THE UNIVERSITY OF ALBERTA

The Design, Instrumentation, and Performance of a Refrigerated Marine Icing Wind Tunnel.

By

Christopher Edward Foy

A thesis

submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science.

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The Design, Instrumentation, and Performance of a Refrigerated Marine Icing Wind Tunnel.

submitted by Christopher Edward Foy in partial fulfillment of the requirements for the degree of Master of Science.

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Abstract

Marine icing is a significant hazard to vessels and offshore structures operating in northern waters. A physical model capable of predicting the growth of spray ice on structures operating in a marine environment would help to reduce this hazard. To assist in the development of such a marine icing model a new refrigerated wind tunnel has been constructed as a joint project involving both the Department of Mechanical Engineering and the Division of Meteorology of the University of Alberta.

This facility will first be used to develop specific aspects of the model through investigation of the heat transfer and thermodynamics of the icing process. Once a suitable model is developed its predictions will be evaluated under controlled conditions in the wind tunnel. In addition, a computer controlled data acquisition system has been developed to monitor the tunnel conditions and to allow for the timely comparison of model predictions with experimental results.

Justification for such a facility and its relationship to the modeling efforts is detailed. A description of the design of the facility is included with particular attention to the innovative aspects of the tunnel. Efforts to instrument the wind tunnel are discussed from the perspective of the hardware and software required to monitor the meteorological conditions simulated in the facility. In addition the performance of the tunnel is evaluated. Finally a brief discussion of its potential to simulate conditions other than marine icing is included.

Acknowledgement

I would like to express my deep gratitude to my supervisors, Dr. E.M. Gates and Dr. E.P. Lozowski, for all of their guidance and insight throughout the course of the project. The construction of this facility would not have been possible without the full support and the valuable contributions of every one of the department's technicians and machinists. I hope they will accept my thanks. I would also like to acknowledge Mr. S. Rizopoulos for his enthusiasm and assistance each summer during the course of the project.

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1. Introduction

1.1. Marine Icing

Exploitation of resources in the northern and eastern coastal regions of Canada requires the use of a variety of structures including off-shore platforms, docking and storage facilities, and small surface vessels. The accumulation of ice due to freezing sea spray is a significant hazard for these vessels and other off-shore structures [1]*. Since these accumulations are often at the level of the deck or higher they not only increase the static and wind loading on the structure [2] but they also affect the stability of the vessel and the safety of the crew and operations. In addition icing on masts carrying meteorological instruments, or communication and navigation equipment can also pose serious problems. The severely iced tanker in figure 1.1-1 graphically illustrates these problems. Cold temperatures, high winds, and a source of water droplets are all that is required for an icing incident to occur. These conditions are often found in northern waters but the severity of ice accretion will depend greatly on the design and sea-keeping ability of the individual vessel.

The primary sources of water droplets in the marine environment are; spray generated by ship wave interaction, marine fog, and freezing rain. Other sources, generally considered to be of lesser importance are; wind generated spray, snow, and hoar frost. By far the most important of these is sea spray generated by ship wave impact because of the large droplets it creates and the large amounts of water it can produce [3].

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* Numbers in square brackets indicate references listed on page 59.

Apart from praying for warm weather the most common practice for ice removal is for the crew to forcefully break the accretion by hammering it free. This technique, illustrated in figure 1.1-2 can be quite effective, but it presupposes that there is good enough weather for the crew to actually be up on deck. If left unchecked icing can have catastrophic consequences for the vessel and its entire crew. A model to predict ice accretion in this environment would be of great benefit to designers, regulators, operators, and others in the marine community.

1.2. Modeling

For the purposes of this discussion a marine icing model will be considered to be a mathematical device which is able to predict ice accretion based on input from environmental parameters. Historically these models can be categorized into two basic types; statistical and physical models.

A typical statistical model uses data from known icing incidents to predict the severity of ice accretion for a given set of conditions. These icing rate algorithms are often presented in the form of nomograms such as the one illustrated in figure 1.2-1. Unfortunately a great deal of variability can be found in icing observations for similar meteorological conditions. This is primarily due to differences in vessel size, type and heading. Much of the data is obtained through radio reports, operating logs, and in some cases even interviews with vessel operators. Unfortunately, despite the best efforts of those researchers working in this area it is often difficult for untrained observers to make consistent observations while operating under adverse conditions.

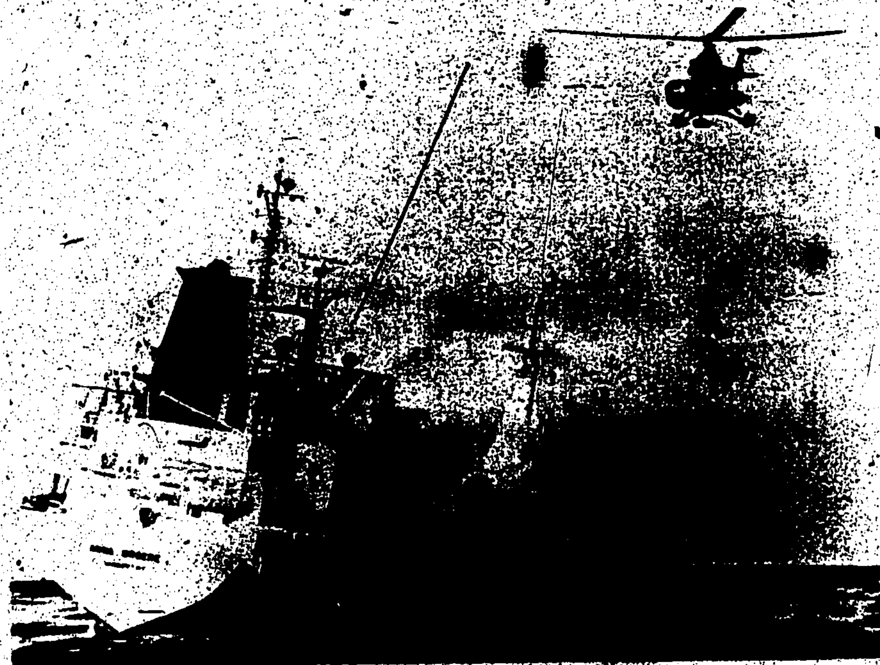

Figure 1.1-1 Ice Accumulation on a small dutch tanker "Anna Broere", aground near Cape Rozewie, (Poland, southern Baltic Sea), January 1, 1979.

Figure 1.1-2 A crewman attempts to remove the ice accretion using a hardwood mallet aboard the C.S.S. Dawson, Feb. 5-9, 1972.

A physical model is one in which the ice accretion process itself is modeled. Again environmental parameters obtained from meteorological and oceanographic forecasts or observations are used as input. Although marine icing is an extremely complicated process a physical model of it would in essence answer three simple questions (see figure 1.2-2):

- how much of the available water hits the structure?
- how much of the water that hits freezes?
- and once it begins to freeze, how does the ice grow?

