stability (30 to 200 ft Delta-T)	Average P at 350 ft (Uncorrected)	St. Dev. (Uncorrected)	Average P at 350 ft (Corrected)	St. Dev. (Corrected)
6/23/92	A	0.08	0.21	0.18	0.20
8/6/92	F/G	-0.09	0.6[illegible]	-0.30	0.74
8/24/92	D (Variable)	-0.40	0.34	-0.11	0.24
9/13/92	F/G	-0.22	0.02	0.02	0.03
10/5/92	A	-0.11	0.09	0.04	0.10
10/6/92	A/C/D/F	-0.24	0.24	0.03	0.22
10/7/92	B	-0.78	0.32	-0.28	0.24
5/10/93	F	0.43	0.81	0.68	0.83
Average (all observations)	-	-0.18	0.57	0.07	0.57

Table 3-5. Summary of calculated power law coefficients (P) for 385 ft.

Date	Stability (30 to 200 ft Delta-T)	Average P at 385 ft (Uncorrected)	St. Dev. (Uncorrected)	Average P at 385 ft (Corrected)	St. Dev. (Corrected)
6/23/92	A	0.20	0.09	0.28	0.09
8/6/92	F/G	0.27	0.24	0.12	0.23
8/24/92	D (Variable)	-0.25	0.16	-0.02	0.15
9/13/92	F/G	-0.08	0.16	0.09	0.13
10/5/92	A	0.00	0.14	0.12	0.14
10/6/92	A/C/D/F	-0.20	0.26	0.04	0.23
10/7/92	B	-0.87	0.64	-0.38	0.46
5/10/93	F	0.08	0.39	0.30	0.36
Average (all observations)	-	-0.17	0.49	0.05	0.35

Table 3-6. Summary of calculated power law coefficients (P) for 430 ft.

Date	Stability (30 to 200 ft Delta-T)	Average P at 430 ft (Uncorrected)	St. Dev. (Uncorrected)	Average P at 430 ft (Corrected)	St. Dev. (Corrected)
6/23/92	A	0.19	0.14	0.25	0.13
8/6/92	F/G	0.15	0.19	0.03	0.16
8/24/92	D (Variable)	-0.17	0.05	-0.01	0.06
9/13/92	F/G	-0.09	0.04	0.07	0.04
10/5/92	A	0.22	0.20	0.33	0.19
10/6/92	A/C/D/F	0.23	0.41	0.38	0.38
10/7/92	B	-0.71	0.31	-0.36	0.21
5/10/93	F	0.47	0.84	0.65	0.85
Average (all observations)	-	0.24	0.73	0.40	0.73

Section 4.0

Detailed Regime Measurements

The coastal transition between land and water complicates attempts to quantify the atmospheric conditions of the shoreline zone. This is true at any shoreline location, including where power generating facilities are located on the southeastern shore of Lake Ontario such as Niagara Mohawk Power Corporation's Nine Mile Point Nuclear Power Station (NMP) and Oswego Steam Station, the Ginna Nuclear Station (Ginna) operated by Rochester Gas and Electric, and Kintigh Station operated by New York State Electric and Gas. In order to learn more about the physical atmospheric processes occurring in the coastal transition zone, a series of intensive observations were performed in the vicinity of NMP and Ginna to collect data for use by researchers and atmospheric modelers to improve conceptual and numerical models of the coastal zone meteorology as it relates to the transport and dispersion of pollutants.

This Section presents the results of the intensive monitoring program. A brief background description of the meteorological phenomena measured during this study is presented in Section 4.1 and the study goal presented in Section 4.2. Descriptions of the equipment and monitoring approach are provided in Section 4.3, with the intensive observation results briefly reported in Section 4.4. More detailed data summaries are presented in Appendix C. Section 4.5 outlines some conclusions and recommendations resulting from the collection of the detailed measurements.

4.1 Background

Many meteorological theories, observations, and methods are based upon air flow over flat, uniform, and homogeneous terrain. The abrupt changes in terrain and frictional characteristics as well as differential heat and moisture fluxes encountered at coastal locations can cause marked departures from conditions predicted by methods which assume flow over uniform and homogeneous terrain.

Since water is slow to heat or cool with respect to adjacent land areas, sharp temperature contrasts can exist between air over land and over nearby water. During the summer daytime, the land surface can become very warm and induce atmospheric instability in the overlying air. Offshore, the relatively cool lake water produces a stable environment which is not conducive to the thermal and convective instability over the land. During winter, the situation is reversed with the relatively warm waters of the lake inducing instability over the water, and the snow covered land remaining relatively cool and stable.

In a similar way, diurnal cycles create differences between the airmasses overlying water and those over land. At night, the land cools quickly, creating a relatively stable air mass compared to the slow or negligible cooling of air overlying the water, which can become relatively unstable. In the winter, when solar insolation is near a minimum and snow frequently covers the ground, the incidence of warm unstable air over the water and relatively cool, stable air over the land can persist even through daylight.

In order to model the behavior of a plume released into the atmosphere, the characteristics of the prevailing airmass must be understood. The atmosphere in a shoreline environment will display characteristics which can significantly deviate from predictions based on idealized conditions. The objective of this task is to further assess atmospheric characteristics in a shoreline environment.

4.1.1 Important Metecrological Regimes Over Eastern Lake Ontario

To further the understanding of the complicated meteorological conditions of the coastal zone, this task focused on the collection of detailed measurement during four different meteorological regimes: on-shore flow, lake breeze, land breeze, and low level jet (LLJ). The following briefly describes each of the four target regimes, and the importance of the condition to the assessment of pollutant transport and dispersion.

4.1.1.1 On-shore Flow

A detailed description of the implications of on-shore flow to the transport and diffusion of airborne pollutants is provided in Section 1.0 of this report. In summary, the flow of air from water to land is important since the air masses overlying each differ, having obtained attributes characteristic of the land or water surface. For instance, on a sunny spring or summer day, the air flowing onshore from the lake will tend to be cooler, more humid, and more stable than the air over the land surface being warmed by the sun. As air moves from one surface to another (i.e. water to land), it is modified at the bottom, taking on the characteristics typical of air resident over the new surface. The layer of modified air near the surface is referred to as an Internal Boundary Layer (IBL) because it grows within another boundary layer associated with the approach flow or unmodified air. When an IBL develops as a result of cooler, stable lake air moving over warmer, unstable land air, the layer near the surface is referred to as a Thermal Internal Boundary Layer or TIBL. Since the vertical distribution of stability is important in the identification of TIBLs, monitoring of the vertical temperature gradient is most important in observing this phenomena.

The most significant result of the existence of an IBL is a vertical variation in the stability which can have a profound effect on the manner in which pollutants are dispersed downwind from a source. Pollutants initially released into the stable layer may eventually intersect the boundary between the stable layer and deepening unstable surface layer. When this occurs, pollutants can be rapidly mixed down to the surface resulting in elevated pollutant concentrations. Knowledge of the existence and elevation of the TIBL with respect to the elevation of stack emission plumes is vital in describing dispersion processes in a shoreline region.

4.1.1.2 Lake Breeze

The lake breeze is a mesoscale circulation caused by the differential heating of the land and water areas in the region during daylight hours. The land areas absorb greater amounts of incoming solar radiation as compared to the water areas. As the day progresses the land areas heat more rapidly than the adjacent waters. The difference in temperature creates a pressure gradient between the land and water, producing a wind which flows from the water towards the land. Often with this situation the formation of a return flow from the land towards the lake will appear at higher altitudes. In the ideal lake breeze, the elevated return flow branch is directed 180 degrees opposing to the surface flow. This large vertical variation on wind direction found in the lake breeze can make it difficult to predict the transport direction of elevated pollutant releases.

The classic lake breeze develops during the late morning and will continue until early evening, when the cooling of the land mass destroys the driving force of the lake breeze. The prediction of the onset, strength, and duration of the lake breeze is complicated by the lake breeze dependance on a number of meteorological factors. Lake breezes are highly depen 'ant on the gradient wind direction and speed (synoptic scale), magnitude and sign of the lake/land temp. 'rature difference, and solar insolation. Other factors have also been noted as influencing sea breezes such as the surface frictional difference between the lake and land, depth and strength of synoptic scale inversions, and terrain.

4.1.1.3 Land Breeze

Like the lake breeze, the land breeze results from a pressure gradient caused by differences in lake and land temperature. However, rat'er than resulting from differential heating during the day, the land breeze is a result of differenti.' .ooling between the land and the water at night. The land mass cools quickly following sunset while the water, with its higher heat capacity changes in temperature only marginally between night and day. During evenings when the land cools to a temperature below the lake, a pressure gradient develops between the lake and the land which drives a flow of air from the land toward the lake. Land breezes tend to develop under stabilizing radiation inversions over the land, and therefore tend to be shallower than lake breezes. This makes the land breeze particularly important since large differences between surface and elevated wind conditions can result.