A physical model of the marine icing process would have several applications, including:

- minimizing the icing hazard through improved design.
- assisting in the design of de-icing and anti-icing systems.
- permitting more accurate and structure specific forecasts of the icing hazard.

The development and evaluation of the model requires comparisons with actual ice accretions. For this reason many researchers seeking to develop a physical model have constructed test facilities capable of reproducing marine icing conditions.

1.3. Other Facilities

A number of wind tunnels have been constructed to simulate atmospheric icing conditions. In Canada, these wind tunnels are located at the University of Quebec at Chicoutimi, at the National Research Council, at the University of Toronto, and at the University of Alberta. However all of these facilities are designed for simulation of fresh water icing [5]. In order to simulate marine conditions a facility has to be capable of generating a cloud of brine droplets suspended in a super-cooled air stream. There are several facilities currently in operation for this purpose. Although they are

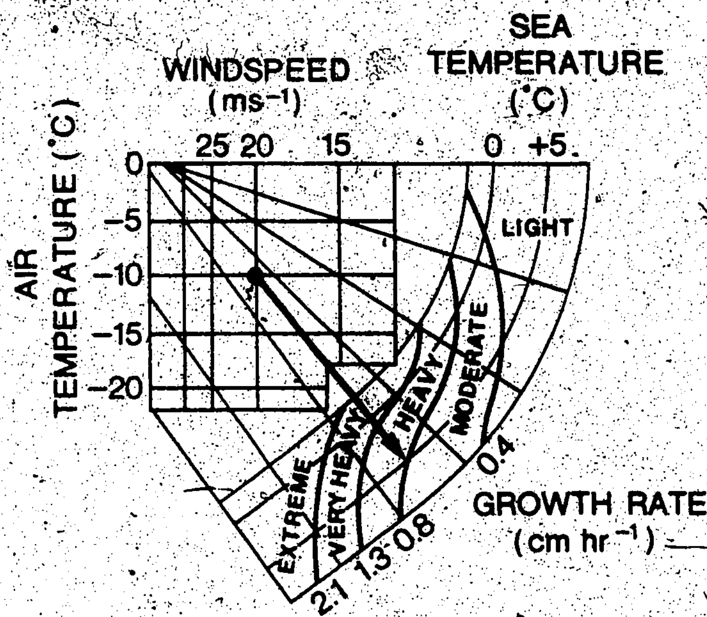

Figure 1.2-1 A nomogram illustrating the ice accretion which can be expected under typical icing conditions [4].

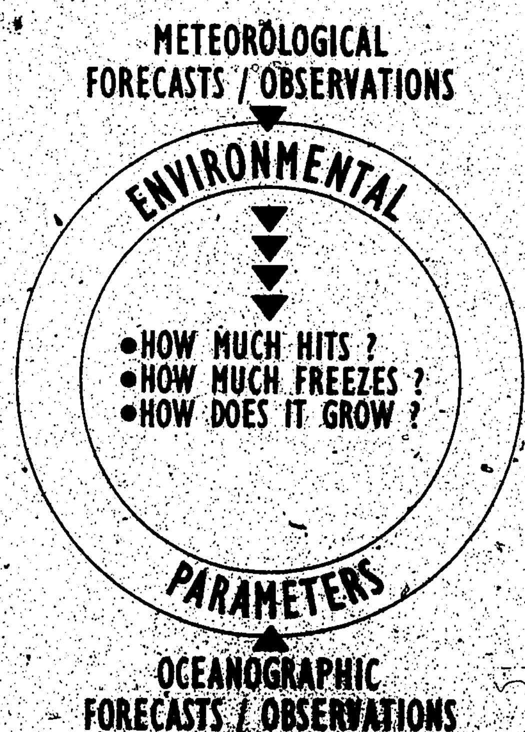

Figure 1.2-2 Environmental parameters such as meteorological and oceanographic forecasts and observations would be used as input for a physical model [3].

all able to produce marine conditions, their ability to control the environmental parameters which lead to marine icing varies considerably.

At the National Research Council in Ottawa a simple open air test facility has been used to evaluate ship de-icing techniques. This outdoor test site illustrated in figure 1.3-1 uses the cold ambient air temperatures in winter combined with a 1.37 m diameter fan to augment the prevailing wind [6]. Spray is introduced into this cold air stream by means of a series of nozzles mounted to the fan housing. While this is a simple and inexpensive design it does not allow much control of the environmental conditions. Because of its reliance on natural phenomena to generate both wind and cold temperatures the degree of control available over the environmental parameters is limited and consequently the nature of the experiments possible with this facility are necessarily qualitative.

A more sophisticated facility is in operation at the Norwegian Hydrotechnical Laboratory in Trondheim, Norway. This facility is basically a horizontal open loop wind tunnel which relies on low outdoor ambient air temperatures for cooling [7] and is illustrated in figure 1.3-2. A similar but much smaller tunnel is operated by the Institute of Marine Research in Helsinki Finland. With these wind tunnels it is therefore possible to establish good control of the wind speed during testing but the experimenter is still unable to control the air temperature. With the horizontal layout of these tunnels another potential problem is the possibility that the large droplets characteristic of marine icing will have a tendency to settle out of the air stream before they reach the test section. A closed loop,

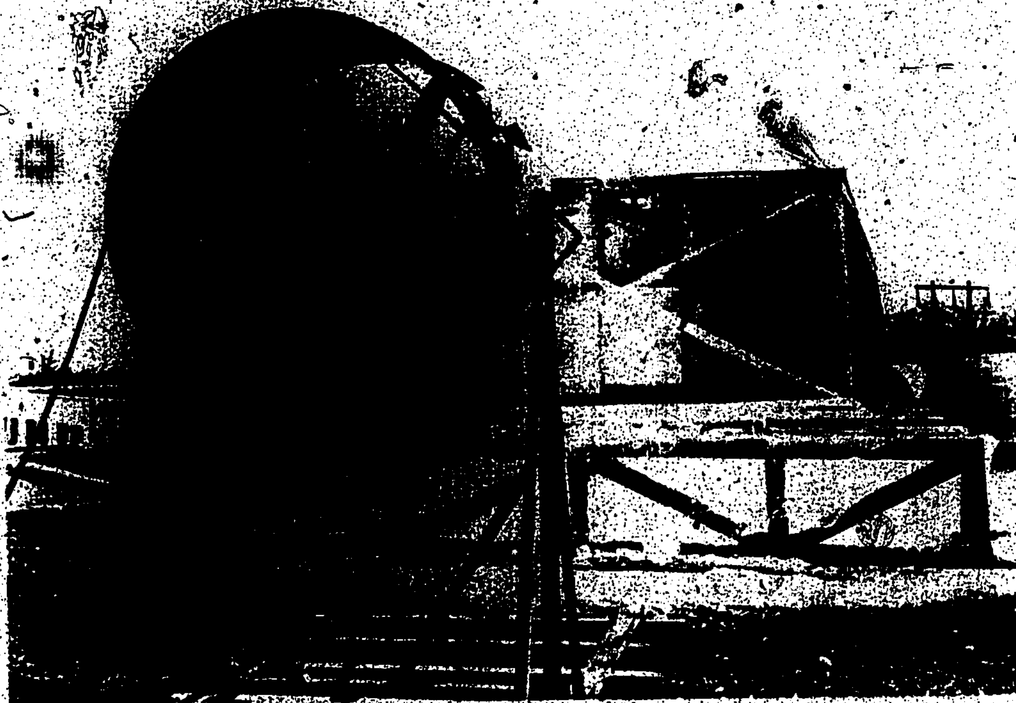

Figure 1.3-1 An open air test facility on the roof of the National Research Council in Ottawa [6].

Figure 1.3-2 [illegible]
[illegible]

vertical test section, refrigerated wind tunnel would enable better control over the air temperature and allow for a more uniform water droplet distribution.

1.4. MIWT Facility

In order to provide the controlled environment necessary for an investigation of the heat transfer and thermodynamics of marine icing, a refrigerated marine icing wind tunnel (MIWT) has been constructed [8]. The basic design of the facility is a vertical closed loop. In addition, a number of sophisticated instruments have been evaluated for use in this facility to measure the important environmental parameters. Also, an array of performance tests have been run which include careful characterization of the air temperature and wind speed in the tunnel.

2. Design

2.1. Design Parameters

The development of a physical model of the marine icing process essentially amounts to finding the answers to the three simple questions discussed in the Introduction. The environmental parameters which govern these processes interact in many different ways ensuring that the answers to the relatively simple questions posed above will be complex. The diagram in figure 2.1-1 illustrates the interactions and feedbacks among the input parameters and between these parameters and the physical processes that make marine icing a complicated phenomenon [3]. The major environmental parameters which govern marine icing are:

- Air Speed,
- Air Temperature,
- Water Temperature,
- Water Salinity,
- Drop Sizes,
- Target Sizes,
- Liquid Water Content,
- Wave Height, Frequency and Speed.

In order to design a facility capable of simulating marine icing it is important to consider all of these parameters paying careful attention to the range required. Considering each of the above parameters separately the design criteria for the wind tunnel are obtained.

Air speed, air temperature and water temperature are the most important parameters in the wind tunnel simulation of marine conditions. They in fact govern whether or not icing will occur at all. Water salinity is also an important parameter and the facility must be capable of reproducing the brine concentrations typically found in the marine environment.

The size of the water droplets used in simulating sea spray is

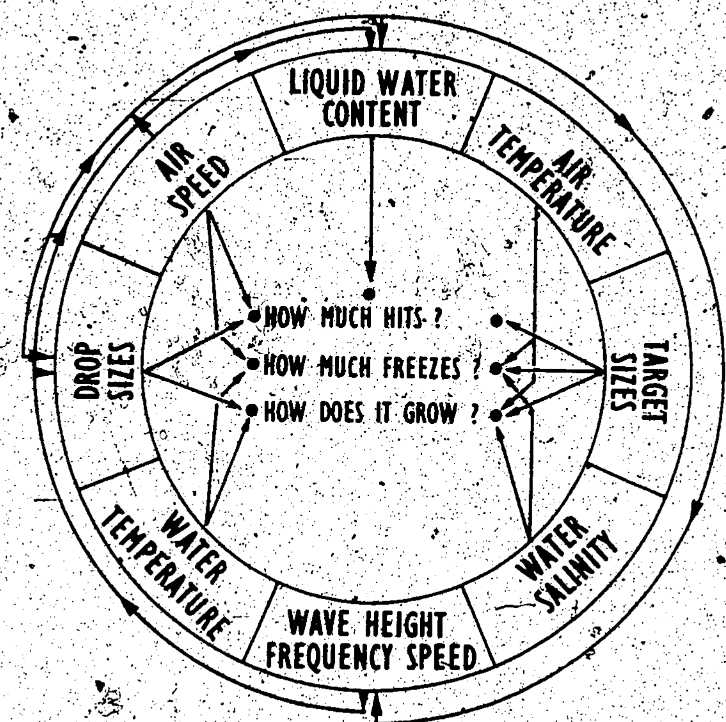

Figure 2.1-1 The interactions and feedbacks (indicated by arrows) among the environmental parameters and between the environmental parameters and the physical phenomena make marine icing a complex non-linear process [3].

important for several reasons. Large droplets are more likely to collide with a structure than smaller ones but they will also require more time to come to thermal equilibrium with the air. Large (millimeter) droplets are most characteristic of marine conditions while small (micron) droplets are most often associated with atmospheric conditions. Target size is also important in determining which droplets will tend to collide with the structure. This becomes particularly important as ice accretion progresses and the target size begins to change.

Liquid water content is defined as the mass of liquid water droplets per unit volume of air. It is usually measured as the number of grams of liquid water per cubic meter of air. A difficult parameter to measure, the liquid water content is also quite important in the simulation of marine icing. Wave height has a direct bearing on the droplet size and liquid water content and in that sense it is indirectly simulated under wind tunnel conditions. Wave frequency and speed determine the duration of each spray cloud and the length of time between spraying incidents. By pulsing the water supply delivered by the spray system in the wind tunnel this parameter is simulated. Table 2.1-1 describes in detail the range of each parameter required for proper simulation of marine conditions.

2.2. General Description

The basic design of the wind tunnel is a vertical closed loop with two available test section positions. Because of this configuration the tunnel may also be used for experiments in hail growth simulation. A more detailed discussion of the hail mode and the potential of the facility to simulate other conditions is given in chapter 5.

Parameters	Range	Units
Air Speed	0 to 30	m/s
Air Temperature	-25 to 0	° C
Brine Temperature	-2 to 10	° C
Water Salinity	0 to 35	ppt
Drop Sizes	10 to 1000	µm
Target Sizes	will depend on test section size	
Liquid Water Content	0 to 200	g/m^3
Wave Parameters	obtained by pulsing spray supply	

Table 2.1-1 Summary of Ranges of Design Parameters.