Land breezes are more common than lake breezes in the study area. They are often enhanced by drainage winds which flow down toward the lake from the elevated terrain surrounding the study area. Drainage winds result when cooling of the land surface causes the air closest to the ground to cool, and, being more dense, flow from higher elevation to lower elevation.

4.1.1.4 Low Level Jet (Nocturnal Wind Maximum)

It has been frequently observed that under certain meteorological conditions, extremely high winds can develop in thin layers above the surface. This phenomenon, which is most common at night, has been observed at Nine Mile Point (NMP) by the 200 ft meteorological tower (9MP) and doppler sodar. Referred to locally as the low level jet (LLJ), the phenomenon is more appropriately described as a nocturnal boundary layer wind speed maximum since the use of the term jet implies a feature of limited horizontal extent. The nocturnal wind speed maximum is caused by an ageostrophic adjustment to the gradient resulting from decoupling of the surface wind due to the nocturnal, surface-based radiation inversion. The wind speed maximum has been observed at relatively low elevations (as low as 100 ft), and is strongly correlated to the height of the surface-based radiation inversion.

The existence of the LLJ has implications for the transport and dilution of pollutant plumes. The appearance of the LLJ at elevations above which routine measurement are taken, yet at potential plume heights, is also of concern. Measurements at nuclear facilities are intended to be representative of plume release height conditions.

4.1.2 Applications to Nuclear Facilities

The meteorological program at Nine Mile Point Nuclear Power Station is subject to regulations and guidance as stipulated by NRC NUREG/CR-0936 and Safety Guide 1.23 Revision 1*. Meteorological data collected in support of the meteorological programs are used for short- and long-term dose calculations, and emergency response plume trajectory and arrival times. Regulations and guidance make specific statements regarding the need, location, availability, quality, and type of meteorological measurements.

NRC NUREG/CR-0936 identifies the following problem areas for meteorological programs at coastal facilities:

- Coastal internal boundary layers
- Tower location
- Instrument height
- Atmospheric stability classification
- Plume meander
- Diffusion calculations

This study will investigate further the first four problem areas identified by NRC and produce recommendations and justifications addressing each problem.

4.2 Study Objective

The objective of this task is two-fold:

- Determine the similarity between Ginna and Nine Mile Point during typical on-shore flow conditions.
- Obtain detailed measurements of several types of lake-induced flow regimes.

The primary concern for the former is whether the boundary layer height equation developed as part of Task 1 is appropriate for use at Ginna Station located approximately 100 km west of Nine Mile Point. The objective of the latter is to provide a data base of regime specific detailed case studies for ongoing mesoscale model development and validation.

4.2.1 Study Goal

The goal of this study was to collect meteorological data with high spacial and temporal resolution during specific meteorological events. The purpose of the data collected was to provide researchers with detailed information for the development and validation of models used to predict dispersion meteorology in shoreline environments.

4.2.2 Potential Applications for Research

Any utility with a source of atmospheric pollution located in a coastal or shoreline area may potentially benefit from improved understanding of the dispersion meteorology in the coastal zone. Detailed observations of the targeted phenomena will allow researchers to develop improved models to better predict the meteorological parameters which are important to the transport and diffusion of pollutants in regions experiencing complex meteorological flows. The detailed study will provide data beyond that typically available using routine measurements.

This research provides information of interest to utilities wishing to investigate the potential for better predicting the dispersion meteorology associated with the following concerns:

- Lake and land breezes,
- Vertical variations in stability associated with TIBLs, and
- Vertical wind profile variations associated with low level jets.

4.3 Approach

4.3.1 Description of Monitoring Systems

Reliable methods for the continuous measurements of the atmospheric boundary layer have only recently become a reality. Below, a summary of boundary layer measurement methods is provided. Each method has specific advantages and disadvantages that are important considerations when designing a boundary layer measurement program. Additional information on some of the measurement techniques is provided in Section 5.0 of this report.

4.3.1.1 Meteorological Tower

Meteorological towers have been the primary method of collecting meteorological measurements for many years. Instrumentation such as anemometers, wind vanes, thermometers, dew cells, and other standard meteorological instrumentation are installed on the tower at fixed elevations. Tall towers can have multiple measurement levels which allow determination of the vertical gradients of parameters such as wind and temperature. In addition, certain thermal and momentum flux parameters can be calculated using measurements at multiple elevations.

In general, the tower method of boundary layer measurement is quite reliable and rugged. There are few operational limits on the equipment other than weather extremes. However, towers suffer from several basic limitations. For example, meteorological towers are limited in practical height; towers higher than several tens of meters must be very substantial structures and erection of such can have rather extreme costs. Because of height limitations, meteorological towers may not be capable of sampling desired phenomena such as the lake breeze return flow. In addition, fixed measurement heights can limit the vertical resolution of observations, and phenomena such as the nocturnal jet may not be observed. Finally, in cases where spatially varying meteorological phenomena are of interest, such as the TIBL, multiple tall towers would be needed, a generally undesirable if not unsightly requirement.

4.3.1.2 Tethersonde

The tethersonde system consists of a large tethered balloon, winch, instrument package, and a ground station for receiving telemetered data. The instrument package provides measurements of air temperature, wet bulb temperature, pressure, wind speed and wind direction. The package is carried beneath the aerodynamic balloon which is connected to the winch by a tether line. The ascent or descent of the balloon is controlled by releasing or retrieving line from the winch. The balloon has a nominal inflated volume of 110 cubic feet which provides sufficient lift to operate to an altitude of over 3000 ft (approx. 1 km). The balloon is controllable by the winch for wind speeds of up to about 25 mph, above which the balloon becomes unstable.

When in flight, measurements are made sequentially over a period of approximately 13 seconds and transmitted as audio tones over a 403 MHz FM transmitter. The ground station receives the signal, decodes the audio tones, scales the values in terms of standard units, and outputs the data reports as serial digital data. The data stream is captured by a small computer and stored for subsequent analysis.

Dry and wet bulb temperature are sensed by linear thermistors housed in a radiation shield aspirated to provide the required ventilation for accurate wet bulb measurements. Combined calibration and linearity errors of the sensors are less than 0.5°F with dynamic response limited by sensor time constants of 15-20 seconds. Pressure is measured using an aneroid capsule which acts as a variable capacitance transducer. Calibration errors are of the order of 0.2 mb with somewhat larger hysteresis errors which are corrected during data analysis. Wind speed is sensed by a cup anemometer mounted on top of the instrument package. It has a linear response with a starting threshold of 2 mph. Static tests indicate a measurement error of less than 5%. Wind direction is sensed using a magnetic compass to record the balloon orientation. Due to its aerodynamic shape, the balloon acts as a large wind vane and remains pointed into the local wind direction. The accuracy of the system is approximately 5 degrees. Due to the balloon's large size, the damped response of the system is relatively slow, limiting its response to the average wind direction.

4.3.1.3 Radiosonde

The radiosonde system consists of a 30 g latex balloon and an attached instrument package (Airsonde) which, like the tethersonde, measures air temperature, wet bulb temperature, and pressure. The

Airsonde has a unique helicoid propeller-shaped housing consisting of lightweight, molded polystyrene which requires no parachute for free fall. Aspiration of the air and wet bulb temperature sensors is produced by the Airsonde's rotation. The sensor accuracy and response specifications are comparable to those for the Tethersonde instrument package. Wind speed and direction are determined by tracking the balloon with an optical theodolite. The theodolite provides measurements of azimuth and elevation angles from which balloon wind speed and direction can be calculated.

The Airsonde can be released during any weather conditions and can reach altitudes of over 30,000 ft. Its transmitter range is over 60 miles. An FM transmitter telemeters data to the same ground station used by the tethersonde system. The Airsonde sampling rate is every 5-6 seconds.

Radiosondes have the general limitation of having considerably lower resolution in the boundary layer due the rate of ascent and the method of wind calculations.

4.3.1.4 Monostatic Acoustic Sounder

Acoustic sounding equipment is based upon the principle that a volume of air scatters incident acoustic energy. Scattering is due to wind speed and temperature discontinuities in the sampled volume of air. Most of the scattering occurs in the direction of propagation, but a small percentage of the energy is scattered back to the source. An acoustic sounder transmits a strong acoustic pulse (typically around 100 watts) vertically into the atmosphere and listens for that portion of the transmitted pulse that is scattered back to the transmitter. The monostatic sounder uses the same acoustic driver to both transmit and receive the signal with a single antenna pointed vertically.

Theoretical equations which relate the amount of return signal to the velocity and thermal structure functions have been developed. The existence of a temperature gradient and small-scale turbulence create local instantaneous temperature differences greater than the mean vertical temperature gradient. A strong return signal can be produced either by an unstable temperature gradient and little wind shear (convective boundary layer) or with a stable potential temperature gradient and large wind shear (stable boundary layer). As a result, qualitative atmospheric stability and temperature profiles can be developed. Thus the monostatic acoustic sounder can be used to sample the boundary between marine and non-marine air during on-shore flow.