The line drawing in figure 2.2-1 illustrates the layout of the facility in its marine icing configuration. Air flow is clockwise around the circuit and down through the test section. A brine solution is introduced into the airstream by hydraulic nozzles located in the contraction above the test section. The resulting brine spray will accumulate on any body placed in the test section. The vertical layout of the facility will make the generation of a uniform spray distribution in the test section possible. Past experience has shown that the differential settling of large water droplets tends to give rise to inhomogeneities in droplet size and liquid water content over the cross section of the test section when a horizontal layout is used. Of course it can be argued that there are inhomogeneities in these parameters during natural icing incidents, but it would be difficult to simulate natural conditions exactly and in any case most of the current cylinder icing models assume a homogeneous spray distribution. A detailed discussion of the performance of the wind tunnel is given in chapter 4, but the main characteristics of the facility are listed in table 2.2-1. It should be noted that the overall dimensions of the facility were determined by the physical constraints of the room. In order to fully describe the design features of the marine icing wind

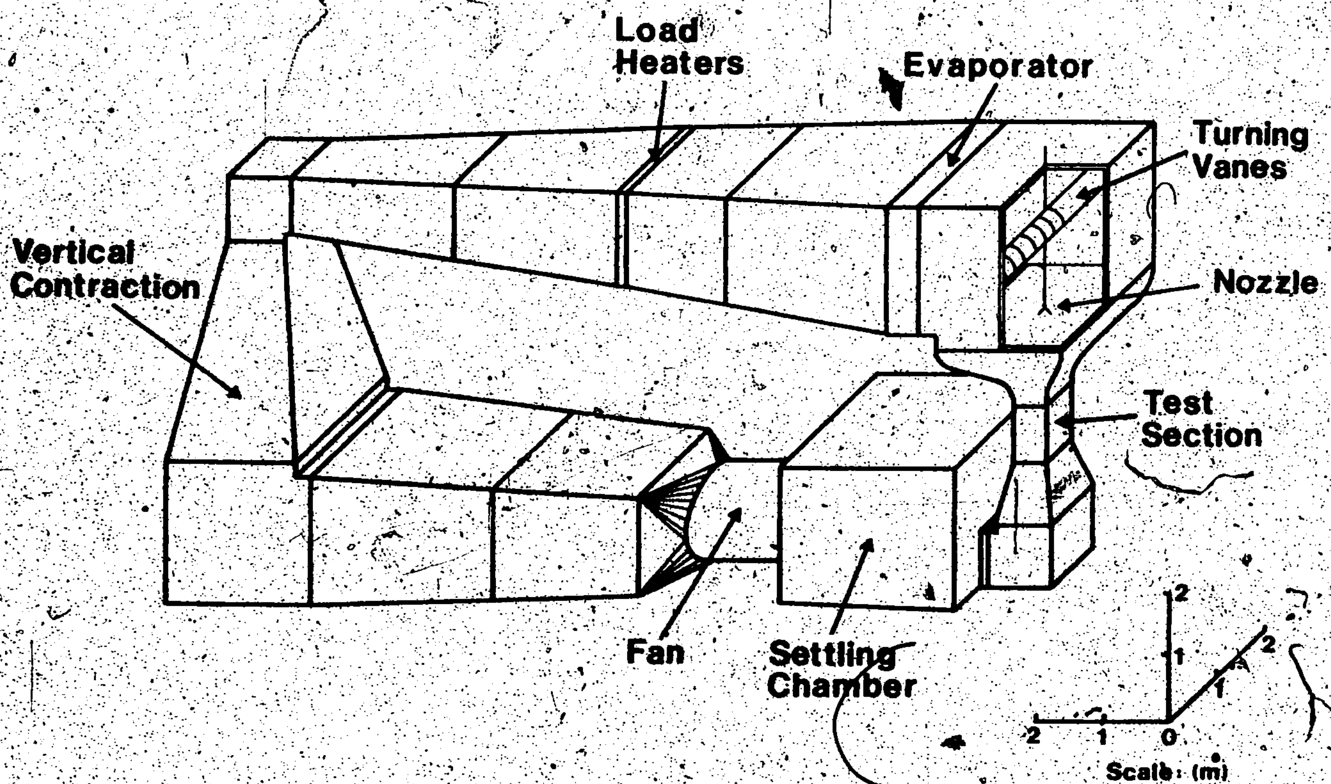

Figure 2.2-1 Line drawing showing an oblique view of the Marine Icing Wind Tunnel in its' marine icing configuration.

tunnel it will be necessary to break it down into its main components.

Overall Length	12.7 m
Overall Height	6.0 m
Test Section Length	0.8 m
Test Section Width	0.5 m
Maximum Air Velocity	32.0 m/s
Temperature Range	+15° to -40° C

Table 2.2-1 Characteristics of the MIWT.

2.3. Components

The major components of the marine icing wind tunnel are the:

- ductwork,
- refrigeration system,
- spray generation system,
- settling chamber,
- and control system.

The approximate relationship of each of these components to one another is illustrated by the schematic in figure 2.3-1.

2.3.1. Ductwork

2.3.1.1. Duct Elements

One of the most innovative aspects of the tunnel construction can be seen in the design of the ductwork itself. The majority of the tunnel ductwork is square in cross section varying in size from 2 m x 2 m at the low speed regions to 0.5 m x 0.5 m at the test section. The square cross section made it relatively easy to pre-fabricate in sections and then hoist the sections into place. This was facilitated by constructing the walls of the square ductwork of 75 mm thick extruded polystyrene (Styrofoam SM) insulation with a 1 mm layer of fiberglass sheeting laminated to the inner surface with contact cement. The polystyrene not only provides thermal insulation but is also a major element of the tunnel structure. The fiberglass