Monostatic sounders can produce both facsimile and digital outputs of signal strength for analysis. The facsimile output is essentially a strip chart recording of the strength of return signal versus height for each acoustic pulse. Dark shading indicates strong signal return while light shading indicates weak. Often, strong returns are associated with boundaries, such as the boundary between modified surface air in a TIBL and unmodified air above the TIBL in on-shore flow. In this way, the height of such mixing layers can be determined. Backscatter intensity data obtained using a monostatic sounder is converted from an analog signal to digital representation and stored in a computer for each of a user specified set of range gates or height increments.

In addition to the qualitative results, one strength of sounders is their ability to detect shifts in the frequency of the transmitted acoustic pulse. Frequency shifts are caused by the doppler effect and are directly proportional to the speed of an air parcel moving away from or towards the transmitter. In this way, vertical velocity (W) and standard deviation of vertical velocity (σW) can be calculated in each of the range gates. Atmospheric stability can be classified according to σW.

Acoustic sounders can reach heights as great as 1000 meters, depending on the atmospheric conditions. However, this range is often limited in high winds, precipitation, and high ambient noise level environments. In addition, fixed echo sources such as buildings and trees must also be avoided. The limitations in siting acoustic equipment are numerous, and all must be taken into account when determining an appropriate location for the system.

4.3.1.5 Doppler Acoustic Sounder

The doppler acoustic sounder is the same in terms of theory and method of operation as the monostatic sounder, except that it is capable of measuring the three dimensional wind profile. These systems are also known as SODARs (Sound Detection and Ranging). SODARs achieve their unique measurements using a combination of three antennas, one vertically pointing, and two pointing at an angle from the vertical and 90° to each other. With this configuration, and the calculation of vertical velocity along the axis of each antenna, simple trigonometry allows the determination of the three dimensional wind.

As with the monostatic sounding system, siting of the equipment is vital. In addition, the range of the sounders is limited during high winds due to the advection of signal out of the sampling volume.

4.3.1.6 Microwave Profiler

Microwave profilers are similar to doppler sodars except they rely upon the scattering of microwave energy to measure the three wind components. This relatively new technology eliminates some of the siting and wind speed limitations of acoustic systems since they operate in a much higher wavelength range. Like the SODAR, the profiler can measure the three dimensional wind profile by directing its signal in a similar manner, either through phasing of the antenna pulse or by physically tilting the antenna.

Two types of profilers are presently under development. The most widely used and tested operated at 404 MHz. This system can measure the three vertical wind components from approximately 1 km above the surface to approximately 10 km. The low resolution near the surface of the 404 MHz system has limited its applicability to the problem of boundary layer measurements. The second, newer type of microwave profiler shows potential for making boundary layer measurements. The new system operates at 915 MHz, and appears to be capable of measuring the three dimensional wind as low as several hundred meters at a higher range gate resolution than the 404 MHz system. This makes the 915 MHz profiler attractive for boundary layer applications. In addition, the 404 MHz system has extremely limited range in cold, dry air. The 915 Mhz systems appear to be less limited by this condition.

4.3.1.7 RASS

The Radio Acoustic Sounding System (RASS) is another emerging technology that may be applied to measuring the atmospheric boundary layer. The RASS uses both the acoustic and microwave profiling technologies. By combining the two techniques, and providing for additional signal processing, the vertical temperature profile can be determined. This is accomplished by essentially making use of the temperature dependence of the speed of sound. Microwaves from a profiler are "bounced" off the acoustic energy waves produced by the sodar, and the change in speed of the wave determined. This speed change is, in turn, used to determine temperature in each of the specified range gates. In general, the technique shows promise for boundary layer measurements of temperature, although the resolution is still too coarse to allow detailed observations of the TIBL and some inversions.

4.3.2 Sampling Technique

The objective of this task is two-fold: 1) to determine the similarity between Ginna and Nine Mile Point during typical on-shore flow conditions, and 2) to obtain detailed measurements of several types of lake-induced flow regimes. These objectives were addressed by performing two subtasks as described below.

4.3.2.1 Subtask 1 - Simultaneous Soundings at Ginna and NMP

A tethersonde/radiosonde station was installed in the vicinities of both Ginna and NMP. The stations were sited approximately the same distance inland relative to the onshore flow in order to maximize the comparability of sites. The Ginna station was operated by personnel from the State University of New York as Brockport (SUCB) and the NMP site by AWS Scientific, Inc. (AWS).

Attempts were made to collect three days of simultaneous measurements at Ginna and NMP, each day representing a different on-shore flow regime. The selection of measurement days was based on forecasts provided by a forecast team headed by State University of New York at Oswego, and verified the morning of the event. The sites were in telephone contact with each other to coordinate measurements. Weather conditions limited the measurements to two successful events.

The primary measurement system was the tethersonde as described above. The proposed measurement protocol was to obtain two vertical profiles every hour, with the tethersonde allowed to ascend at a near constant rate up to an altitude of approximately 1000 ft, hold briefly, then descend. This sequence was continued for up to 8 hours or as long as on-shore flow persists. Launches of radiosondes were scheduled for twice per day in order to quantify the synoptic scale conditions. The following parameters were measured with either system: dry bulb and wet bulb temperature, wind speed, wind direction, and pressure (from which altitude is determined).

4.3.2.2 Subtask 2 - Detailed Lake-Induced Regime Case Studies

Two tethersonde/radiosonde monitoring locations (sites) were operated in the vicinity of Nine Mile Point to characterize the over land and vertical structure of four types of lake flow regimes: on-shore flow fumigation (3 events), lake breeze (5 events), land breeze (2 events), and the nocturnal low-level jet (2 events). Table 4-1 presents a summary IOPs and regimes sampled. Tethersonde Site 1 was located southwest of NMP, approximately 1 km inland from the lake, and Tethersonde Site 2 was south of NMP, approximately 3.5 km inland from the lake. Radiosondes (Airsondes) were launched from the more inland site, Site 2. Site 1 was operated by AWS and Site 2 by SUCB.

Each station had the capability to launch tethersondes. The tethersonde was the primary measurement system, providing frequent, high resolution data within the boundary layer. Site 2 also had the capability to launch radiosondes which were intended to obtain vertical profiles through a deeper layer of the atmosphere (up to 500 mb if possible) and provide information regarding synoptic scale features influencing the area. The meteorological parameters to be measured from either system are dry and wet bulb temperature, wind speed, wind direction, and pressure from which the altitude can be determined. The sampling interval during tethersonde flights was every 13 seconds.

The field program was designed to measure the targeted case studies in an efficient, organized manner. Intensive observation periods (IOPs), were scheduled to correspond to weather conditions favorable for the development of the desired phenomena. Each sampling period was continued as long as the desired conditions prevailed or until conditions became relatively static. In one case, it was possible to sample more than one regime in the same 24-hr period (e.g., Land breeze followed by a lake breeze), however, this was subject to the availability of fresh work crews. In the event of an extended period of inclement weather, an intensive was interrupted and a new intensive was scheduled when conditions were forecast to improve.

To ensure a successful, coordinated effort throughout each intensive, the field modeling task was organized as follows:

- The Galson task leader coordinated the overall intensive program and, through consultation with the other members of the task team, was responsible for day-to-day planning and communicating with the monitoring site contractors.

- Each site had a team leader responsible for conducting measurement operations, supervising the site work crew, and maintaining direct communications with the task leader. A cellular telephone communication system was established between all field stations.

- A forecast team, including members of NMP meteorological staff and the State University of New York at Oswego Meteorology Department, provided weather guidance during the intensive measurement periods by predicting the timing of case study onset and offset, and maintaining communications with the task leader. The task leader was responsible for determining the start and stop times of the field crews.

- Task team meetings were held during each intensive period to discuss the weather forecast, review data from the previous event, and discuss problems.

The measurement protocol proposed in Phase 1 of this task was used in this phase, resulting in two vertical profiles every hour for the duration of the event up to a limit of 12 hours. Radiosondes were launched once in the morning and again in the evening in an attempt to correspond with the 0000 GMT and 1200 GMT routine sounding time at National Weather Service Offices. If, after 2-3 hours of measurement, a forecast regime failed to materialize or meteorological conditions had changed sufficiently to make the regime unlikely, the measurement program for that event was terminated.

4.3.3 Data Analysis

Tethersonde data collected during the field experiment was validated, plotted, and summarized by the operators (AWS Scientific, Inc. and SUCB). Data from the profiler and RASS underwent validation by Radian Corporation. The 10-meter micrometeorological tower data was validated by Galson. Validation of the data included inspection by a meteorologist for reasonable data values based upon conditions observed, removal of suspect data and bad data, and calibration adjustments. Data from the 9MP tower was provided by the operator, Niagara Mohawk Power Corporation, and was assumed to be already validated.

4.4 Data Summary

4.4.1 IOP Event Summaries

4.4.1.1 IOP Number 1 - May 20 to 22, 1992 (On-shore Flow and Lake Breeze).
Temperature, dew point, wind direction and wind speed profiles for each of the IOP Number 1 tethersonde and airsonde flights from Sites 1 and 2 are provided in Appendix C. Following is a brief

summary of each event measured during IOP 1.

May 20, 1992. The event was performed to capture a lake breeze and associated on-shore flow conditions. A large area of high pressure was located east of the IOP region and gradually drifted south through the day. A westerly gradient wind controlled the synoptic scale setting, gradually increasing over the course of the day. Very windy conditions associated with a LLJ limited tethersonde operations in the morning until 0815. Measured winds were generally from the south to southwest from the surface to 1200 ft, with speeds peaking at 12 to 15 mph between 800 and 1200 ft. The onset of a lake breeze was observed at the 9MP tower between 1045 and 1100, at site 1 around 1100, and at site 2 around 1145, with surface winds shifting to the north and lower temperatures. The mid-day tethersonde flights showed winds at speeds of 6 to 12 mph associated with the lake breeze from the surface up to 900 feet, veering to east and then south between 1000 and 1500 ft. A slight temperature inversion was noted at the elevation separating the lake breeze from the synoptic scale flow. The lake breeze continued to deepen to be about 1200 ft deep by early afternoon. The depth of the lake breeze then decreased to as low as 600 ft by 1645. The southerly return flow persisted above the inversion level, with peak speeds reaching 12 to 14 mph at 1400 ft during the late afternoon.

May 21, 1992. On-shore flow with a potential lake breeze component was the focus of monitoring for this event. In the early morning, strong winds (> 20 mph) above a surface based radiation inversion prevented full tethersonde profiles. The winds slackened somewhat by mid-morning to allow tethersonde flights into the persistent on-shore gradient flow of northwest winds. Once the morning inversion had mixed out following sunrise, the wind remained generally 6 to 12 mph throughout the day. A relatively moist layer from the surface up to about 600 to 800 ft was observed during the afternoon. This may have been associated with a TIBL type of vertical stability shear, with cooler, more moist marine air undercutting drier environmental air. This day is deserving of further investigation as to the causes of differences observed between site 1 and site 2. Site 1 may have observed more radical differences due to its proximity to the lake, and better exposure to the lake air.

May 22, 1992. An early morning low level jet was followed by light on-shore flow and a weak lake breeze during this event. High pressure continued south and southwest of the IOP area, with a variable gradient form west to north through the event. The early morning tethersonde launches showed a shallow low level jet in a strong temperature inversion in the lowest 300 ft of the profile. A maximum wind of 17 mph from the south-southwest was observed in the jet, decreasing in speed and veering to west-northwest at 1100 ft. Solar heating created thermal mixing which destroyed the inversion and allowed the jet to mix out during the morning. By late morning, the southerly land breeze winds had diminished, and were replaced with the northwesterly gradient wind. A lake breeze component developed throughout the afternoon as winds in the lowest several hundred feet became north-northwest with northwesterly wind above. Winds were relatively moist in the lowest portion of the profile, with drier air aloft.

4.4.1.2 IOP Number 2 - June 22 to 23, 1992 (Land Breeze and Low Level Jet).
Temperature, dew point, wind direction and wind speed profiles for each of the IOP Number 2 tethersonde and airsonde flights from Sites 1 and 2 are provided in Appendix C. Following is a brief summary of each event measured during IOP 2.

June 22 to 23, 1992. The focus of this IOP event was to capture a complete land breeze and a LLJ cycle through collection of observations overnight. These phenomena are often observed together since an offshore directed land breeze develops in the cooling air over the land as heat radiates to space, and the LLJ develops at the top of the radiation inversion which develops on clear, relatively calm nights. A high pressure ridge passing over the IOP sampling area during the night with clear skies and light gradient winds provided an optimal setting for the development of a land breeze. A shallow radiation inversion had already set up by the time the first tethersonde launches took place, and an extremely shallow land breeze with light south winds in the lowest 50 ft of the profile veering to northwesterly gradient aloft. By midnight, the land breeze had deepened to several hundred feet, and a wind speed maximum observed at the top of the surface-based radiation inversion. The land breeze maintained itself through the evening, and the LLJ reached a peak of approximately 17 mph overnight.

4.4.1.3 IOP Number 3 - August 5 to 7, 1992 (Ginna Comparison, On-shore Flow and Lake Breeze)
Temperature, dew point, wind direction and wind speed profiles for each of the IOP Number 3 tethersonde and airsonde flights from Sites 1 and 2 are provided in Appendix C. Following is a brief summary of each event measured during IOP 3.

August 5, 1992. Predicted on-shore winds provided an opportunity to perform a Nine Mile Point/Ginna Comparison. High pressure west of the Lake Ontario produced a moderate northwesterly gradient for the day. Strong onshore winds resulted in tethersonde balloon stability problems at both the NMP and Ginna monitoring site throughout the event. By mid-morning, the winds had become somewhat more stable to allow normal operations at Ginna, even though the flow remained strong at 15 to 25 mph above the 500 ft level during the entire event. However, winds remained strong and actually increased by mid-day at the NMP site, resulting in a suspension of all monitoring following the 1300 tethersonde launch. It is believed that the difference in conditions between Ginna and NMP resulted from a mesoscale thermal trough embedded within in the unstable northwest flow as cooler air associated with the high moved across the lake. Due to the instability of the day and the resulting limited data collected, and the apparent importance of other mesoscale features during this event, little information of value regarding comparisons of onshore flow regimes between Ginna and NMP is expected from this event.

August 6, 1992. High pressure passing over the southern teir of New York State, south of the study area, offered an opportunity to measure onshore/along-shore flow near NMP. Both tethersondes were deployed near NMP to measure this event. Mostly clear skies overnight allowed a radiation inversion to develop with very light winds at the surface overnight. With the first tethersonde flights at 0600, surface winds were near calm to 5 mph from the south in a weak land breeze, increasing to about 15 mph from west-northwest in the gradient wind regime 400 ft above the surface at tethersonde site 1, and 200 ft at the higher base elevation of site 2. The base of the temperature inversion was located around 200 ft with nearly isothermal conditions above. A weak LLJ may have been in progress around the inversion base as evidenced by the first few tethersonde flights, however, the dominance of the westerly gradient winds appears to have lessened the jet's prominence. After sunrise and the early heating of the day, the radiation inversion mixed out of the profile, and the northwest gradient winds mixed down to the surface at both sites. During the afternoon, winds slowly backed to the southwest reflecting a backing gradient as the high moved southeast of the area.

August 7, 1992. High pressure over New England and a weak southerly gradient provided conditions favorable for the development of a lake breeze with both tethersonde teams taking measurements in the vicinity of NMP. The morning commenced with a strong surface-based inversion and a 25 mph

LLJ from the SSE. The inversion at the lower tethersonde site 1 was just above 400 ft, with the wind speed maximum extending from 400 ft to 800 ft in elevation. At the higher base elevation of site 2, the temperature inversion was near 200 ft and the maximum winds extended from 200 to 500 ft. The LLJ appeared to be stronger at tethersonde site 2, where the temperature inversion was closest to the surface. As the heating of the day worked to lift and weaken the inversion, the LLJ rose and weakened in response. The morning profile was replaced by a generally southerly wind between 5 and 10 mph throughout the boundary layer. During the early afternoon, the wind direction profile became quite variable by the 1345 flight. At site 1, a lake breeze passed dramatically around 1400, with the entire wind direction profile becoming north at very light speeds by the 1415 sounding. The lake breeze veered into the northeast during the afternoon and gradually became shallower with southerly gradient winds appearing in the profile by 1600. The lake breeze never penetrated the short distance between sites 1 and 2, with site 2 recording variable south winds most of the afternoon. This event is a dramatic example of the localized nature of some lake breezes and the potential difficulty this regime presents to the prediction of transport and diffusion of pollutants in the shoreline zone.

4.4.1.4 IOP Number 4 - August 21 to 23, 1992 (On-shore Flow and Lake Breeze)

Temperature, dew point, wind direction and wind speed profiles for each of the IOP Number 4 tethersonde and airsonde flights from Sites 1 and 2 are provided in Appendix C. Following is a brief summary of each event measured during IOP 4.

August 21, 1992. A synoptic situation similar to that observed on August 5 once again afforded the opportunity to measure onshore flow regimes at both NMP and Ginna. A high pressure area was south of the area over central Pennsylvania, resulting in a northwesterly flow over the south shore of Lake Ontario. In the early morning, surface winds at both NMP and Ginna were relatively light near the surface, but considerably stronger winds were observed during the first tethersonde flight of the day just a short distance above the ground. The Ginna tethersonde team was forced to abort monitoring when the winds increased from 3 mph at the surface to nearly 25 mph at 300 ft. The NMP tethersonde team observed more modest wind speeds generally in the 10 to 15 mph range. The winds were generally westerly at both sites, however as the day progressed winds veered and became more onshore northwesterly at both locations. At Ginna, the wind veered to Northerly for a time during late morning through mid-afternoon indicating a possible, slight lake breeze. Winds veered slightly from west-northwest to northwest in the low levels at NMP, but the effect was not as dramatic. As with the August 5, 1992 case, Ginna and NMP do not appear to compare well on a case specific basis due to the importance of mesoscale feature at each site.