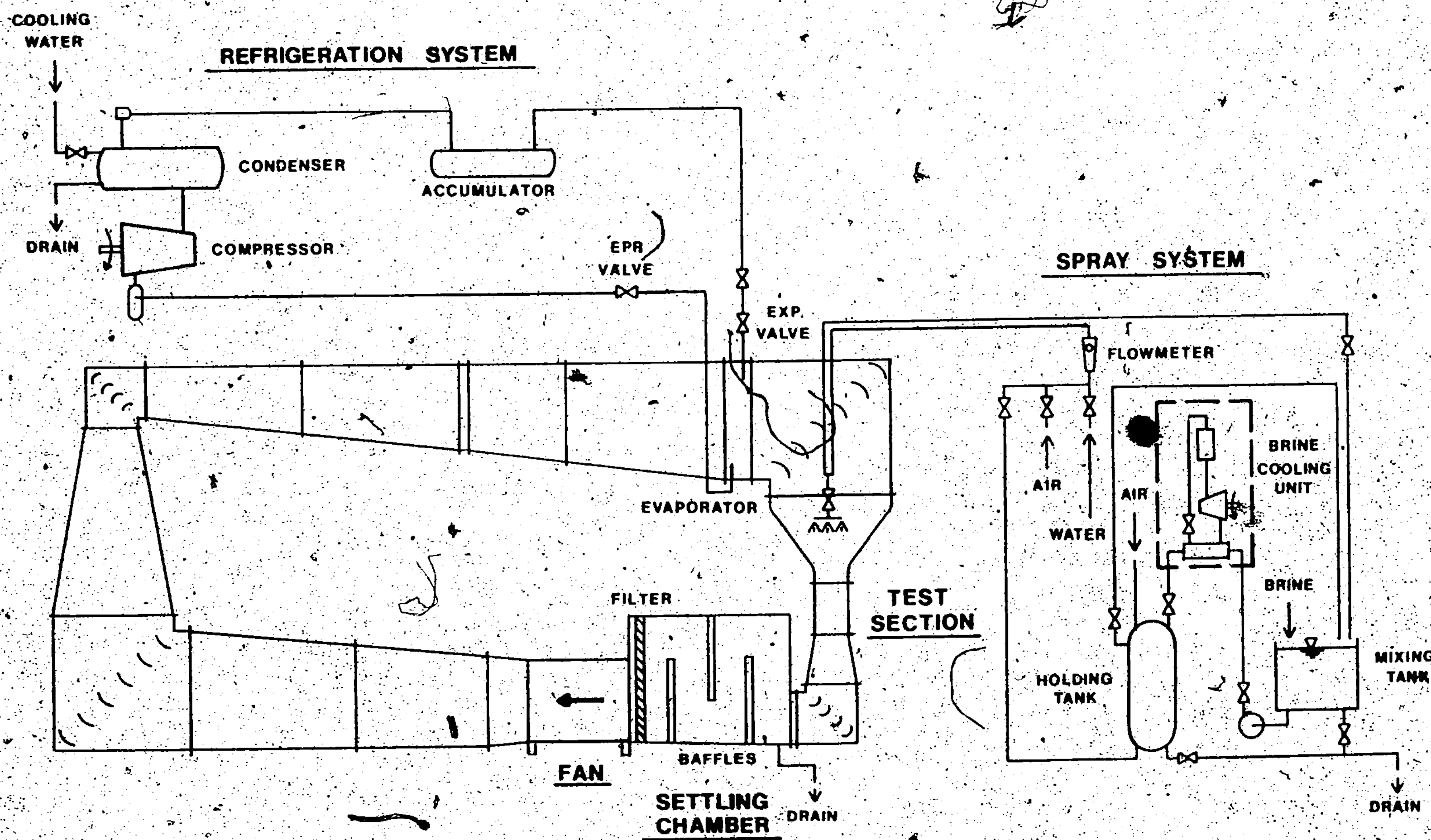

Figure 2.3-1 Schematic drawing of the Marine Icing Wind Tunnel illustrating all major components.

protects the insulation and adds additional rigidity to the structure. These walls were then laminated together using a two-part epoxy to glue the joints and to attach the plywood flanges to each end of the duct elements. The elements were then bolted together using a layer of neoprene gasketing material between each set of flanges to seal the joints and to allow for expansion and contraction of the individual elements. The resulting tunnel ductwork is lightweight, rigid, well insulated, corrosion resistant, and inexpensive when compared with more conventional construction techniques.

The only elements of the ductwork not constructed using this method were those requiring complex surfaces. One was the contraction immediately upstream of the test section which had to be designed to allow for the smooth transition from a 2 m x 2 m cross-section to the 0.5 m x 0.5 m test section. The design of this element was based on research into wind tunnel contraction shapes and their effect on droplet trajectories performed by Mr. W. Lam [9]. The contraction was constructed by laying fiberglass up on a wood framework. The other element of the ductwork requiring special attention was the connecting diffuser between the circular fan outlet and the square ductwork. This was fabricated by the technical services sheet metal shop at the university out of sheet steel and coated with a protective layer of corrosion resistant paint. The insulation characteristics of both of these components was improved by coating them externally with a layer of blown on insulation.

2.3.1.2. Test Section

One of the most important elements of the tunnel ductwork is of course the working section. The test section of the marine icing wind tunnel is 0.8 m long and 0.5 m x 0.5 m in cross-section with 19 mm thick walls of clear polycarbonate (plexiglass). Each of the four walls has two windows (one large and one small), to permit access to the airstream. The aluminum flanges at each end of the test section are rigidly attached to one another by means of four aluminum support columns, one at each corner of the duct. These columns provide support for the large contraction immediately upstream of the test section without subjecting the polycarbonate walls to an undue amount of stress. In addition there are slots in the flanges immediately upstream and downstream of the test section which can be used to hold protective screens. These safety screens are intended to be used to reduce the risk of damage caused by tools or instruments dropped into the ductwork. During normal tunnel operation blank frames are used to fill the screen slots. The test section itself is illustrated by the schematic in figure 2.3-2 and the picture in figure 2.3-3.

2.3.1.3. Fan

A centrifugal axial flow fan with an impeller diameter of 0.905 m is used to circulate air through the ductwork. The fan is belt driven by an externally mounted variable speed 37 KW direct current motor. Variation in wind speed is attained using this system by varying the speed of the drive motor. This particular fan-motor combination was chosen by first estimating the total pressure loss expected in the ductwork coupled with the maximum desired wind speed (or flow rate) in the test section.

2.3.1.4. Heaters

Four sets of heaters have been incorporated into the tunnel ductwork. One set is used to provide additional load on the

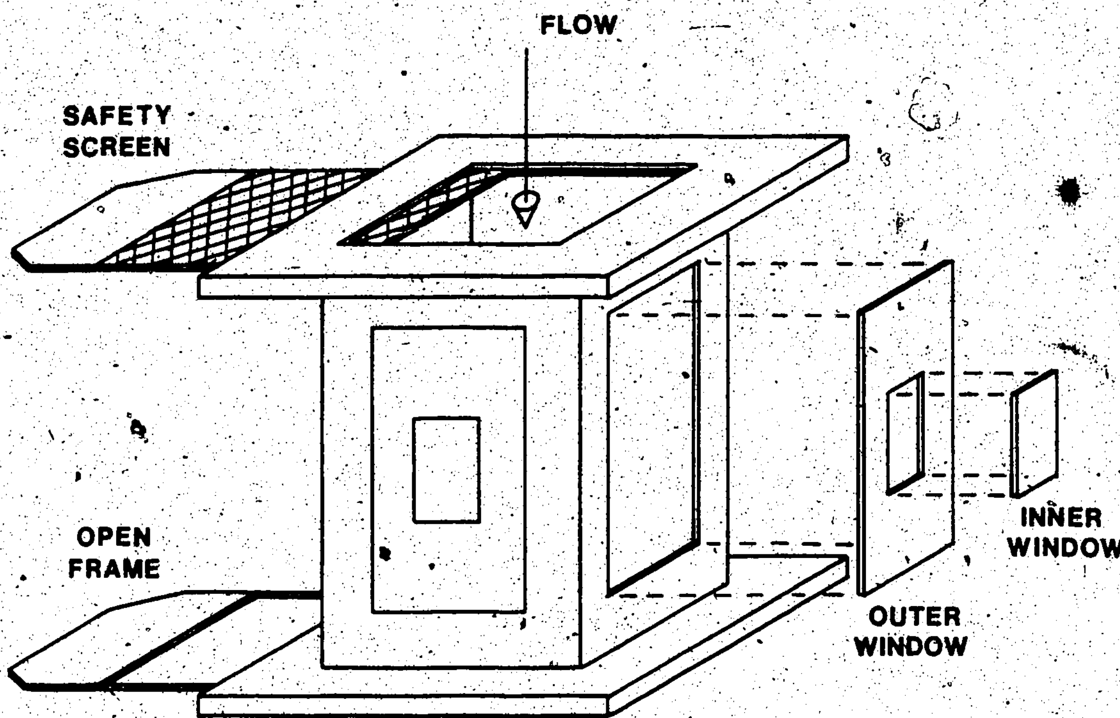

Figure 2.3-2 Schematic of the test section illustrating the position of the windows and screens.