August 22, 1992. Weak high pressure over New York State with clear skies and a weak pressure gradient provided conditions favorable for the development of a lake breeze. Monitoring was initiated just prior to sunrise with an airsonde launch. Initial tethersonde launches indicated a surface-based radiation inversion with moderate LLJ around 200 to 300 ft above the surface. Following sunrise, the radiation inversion quickly mixed out, bring northwesterly winds aloft down to the surface which persisted through much of the afternoon. The light winds slowly veered into the north by the end of the afternoon. This veering is believed to have been a lake breeze influence, however the effect was quite weak and may have been a result of the proximity of the synoptic high pressure area which was just west of the area by evening. Note that several parameters were missing during some of the Site 2 profiles due to malfunctioning equipment.

August 23, 1992. Warm air with a high pressure area over New England and an increasing southerly gradient offered the potential of a lake breeze. Monitoring began at both sites around sunrise. A fairly deep radiation inversion with an offshore directed LLJ of over 20 mph was observed. The gradient winds were from the south at better than 15 mph. Following sunrise, the LLJ briefly gained strength at both sites, exceeding 25 mph and mak[illegible] tethersonde profiles throughout the layer difficult. By 0900, the inversion was mixing out and the LLJ gradually becoming more elevated. Once the LLJ and inversion had mixed completely out, a south to southwest gradient-type wind regime dominated, with wind speeds dropping to 5 to 10 mph. The expected lake breeze failed to materialize during the observing period, although the light southerly winds with respect to the stronger gradient winds aloft observed by the evening airsonde, and a few brief observations of extremely light northwest winds at Site 1 indicated that a lake breeze was near forming. This case appears to be valuable from a sense of bracketing the limits of synoptic conditions within which lake breezes develop at NMP.

4.4.1.5 IOP Number 5 - September 12 to 13 (Land Breeze, LLJ, Lake Breeze)

Temperature, dew point, wind direction and wind speed profiles for each of the IOP Number 5 tethersonde and airsonde flights from Sites 1 and 2 are provided in Appendix C. A stable synoptic pattern allowed a unique opportunity to study both a land breeze with embedded LLJ followed by a lake breeze, all within the same 24 hour period. Following is a brief summary of each event measured during IOP 5.

September 12 to 13, 1992 (Land breeze/LLJ). Clear sky, cool temperatures, high pressure centered nearly directly over NMP and calm gradient indicated a potential for land breeze and LLJ conditions. Monitoring at both Sites 1 and 2 was initiated shortly before sunset. Both sites indicated a very shallow and intense surface-based radiation inversion. At Site 2, an inversion of 7 F was noted in the lowest 30 to 50 ft, and at approximately 100 ft at the lower base elevation of site 1. A low level southerly wind speed maximum was already apparent at the base of the inversion at site 1, with a land breeze 400 ft deep below northerly winds aloft. The LLJ gradually intensified to speed in excess of 20 mph just 150 ft about the surface at Site 2. Both sites observed strong winds at tree top level at the same time calm winds were observed at the surface. The land breeze deepened to envelop the entire 1000 ft profile by midnight. The LLJ was most pronounced at Site 2, with maximum winds reaching 22 mph. During the night, the inversion became less intense and deepened with the surface temperature actually rising several degrees. Following sunrise, both sites observed a rapid weakening of the inversion and broadening of the wind speed maximum until it had mixed out by mid-morning on the 13th.

September 13, 1992 (Lake Breeze). The daylight hours began with the land breeze and LLJ as discussed above. High pressure was located southeast of the area resulting in a weak south to southwest gradient. A general southerly wind flow of 5 to 12 mph was observed between the surface and 1000 ft through late morning. Winds became more light and variable after 1200 as the tethersonde balloons would occasionally traverse 360 degree circles during the night. A weak, shallow lake breeze was observed to develop at Site 1 between 1310 and 1320, deepening from 100 to 900 ft by 1400. The lake breeze penetrated very slowly, reaching Site 2 around 1510, with the tethersonde showing light northeast winds between the surface and 700 ft, veering to the southwest above. Lake breeze velocity was between 5 and 10 mph at Site 1, but just 5 mph at site 2. The lake breeze persisted until after 1700, when winds shifted into the southeast and a surface-based inversion began developing, indicating the offset of the lake breeze and the onset of a new land breeze.

4.4.2 Digital Data Files

All profiles from each of the tethersonde sites for all events has been archived into digital data files. Over 250 profiles were collected between the two tethersonde sites. Each profile is separated into a digital file and named with the date and approximate time of the profile. Filenames are tagged with a filename extension. The "A" filename extension represents a profile collected while the tethersonde was ascending, and a "D" extension indicates the data was collected while the tethersonde was descending. In most instances, descending profiles are believed to be of higher quality than ascending profiles. Each file contains a single profile; and each profile consists of the following parameters:

- Data Field 1 – Year, Month, Day, Hour, Minutes, Seconds (EST)
- Data Field 2 – Height above ground level(m)
- Data Field 3 – Pressure (in Hg)
- Data Field 4 – Air Temperature (°C)
- Data Field 5 – Dew Point Temperature (°C)
- Data Field 6 – Wet Bulb Temperature (°C)
- Data Field 7 – Wind Speed (m/s)
- Data Field 8 – Wind Direction (° True)

The data files are stored as ASCII text and should are readable by employing simple text editing software. Questions regarding the data files should be addressed to:

Galson Corporation
Modeling/Meteorology Unit
6601 Kirkville Road
East Syracuse, NY 13057

4.5 Conclusions and Recommendations

Detailed measurements of specific meteorological regimes were collected in order to develop a detailed data base for use in the development and validation of models for predicting the transport and dispersion of pollutants from power generating facilities located in shoreline environments. Although the goal of this task was mainly one of data collection, the following conclusions are made:

- In general, good quality, high resolution data was obtained during weather conditions favorable for each of the four target meteorological regimes. This data, combined with the other special measurements taken during the Eastern Lake Ontario On-shore

Flow Field Study as well as routine meteorological measurements in the area should provide researchers with a data set suitable for developing and validating conceptual and numerical models of the dispersion meteorology along the southern shore of Lake Ontario.

- Of the various meteorological regimes measured, the LLJ was perhaps the most dramatic and consistently observed regime. Some form of LLJ was observed during all IOPs, and two detailed case studies were obtained.

- Land breezes and LLJ were observed together. Considering the conditions which lead to the development both phenomena, it is believed that these events often occur simultaneously.

- This monitoring was successful in obtaining data during a variety of lake breeze types. The data is expected to be useful in investigating the lake breezes of moderate strength and deep inland penetration; weak lake breezes with limited inland penetration; lake breeze enhancement of gradient wind flow; and no lake breeze under conditions when a lake breeze would typically be expected.

- Onshore flow offers the most subtle measurements. Some moisture layering was observed along with slight temperature fluctuations. However, the subtle nature of the measurements makes comparisons between the two tethersonde sites difficult during onshore flow conditions.

- Difficulty in obtaining concurrent measurements at Ginna and NMP in similar weather conditions made direct comparison between the two sites impossible.

Based upon the above conclusions and the experience of the project team in the performance of this task, the following recommendations are made:

- Obtaining detailed measurements of meteorological phenomena of concern to utilities is valuable and should be considered whenever possible.

- Use of the monitoring data by researchers involved in the development and validation of models over southern Lake Ontario should be actively encouraged.

- Coordination of multiple field teams is challenging due to the high variability of weather conditions over short distances. A high quality, reliable forecast and communication system should be tested and in place prior to initiating sampling such as that performed during this task.

- Further investigation and monitoring in onshore flow environments should be performed in order to better understand the subtle measurements which occur under these flows.

Table 4-1

IOP Monitoring Data Summary

		Number of Hours						
		IOP[1]	IOP[1]	IOP[1]	IOP[1]	IOP[1]	IOP	
Task	**Proposed**	**#1**	**#2**	**#3**	**#4**	**#5**	**Total**	**Remaining**
4.1 NMP/Ginna Comparison	36	0	0	12	12	0	24	12[2]
4.2 Detailed Regimes								
Onshore Flow	36	12	0	12	0-12	12	36	0
Lake Breeze	60	24-36	0	12	12-24	12	60-84	0
Land Breeze	24	0	12	0	0	12	24	0
Low Level Jet	24	0	12	0	0	12	24	0
Total	144	36-48	24	24	12-36	24	144-168	0

[1]IOP #1 - May 19 through May 22, 1992

IOP #2 - June 22 through June 23, 1992

IOP #3 - August 4 through August 7, 1992

IOP #4 - August 21 through August 24, 1992

IOP #5 – September 12 through September 13, 1992

[2]Due to the lack of favorable weather conditions and the difficulty in obtaining comparable data during the first two attempts, a third Ginna NMP comparison was not performed.