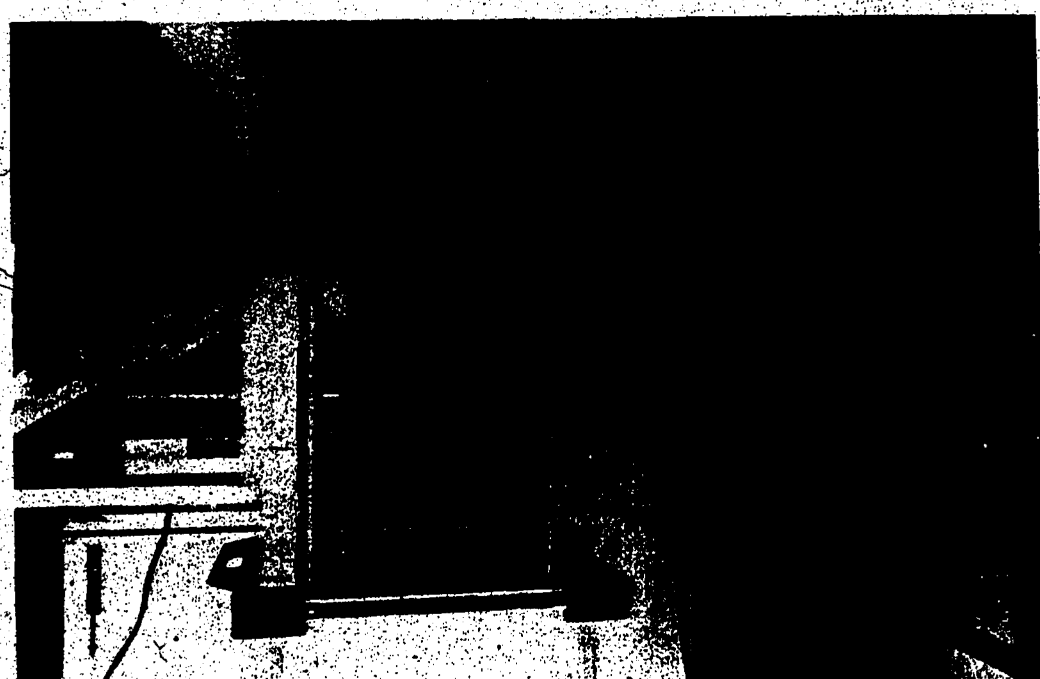

Figure 2.3-3 Photograph of the test section and control panels of the Marine Icing Wind Tunnel.

refrigeration system. This extra load (4 kW) will allow better control of the air temperature in the tunnel at conditions of low load. Heaters have also been installed in each of the two small corners to minimize icing on the turning vanes in those regions immediately downstream of the two possible test section locations (2 kW each). Another heater is used to keep the water being supplied to the spray nozzles from freezing during testing.

2.3.2. Refrigeration

The refrigeration system used in this facility was designed by an external consultant based on the expected heating load and the minimum attainable temperature required. The total heating load on the system was assumed to originate from the fan (30 kW), the amount of water injected into the tunnel (22 kW), the anti-icing heaters (2 kW), and the losses through the insulated and uninsulated sections of the ductwork (5 kW).

The refrigeration system used in the tunnel is comprised of a 12 cylinder compressor, driven by a 74 kW, 1800 rpm, alternating current motor with an evaporator and water cooled condenser. The system is charged with refrigerant 502 and is capable of maintaining temperatures as low as -40 degrees Celsius when operating at full capacity. Air temperature control to within ±0.5 degrees Celsius is obtained using an evaporator pressure regulating (E.P.R.) valve. Air pressure equivalent to the desired refrigerant pressure is applied to the valve to enable it to regulate the refrigerant pressure at the outlet of the evaporator. With this system the usable temperature range of the tunnel extends from +15 to -40 degrees Celsius.

2.3.3. Sprays

Brine spray is introduced into the airstream using a system of nozzles positioned upstream of the test section in the tunnel contraction. The support mechanism for the nozzles is designed to enable their orientation, configuration and distance from the working section to be easily altered and customized depending on the simulation requirements. In order to change the characteristics of the spray, different nozzles are used at a variety of flow rates. In order to accurately simulate the periodic nature of marine conditions, the spray can be pulsed using a system of solenoid valves regulated by electronic timers. The solenoid which regulates brine flow to the nozzles is located as close as possible to them in order to reduce the time lag between turning on and off the sprays. In the mixing tank salt and water are combined to form a brine solution. This solution is then pumped through a small refrigeration unit on its way to the holding tank. An overflow on the holding tank permits the brine to be circulated until the desired water temperature is achieved at which point the holding tank (now full) can be isolated from the rest of the system and pressurized. Air pressure is then used to force the brine solution out of the holding tank and down the line to the nozzles. In order to keep the system from freezing at those times when the spray is shut off but the air temperature in the tunnel is below freezing two techniques are used. The brine solution can be constantly circulated through the lines from the holding tank to the nozzle solenoid and back to the mixing tank. In order to keep the nozzles themselves from freezing thermostatically controlled heaters are used.

2.3.4. Settling Chamber

Due to the corrosive nature of brine spray efforts have been made to choose materials unaffected by brine and to limit the extent of the tunnel exposed to the spray. To accomplish this latter goal a settling chamber has been incorporated into the tunnel circuit upstream of the fan. This chamber is designed to remove the brine spray from the airstream before it enters the fan. Baffles are used to redirect the airstream and trap large droplets through settling and inertial impaction. Smaller drops that are able to remain suspended in the air are removed with a filter. The settling chamber is quite efficient at collecting spray, but the added pressure drop caused by the baffles and filters reduces the maximum attainable wind speed from 50 m/s (without baffles) to 32 m/s. As a further measure to limit the effects of corrosion the evaporator is located just upstream of the spray nozzles.

2.3.5. Control System

All of the controls for the marine icing wind tunnel are centralized in one area on two panels located close to the working section as can be seen in figure 2.3-3. As mentioned previously the wind speed is controlled by increasing and decreasing the fan motor speed as desired. The air temperature in the tunnel is regulated by maintaining the pressure at the outlet of the evaporators at a constant pressure. All of these controls as well as the heater switches and some of the permanent tunnel instrumentation are mounted on the central control panel. While the flow control and pressure regulating valves and indicators for the spray system are located on a secondary panel. As a safety precaution the three main heaters in the tunnel ductwork are normally locked out and cannot be energized unless both the fan and the refrigeration system are in use.

3. Instrumentation

Instruments are used to measure all of the major environmental parameters which govern marine icing, including:

- Droplet Size,
- Liquid Water Content,
- Salinity,
- Velocity and
- Temperature.

Each of these variables and the instruments being used to monitor them is discussed. A review of the data acquisition system is also included.

3.1. Droplet Size

Traditional methods of measuring droplet size, such as the oil slide technique, the dyed filter paper method or the rotating cylinder method are inaccurate, time-consuming and cumbersome [10]. This is especially true when these techniques are applied to large water droplets, such as those generated under marine conditions. In addition, most ice accretion models treat the droplet size distribution statistically as a single variable known as the mass median diameter.

An optical array precipitation probe (OAP) from Particle Measuring Systems has been modified for use in the wind tunnel. Using this device a measure of the droplet size distribution may be obtained and relayed to the computer as often as once every second over a range of particle sizes from 10 to 1250 μm. It provides the particle size distribution as the number of droplets in each of sixty-two 20 μm wide bins. It was designed to be used as an airborne measurement device and is most commonly mounted to the wing of an aircraft. Consequently, in order to minimize the amount of flow disruption in the test section this OAP has been modified by the manufacturer to view "sideways" by rotating its optics 90 degrees. Because the documentation supplied with this instrument does not describe these modifications in detail a brief description of the modified imaging technique will be given.

A 5 milliwatt helium-neon laser is used as the light source. As illustrated in figure 3.1-1 The beam is first collimated into an oval of light by a pair of cylindrical lenses (-7.5 and +16 mm) in the front of the laser mount tube. A third cylindrical lens (+300 mm) then focuses the short axis of the oval in such a manner that by the time it reaches the sampling region the light beam becomes a well defined ribbon of light. An objective lens (60 mm) and secondary zoom lens (29 mm) are used to magnify this ribbon of light in order for it to fill the optical array. A dove prism between these two lenses allows the instrument to view "sideways" by re-aligning the oval of light with the photodiode array. Most of the lenses are located in the two optical tubes which can be seen protruding from the main body of the probe in figure 3.1-2. The faint white line joining these tubes is caused by the reflection of water droplets passing through the ribbon of laser light in the sampling region.

The probe is oriented horizontally and inserted into the test section as illustrated in figure 2.3-3. Unfortunately even with this configuration the OAP still disrupts the flow field. There are of course particle measuring instruments which do not intrude on the flow at all. Unfortunately the high cost of these devices makes them prohibitive at present. A practical alternative might be to extend the reach of the two optical tubes on the OAP slightly. This configuration would enable the OAP to monitor the spray in the center of the test

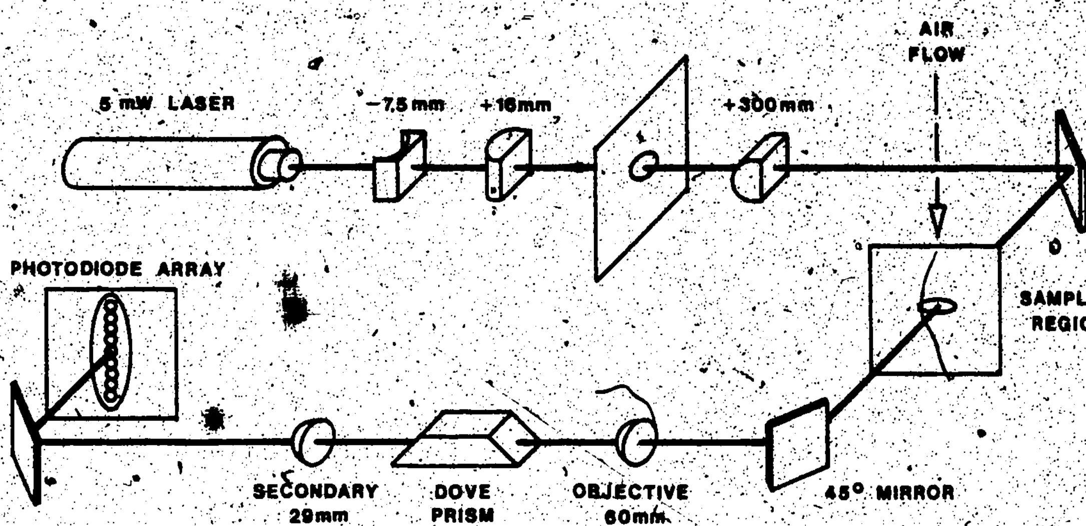

Figure 3.1-1 Optical configuration of the OAP.

Figure 3.1-2 [illegible]

section without intruding on the flow with its main body. The manufacturer will perform this type of modification but the added tube length would result in the instrument having a limited available range.

3.2. Liquid Water Content

A C.S.I.R.O. King liquid water content probe, also manufactured by Particle Measuring Systems, is used to monitor the liquid water content. Figure 3.2-1 shows this device in use in the test section of the Department of Mechanical Engineering's FROST wind tunnel. The probe uses the principles of hot wire anemometry to track liquid water contents as large as 6 g/m^3. The technique involves the use of copper wire sensor element heated by a bridge circuit to a constant temperature of 180 degrees Celsius. By monitoring the amount of power consumed by this wire and subtracting that required to maintain the temperature in dry air flow the liquid water content can be obtained. Unfortunately if the probe is subjected to more than 6 g/m^3 the circuitry will supply enough power to the sensor element to cause irreparable damage.

This is a distinct limitation when one considers that most marine icing incidents require the simulation of much larger water flux rates. For this reason some effort has been made to obtain liquid water content readings using the droplet size information gathered by the OAP. The details of this technique are described in the software documentation section of this chapter (3.6.2).

In order to obtain liquid water content from either the King probe or the OAP measurements it is assumed that the water droplets are moving with the air. This is certainly true for small droplets. However, larger drops may tend to cross streamlines and violate this

Figure 3.2-1 Photograph of the C.S.I.R.O. King liquid water content probe in the test section of the FROST tunnel.

assumption. It has been suggested that the liquid water flux rate with units of grams per square meter per second be used. This probably a more useful and less uncertain quantity than the liquid water content. It circumvents the assumption of all the water droplets moving with the air and is related to the liquid water content by the wind speed.

3.3. Salinity

A Yellow Springs Instruments Model 33 conductivity probe is available to monitor brine concentrations. Using this device salinity readings are based on the measured conductivity and manually compensated for temperature by directly dialing in the brine temperature. Each batch of brine mixed can be checked using this probe. It has an available range of 0 to 40 ppt with an accuracy of ±1 ppt and can be used over a temperature range of -2 to +45 C. The probe gives an analog readout of salinity.