Section 5.0

Evaluation of Wind and Temperature Remote Sensing Technology

This section presents the results of a one year evaluation of wind and temperature remote sensing technology installed at the Nine Mile Point Nuclear Facility (NMP). The facility has existing meteorological measuring systems including a 200 ft meteorological tower and a doppler acoustic sodar located approximate 0.5 km west of the facility. Special remote sensing instrumentation was installed for this task near the facility for a period of one year to evaluate its performance in collecting continuous wind and temperature data aloft. A background summary of profiling equipment is provided in Section 6.1. Section 6.2 overviews the study objective, potential applications for the research, and limitations of the study. A brief summary of the field monitoring involved in this project is presented in Section 6.3 and the evaluation of the profiler and RASS is in Section 6.4. Finally, conclusions and recommendations are provided in Section 6.5.

5.1 Background

Measurements of atmospheric parameters are most commonly obtained as direct measurements by placing the appropriate instrument in the fluid at the location (horizontal and vertical placement) where the data is sought and record the appropriate values. Typically, the sensors are located in shelters, on towers, attached to balloons, or on aircraft. Data obtained in this manner are termed in situ measurements (Schotland, 1985). Instrumentation technology involved with making in situ measurements is well established within the meteorological community. However, the need to continuously make measurements of the atmospheric environment in three dimensions complicates the use of in situ measurements systems, particularly in the vertical dimension.

Meteorological phenomena are three dimensional, and data describing this structure is vital to the complete understanding of phenomena in question. Examples of boundary layer meteorological phenomena having complex three dimensional structure include lake and land breezes, vertical wind speed profiles, internal boundary layers and terrain flows. Collection of data only near the surface is inadequate to describe complicated vertical structures.

5.1.1 Tower-based Instrumentation

Where meteorological measurements are required close to the ground, the use of in situ measurement systems is simple. The necessary instrumentation can be placed in shelters or attached to towers. However, when measurements are required at elevations above ground, these techniques limit the options available. The height of towers is limited to a maximum of approximately 1000 ft due to structural considerations, and in practice is often limited to several hundred feet due to public concerns related to visual impacts and safety concerns due to aviation hazards.

5.1.2 Balloon-borne Instrumentation

In the past, "temporary" systems have been employed to gather needed measurements of meteorological parameters above the height typically covered by tower-based instrumentation. These temporary measurement systems have most commonly taken the form of instrumented free flying balloons called radiosondes (or airsondes). The instrument package of a typical radiosonde is capable of measuring air temperature, wet bulb temperature, and pressure. The height obtained by the instrument is determined from the pressure and temperature relationships. Wind speed and direction is determined by either manually tracking the balloon using an optical theodolite system, tracking the balloon with radar, or using a Loran navigational tracking system in the instrument package.

While radiosonde systems are capable of providing atmospheric data between the surface and tens of kilometers in elevation, they are limited in that they provide only single point data in space and time as the instrument passes through any given elevation. Thus, radiosondes do not allow continuous observations at a specific elevation. In addition, the instrument package may only be used once since it is impractical to retrieve the systems following use. Thus radiosondes are relatively labor intensive and expensive for use in obtaining continuous measurements of meteorological parameters in the vertical dimension.

An alternative to the "disposable" radiosonde is the tethersonde. Like the radiosonde, the tethersonde system consists of an instrumented package attached to a balloon. However, in this instance, the balloon is tethered to the ground and may be raised, lowered, or remain at a given elevation using a power winch system. The instrument package contains a radio transmitter which telemeters data to a ground receiver where the information is logged on a computer. The tethersonde offers more control than the radiosonde over the elevation and duration of measurements taken in the boundary layer.

Most tethersonde systems are limited to use below 1000 meters, are unstable and unreliable in strong winds (>10 m/s), must be brought to the ground frequently in order to replenish batteries, and are labor intensive. In addition, only one elevation can be sampled at any given time. Recently though, several manufacturers have developed tethersondes capable of handling several instrument packages along the tetherline at varying elevations.

5.1.3 Atmospheric Remote Sensing Instrumentation

Recent technological advances have led to the development of remote sensing atmospheric profiling systems which are capable of continuously measuring atmospheric parameters above the ground. This technology offers many advantages over the older techniques described above; namely, the continuous, unattended observation of meteorological parameters at a number of vertical elevations simultaneously without having to rely on in situ instrumentation.

5.1.3.1 Acoustic Sounders and Sodar

Acoustic remote sensing equipment is based upon the principle that a volume of air scatters acoustic energy incident upon it. Scattering is due to wind speed and temperature discontinuities in the sampled volume of air. Most of the scattering occurs in the direction of propagation, but a small percentage of the energy is scattered back to the source. An acoustic sounder transmits a strong acoustic pulse (typically around 100 watts) vertically into the atmosphere and listens for that portion of the transmitted pulse that is scattered back to the transmitter. The monostatic sounder uses the same acoustic driver to both transmit and receive the signal with a single antenna pointed vertically.

Theory relates the amount of return signal to velocity and thermal structure functions of the atmosphere (C_t and C_v). The structure functions can be interpreted as expressing the degree of instantaneous velocity or temperature difference between points a unit distance apart. The existence of a temperature gradient and small-scale turbulence create local instantaneous temperature differences greater than the mean vertical temperature gradient. A strong return signal can be produced either by an unstable temperature gradient and little wind shear (as is found in the convective boundary layer) or with a stable potential temperature gradient and large wind shear (as is found in the stable boundary layer). As a result, qualitative atmospheric stability and temperature profiles can be developed.

One strength of sounders is the ability to detect frequency shifts between the transmitted and backscattered acoustic pulse. Frequency shifts are caused by the doppler effect and are directly proportional to the speed of sound of an air parcel moving toward or away from the transmitter. In this way, the speed of the air along the axis of transmission can be determined at various elevations between the surface and roughly 1000 meters aloft. This range is highly dependent on atmospheric conditions and can be limited by such as things as high wind speeds, precipitation and high ambient noise levels. In addition, environmental factors must be considered in locating acoustic sounders giving adequate consideration to stationary sources of backscatter such as building and trees, which could lead to erroneous data.

The doppler sodar uses the acoustic backscatter and frequency shift detecting capability of the sodar in a three axis system capable of measuring the three dimensional wind profile. The sodar achieves such measurements using a combination of three antennae, one vertically pointing, and two angled obliquely to the vertical (approximately 18°) and horizontally oriented 90° to each other. With this configuration, and calculation of velocity of the air along each axis of the antenna, simple trigonometry allows the calculation of the three dimensional wind profile at heights above the sodar. The two tilted antenna are used to calculate the horizontal wind speed and direction, and the vertical antenna is used to calculate the vertical wind speed as well as correct the calculation from the tilted antenna for the vertical component of wind. Recently, advances in sodar technology have done away with the three antenna concept, replacing it with a single array of vertically-pointing small acoustic drivers. The acoustic driver array is then sequenced to operate in a way such that the beam is "steered" to obtain the backscatter data from the direction oblique to the vertical allowing calculation of the horizontal wind. This type of antenna system is referred to as a phased-array sodar. The doppler sodar suffers from the same height and operational limitations as the acoustic sounder.

5.1.3.2 Radar Wind Profiler

Microwave atmospheric profilers are similar to sodars in that they rely on the scattering of microwave energy to measure the three dimensional wind component. This relatively new technology improves upon some of the range and environmental limitations of acoustically-based systems by operating in a much higher much higher wavelength range. Like the sodar, the profiler obtains measurements of the vertical and horizontal wind profile by directing the signal. Three antennae are oriented in a similar manner similar to the sodar, or, more recently, by electrically steering the microwave beam direction in a way similar to the phased-array sodar system described above.

A number of different profiling systems are under development in the United States and several radar profiler systems have recently been commercialized (eg. the NOAA 50MHz deep tropospheric profiler, the UNISYS 404 MHz Radar Profiler, and the Radian/STI LAP-3000 915 MHz lower atmospheric profiler). The 50 MHz system is a research grade profiler capable of sensing winds from 1 or 2 km to over 10 km. The 404 MHz profiler is termed a "middle tropospheric" profiler and is capable of returning reliable data between about 500 m and 7 or 8 km above the surface. The National Weather Service is currently installing a demonstration network of 404 MHz profilers in the U.S. great plains region. Finally, the 915 MHz profiler has recently been commercialized under an agreement between Radian, STI and NOAA for use as a lower tropospheric profiler, and is believed capable of returning reliable data between 100 m and 5 km.

As in the case of sodars, care must be taken in siting Radar wind profilers to avoid exposing the microwave beam to objects which pose a threat of backscatter and resulting "ground clutter". Ground clutter objects such as trees, power lines, etc., sway with the wind and energy reflected from the swaying objects may be interpreted by the profiler as good data.

5.1.3.3 Radio Acoustic Sounding System

The Radio Acoustic Sounding System (RASS) is another emerging technology for measuring the atmospheric boundary layer. RASS makes use of both sodar and radar profiling technologies. By combining the two techniques, and providing for additional signal processing capability, the vertical profile of virtual temperature[1] (T_v) can be determined by making use of the relationship between the

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[1] Virtual temperature is the temperature of dry air having the same density and pressure of moist air. The virtual temperature is always greater than the actual temperature and is approximated by

$$T_v = (1+0.61q)T$$

where T is the temperature and q is the specific humidity (Huschke, 1959).

and temperature[2].

In the RASS configuration, only the vertically pointing antenna of the Sodar and Profiler are used. Sodar produces an acoustic disturbance which is tracked by the radar profiler as it travel vertically away from the antenna. Radar is capable of determining the speed of the acoustic disturbance as it travels vertically, which in turn is used to calculate T_v at each of a series of user specified range gates.

RASS suffers from some limitations in range due to atmospheric dissipation of the acoustic pulse and also transport of the pulse out of the radar's field of view by horizontal winds. In general, RASS will perform best in a strongly stratified atmosphere with light winds.

5.1.4 Applications to Nuclear Facilities

Understanding meteorological influences on the transport and diffusion of air pollutants emitted from power generating facilities is greatly enhanced with knowledge of meteorological parameters at various elevations above the ground. Current pollutant dispersion and transport models make relatively simple assumptions regarding the atmospheric parameters influencing any pollutants that may be released by a source. Some of the more significant assumptions with respect to meteorological inputs are:

- Wind speed and direction is assumed to be uniform throughout the horizontal domain of the model,
- Only one stability class is generally accepted to describe both horizontal and vertical diffusion of the plume (although some models are capable of accepting different horizontal and vertical stabilities),
- Stability, wind speed, and wind direction are assumed to be constant in time up to about one hour, and
- Vertical variations in the stability class are not allowed below the mixing height.

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[2] The speed of sound is related to temperature by the expression

$$c=\sqrt{\gamma RT}$$

where R is the gas constant; T is the temperature; γ is the ratio of specific heat of air at constant pressure (c_p) to the specific heat of air at constant volume (c_v) (Huschke, 1959).

Such assumptions can be restrictive when trying to predict transport and diffusion in areas where meteorological parameters such as wind speed, wind direction and stability change spatially and over short time periods. Such situations are frequently observed in coastal regions which are influenced by land and lake breezes, vertically varying stability conditions (particularly during on-shore flow), and locally induced wind speed and direction changes caused by changes in surface roughness between land and water ares. In such cases, high resolution observations of the spatially (horizontal and vertical) varying wind field can be important in describing the transport and diffusion conditions at any given moment.

Tall towers are capable of measuring some conditions, however due to the limitations on tower measurements discussed above, remote sensing technology offers the opportunity of collecting data at elevations which may be more closely related to the wind and stability conditions that pollutant plumes from an elevated source undergo. For instance, in the case of lake breeze, near the surface the flow is generally on-shore (air flowing from the water body toward the land), while aloft, the flow is usually opposing this circulation (from the land toward the water). In this instance, prediction of the transport of a plume which is elevated to the height of the opposing circulation may be improperly handled if wind data from a meteorological tower with limited vertical extent indicates that on-shore flow is occurring.

Therefore, monitoring of meteorological parameters at elevations well above 60m provides valuable data for operations involving the calculation of transport and diffusion in regions of complex meteorological flows.

5.2 Study Objective

The objective of this task was to install and operate a 915 MHz radar profiler and RASS for a period of one-year in the vicinity of NMP for the purpose of evaluating the performance of the two systems and assessing their potential as replacements for tall, tower-based monitoring instruments.

5.2.1 Study Goal

The goal of this task is to successfully operate the radar profiler and RASS for a period of one year and evaluate the system performance on the following criteria:

- Quantity of data (ie. Annual data recovery rate greater than 90%),
- Quality of data (based on comparison with independently collected data sets),
- Level of effort required for routine servicing,
- Frequency and severity of system failures, and
- Estimate of the level of performance that can be expected if the systems were permanently deployed.

Following the evaluation, recommendations will be made regarding the ability of the radar profiler and RASS to serve as a replacement for tall meteorological towers and monitoring the lower troposphere in enough detail to define the complex meteorological conditions often encountered in the coastal zone.

5.2.2 Potential Applications

As indicated in the task objectives, the evaluation of the radar profiler and RASS will serve as a basis for determining the ability of these systems to serve as reliable lower atmospheric monitoring systems for the purpose of observing meteorological parameters important to the transport and diffusion of pollutants in regions experiencing complex meteorological flows. The evaluation addresses the ability of the profiler and RASS to serve as a potential replacement for tall tower-based monitoring systems by evaluating the comparability of the measurements to accepted standards, data recovery rates expected from meteorological systems at nuclear facilities, and operation and maintenance requirements.

This research provides information of interest to utilities wishing to investigate the potential of radar wind profilers and RASS to provide additional information related to the following concerns:

- Localized atmospheric flow regimes,
- Regional pollutant transport,
- Mixing height, and
- Vertical wind profile variations.

5.2.3 Limitations of Study

Every effort was made to minimize the limitations of this study. However, inevitable limits to the operation and evaluation of the equipment exist that are beyond the control of the investigators. First, during this field study, the LAP-3000 profiler underwent a generational change in sensing technology. Due to the time-table required by this particular study, the first generation technology was employed. The second generation system employs a phased, single-antenna system and new pulse coding, both of which maximize the data recovery rate.

Secondly, siting factors can improve or decrease profiler performance. Among these factors include instrument configuration, presence of clutter sources, sources of radio interference, and atmospheric conditions. As will be discussed, this particular study suffered from ground clutter problems which limited data recovery. The evaluation study looks closely at the effect of atmospheric conditions on profiler performance.

Finally, the evaluation of the profiler performance and comparability to other measuring systems is limited. These limitations stem from the difficulty of matching the profiler and comparison instrument measurements in space and time. Also, errors involved in the use of comparable instruments can, themselves, limit the analysis.

5.3 Field Monitoring Summary

For this task, Galson Corporation provided overall task management, site operation, and final report oversight. A LAP-3000 915 MHz Radar Profiler and RASS was leased from Radian Corporation for a period of thirteen months. Radian also provided data validation and reporting. The evaluation of the radar profiler and RASS was performed and reported by Sonoma Technology, Inc. (STI) under a subcontract with Radian. Both Radian and STI are jointly licensed under the terms of a Cooperative Research and Development Agreement (CRDA) with the National Oceanic and Atmospheric Administration (NOAA) to provide the LAP-3000 and RASS technology to non-government users.

During the project kickoff meeting in July, 1992, the project team discussed, among other topics, the siting and operating parameters of the Radar Profiler and RASS for the one-year field monitoring effort that would best address the task objectives. Upon selecting a number of candidate sites, representatives of Galson and Radian surveyed the locations, taking photographs in all directions and identifying visible sources of potential interference. The final site selected (PRF) was located near the micrometeorological tower installed for the evaluation of stability classification schemes, approximately 0.75 km from the lake shore (See Figure 1-1).

Galson Corporation prepared the PRF site for the instrumentation including supplying power and telephone and prepping the shelter for the profiler and RASS computer equipment. Radian engineers along with Galson technicians installed a LAP-3000 Radar Profiler and RASS on October 31, 1991. Galson Corporation then operated this profiler continuously until November 1, 1992. On a routine basis, the Galson site operator would perform data backup procedures on the control computers and perform other routine tasks. In the event of problems, the site operator would make emergency visits to the site.

Both Galson and Radian routinely contacted the profiler and RASS control computers through telephone telemetry and downloaded data and determined operational status. Galson and STI, through a separate contract with NMPC, developed software to allow near real-time access to the data once per hour. The downloaded data formed the raw data set used in the data validation and reporting. Data reports were developed monthly, and provided to ESEERCO through monthly progress reports.

Shortly after installation, it became apparent that radar profiler performance was degraded by reflection of the signal off trees and power lines in the vicinity of the profiler. This effect is referred to as ground clutter. The ground clutter problem was first noted in the November 1991 Data Summary Report (Galson, 1992). While care was exercised in selecting the location for the profiler and the location met the siting criteria as originally outlined by Radian, several clutter sources out of view from the site became important reflectors of the microwave energy emitted by the profiler. The most notable ground clutter source appears to have been the main power transmission lines extending south from NMP approximately 0.5 km east of the profiler. The ground clutter effects appeared to be greatest within the lowest range gates measured by the radar, and rarely extended above 1500 m (approximately equivalent to the distance between the radar and the ground clutter objects).

Once the ground clutter problem was noted, a series of actions were initiated in an attempt to alleviate or at least reduce the problem. First, the antennae were re-oriented, attempting to move the ground clutter targets out of the microwave signal beam. While it was possible to get the ground clutter out of the main beam of the profiler antennae by repositioning, the objects presented such a large reflection target that the side lobe transmission caused reflections which continued to dominate the signal. Next, Radian Corporation attempted to modify some of the operating parameters such as signal pulse length, range gate height and other, critical operating parameters. These modifications appeared to have minimal effect on the profiler performance. Subsequently, Radian, STI and NOAA personnel reviewed the ground clutter suppression algorithm employed in the profiler software, attempting to determine if improvements could be made. A revised program was implemented and tested during June, 1992, with only modest improvement.

Finally, it was discussed whether moving the profiler to an alternative site would be possible within the project budget. During a routine maintenance visit, the Radian engineer identified a potential site west of NMP which appeared to present fewer ground clutter targets. However, after discussion among the project team, including the ESEERCO project manager, it was determined that relocation was not practical within the current project scope. First, the relocation would have represented a major additional cost in prepping the alternate site and relocating the equipment. Second, at the time the relocation was discussed, nearly six months of data collection had been completed covering mainly the cold weather months. Since one of the task objectives was to evaluate operation during different weather conditions, it was felt that relocation would make a comparison between winter and summer performance at the same site impossible. Finally, there was significant concern over the potential for offsite noise impacts from the RASS acoustic signal generators. A privately owned summer camp is located just west of the NMP property line near where a better profiler operating location had been identified. The project team concluded that the 10-minute acoustic emission from the RASS each hour would have been audible at offsite receptors, and presented a potential noise nuisance to anyone located at the camp.

As a compromise solution to relocated the profiler mid-way through the project, a short-test of the profiler at an alternative site was organized to take place at the end of the monitoring program. The project team arranged to operate the latest production version of the profiler for approximately 4 days. It was hoped that a variety of weather conditions would be available in which to test the performance of the system and provide at least a qualitative estimate of profiler performance in the absence of significant ground clutter sources.

It should be noted that the ground clutter problem appears to have been confined to the Radar Profiler and should not have influenced the RASS. Since the RASS uses only the vertical antenna, it is believed that the side lobe reflections were less important.

Another problem observed with the site was transport of the cooling tower plume directly over the profiler. The cooling tower plume presented such a significant target that it dominated the signal from both the profiler and RASS to such an extent that data collection above the plume could not be performed. Little can be done to prevent this problem, other than relocating the profiler to a location farther away from the facility and in a direction where the frequency of winds is such that cooling tower plume overflight is minimized.

Details on the data collected and a summary of this activity are provided in the Monthly Progress reports submitted to ESEERCO at regular intervals throughout the field operations of this project.

5.4 Summary of Radar Profiler and RASS Evaluation

Following the close of monitoring, all system data and relevant operational information was provided by Radian and Galson to STI for use in the evaluation report. In addition, other data from the project was made available to STI including 9MP tower and sodar data, micrometeorological tower data (MMT), and tethersonde and airsonde profiles from TS1 and TS2. During the development of the evaluation, a number of problems were noted with the comparative data. First, significant reformatting was required before the various data bases could be compared. Secondly, calibration errors were noted in the tethersonde temperature soundings which were used to evaluate the performance of the RASS. Finally, an error was discovered in the manner in which the tethersonde and airsonde wind direction had been calculated. Data errors were corrected prior to analysis.

The complete evaluation report, "Evaluation of the Performance of a 915 MHz Radar Profiler and RASS during the Eastern Lake Ontario On-shore Flow Field Study," submitted to Galson by STI is provided in Appendix D-1. The evaluation report provides extensive information on the following topics:

- specific objectives of this task
- detailed radar profiler and RASS system descriptions
- data sources available for determining the profiler and RASS performance,
- service and maintenance requirements of the system
- data recovery performance as a function of site factors and atmospheric conditions

- intercomparison of the system with other data collection platforms
- conclusions and recommendations for profiler and RASS performance

The reader is referred to Appendix D-1 for the detailed evaluation conclusions and recommendations. However, in the interest of brevity, we have attempted to summarize the conclusions of the evaluation report below:

1) System availability was excellent. Total downtime amounted to just 3.7% of the year.
2) Data communications systems operated nearly flawlessly throughout the experiment.
3) Reliability with respect to data recovery was not demonstrated for this installation. This is almost exclusively due to interference with ground clutter.
4) Data recovery for wind data was best during the following conditions:
   - Summer daytime
   - Low atmospheric pressure at altitudes above 1500m
   - High atmospheric pressure at altitude below 1500m
   - Wind blowing from the north, east, and southeast
   - Precipitation
5) Data recovery rates for temperature were much lower than expected. The causes are not clear.
6) Data recovery for temperature data was best during the following conditions:
   - Summer and winter daytime
   - Cold and dry conditions
   - Wind blowing from the northwest through east
7) Comparative performance of the profiler and RASS against the tethersonde and airsonde systems was very good and comparable to results obtained in previous investigations. Average bias for wind speed was -0.15 to -0.5 m/s and -4.2° to -6.7° for wind direction. The Root Mean Square (RMS) difference for wind speed was 2.0 m/s and was 37° for wind direction. Average differences for virtual temperature measurement were -0.17°C, with an RMS difference of 0.63°C and a correlation 0.98.
8) With the exception of the need to remove snow and ice buildup in the antennae, maintenance and service requirements for the system were minimal.

The STI evaluation report states "...that these remote sensing instruments can be an excellent source of data to meet meteorological monitoring requirements for air pollution and emergency response applications in the shoreline environment of Lake Ontario." However, Galson concludes that the evidence is clear that the systems can not replace tall tower measurements but rather serve as enhancements. The lowest achievable range gate for the current radar profiler and RASS system, is around 100 m. This is still too high to resolve boundary layer structure near the ground where most of the thermal and mechanical fluxes occur. In addition, limitations on data recovery rates presents a problem, particularly for regulatory applications. While the evaluation report shows that data recovery rates over 90% are achievable in the lower range gates, the dependance of this performance on siting and atmospheric conditions is worrisome.

The STI evaluation report concedes our above conclusion by stating: "In conjunction with tower observations to fill the data gap between the profiler's lowest range gate, the profiler and RASS can provide aloft data suitable for use in regulatory and or research transport diffusion models."

The results of the profiler resiting tests are presented in a report from STI to Galson entitled "Results of the Re-siting of the 915 MHz wind profiler at the Nine Mile Point Nuclear Generating Facility" and is provided in Appendix D-2. In reviewing the profiler re-siting report, it should be emphasized that the profiler was not an exact clone of the system used during the one-year monitoring program, but rather the latest production version of a phased-array system. The phased-array profiler represent the latest in technology and are an improvement of the older three-axis system. Never-the-less, the following results were obtained from the re-siting study:

- Ground clutter at the new site was significantly less than the previous site.
- The overall quality of the wind data collected at the shoreline site appeared better than that collected at the previous site. This is likely due to the use of the phased-array system and the reduction in ground clutter.

5.5 Conclusions and Recommendations

A 915MHz Radar Profiler and RASS were operated for a period of one year in the vicinity of NMP. The purpose of the monitoring was to evaluate the performance of these new monitoring systems as possible replacements for exisiting tall meteorological towers and provide enhanced data at levels well above that typically observed by the tall towers.

Based upon the performance and operational evaluation of the systems, the project team presents the following conclusions and recommendations based upon our analysis of the data and evaluation report:

- Radar profilers and RASS are not a replacement for tall towers. They are, however, capable of supplementing the tower-based measurements with detailed observations between the boundary layer and the middle troposphere.

- Combined with the existing NMP 200 ft meteorological tower and sodar for profiling n the lowest portion of the boundary layer, the profiler and RASS can provide valuable information on plume level wind and temperature structure, particularly in lake breeze return flow, and onshore flow conditions.

- The profiler and RASS provide aloft data with considerably better time and vertical resolution than that available from traditional balloon-borne profiling systems, providing data of sufficient detail and accuracy for regional scale numerical modeling and initialization of site-specific numerical models.

- Operational reliability is high, even considering that the profiler system operated is still developmental and not the current commercial version available.

- Data recovery is dependent on operational status, weather and siting conditions.

- Resolution is good, but is still too coarse at low elevations for observing some very localized features such as a TIBL structure.

- Great care must be taken in siting the equipment to avoid sources of ground clutter. A thorough siting study which includes testing the profiler at candidate locations prior to permanent installation at the selected site is highly recommended.

- Future use should be limited to the latest production version of the equipment.

- Prior to installation, it should be verified that the approach for dealing with snow and ice buildup is appropriate for the site.

- Maintenance visits occurring regularly every 1 to 2 weeks should be sufficient for most operations.

- A shorter pulse length (60 m instead of 100 m) should be employed for the RASS if the application is to better resolve boundary layer temperature structure. The shorter pulse length allows use of smaller range gates, thus increasing the number of available data points in the vertical. Care should be take to assure that data recovery is not effected by use of a shorter pulse length.

- A detailed Quality Control and Quality Assurance plan should be developed for a permanent installation which includes routinely comparing the profiler and RASS data with an independent observation set is recommended.

5.6 References

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