3.4. Velocity

Air velocity can be determined by measuring the differential pressure across the contraction or from a pitot-static tube. Using a variable reluctance pressure transducer and amplifier this pressure difference is monitored as an analog voltage signal and fed directly to the data acquisition unit. In addition the differential pressure across the contraction is relayed to a calibrated analog voltmeter on the control panel. This meter should only be used as a rough guide for setting wind speed since its calibration is temperature dependent.

3.5. Temperature

Copper constantan (T-type) thermocouples are used to monitor the tunnel temperatures. At the time of publication there are four sensors in place; one dedicated to tunnel air temperature and three to the sprayed water temperature. The voltages generated by these sensors are relayed directly to the data acquisition unit using thermocouple extension wire. This insures that the data acquisition unit's reference junction can be used effectively. If standard copper-copper wire were used a significant error equal to the difference in temperature between the external junction and the reference junction (in the data acquisition unit) would result. A digital readout device on the control panel has also been supplied to enable the operator to directly read the temperature from each thermocouple.

3.6. Data Acquisition

All of the data measured by the above instruments with the exception of the salinity information can be relayed directly to a computer-aided data acquisition system for storage, readout or further manipulation.

3.6.1. Hardware

This system consists of a computer and data acquisition unit. As shown in figure 3.6-1 the computer is a Hewlett Packard 9000 series model 520. Using an HP-IB parallel communication bus it communicates with the Hewlett Packard 3497A data acquisition unit. Figure 3.6-2 shows both of these devices as well as an external printer. The data acquisition unit is basically a digital voltmeter and is used to monitor 19 channels representing liquid water content, pressure (air velocity) and temperature data. It should be noted that 9 of these channels (numbered 10 through 18) are dedicated to T-type thermocouple measurements only, because thermocouple extension wire has been used for each of these channels. A serial interface allows the computer to communicate directly with the P.M.S. Smart Probe controller for the

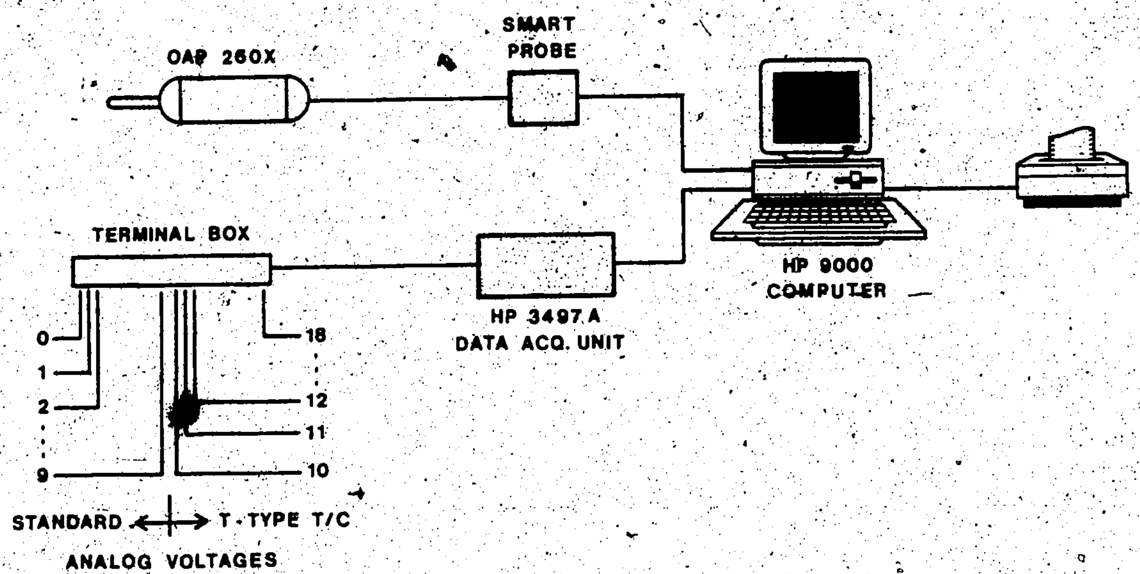

Figure 3.6-1 Schematic of computer-aided data acquisition system.

Figure 3.6-2 Photograph of the computer, data acquisition system and printer.

OAP. Using this interface ASCII commands can be transferred to the probe to change its configuration and ASCII data can then be relayed back to the computer.

3.6.2. Software

To date three main software applications have been developed for use with this system. They are:

- MIWT_LOG_2.01 - velocity and temperatures.
- KING_LWC_2.01 liquid water content data.
- OAP_DRIVER_2.01 spray characteristics.

Velocity, temperature and any other data, based on measurements made by the digital voltmeter can be acquired using MIWT_LOG_2.01. It is a general purpose data logging program and was designed to be used by the operator to monitor conditions during a test while running the wind tunnel. Voltages are read from the data acquisition unit and operated on to produce velocity, pressure or temperature measurements which are then displayed on the screen. At the end of a given test the results from selected channels are plotted as functions of time. The ability to modify some of the major parameters such as the data acquisition rate (maximum of one sample every two seconds) and the total test time (maximum of 1400 data points) is included.

The program is designed to record the voltages of all 19 channels each time a sample is taken. However, only those channels which are specified in the Initvar subroutine will be displayed, operated on or plotted. By modifying Initvar the user can modify the default settings to control those channels whose results are; displayed, treated as thermocouple readings, or plotted by the printer. Subroutines to convert voltage readings to temperature and velocity (based on differential pressure calibration) are provided. Other routines can easily be developed if the user intends to measure some other quantity. The structure of this program makes use of a modular approach based on separate subroutines for each major function.

Liquid water content measurements using the C.S.I.R.O. King device can be obtained using the KING_LWC_2.01 routine. This program is also modular in nature but not based on subroutines. Instead the main program has been divided into separate blocks for each major task. The voltage corresponding to the amount of power consumed by the hot wire element ($-V_a$) is fed into channel 0 of the data acquisition unit. Two periods of data acquisition corresponding to measurement of dry power and total power are required for a measurement of liquid water content. The dry power reading is normally taken first and constitutes a measurement of the amount of power consumed by the sensor element due to the forced convection of dry air flowing past the probe. The amount of power consumed by the sensor undergoing both forced convection and the sensible and evaporative cooling of the spray is referred to as the total power measurement. The liquid water content is determined by considering only the power needed to heat and vaporize the spray, known as the wet power. It is taken to be the difference between total and dry power measurements. Finally graphs of the liquid water content, either as a function of time, or in terms of a frequency histogram can be plotted.

A separate program is also provided for the control and acquisition of data from the OAP. OAP_DRIVER_2.01 can be used for all serial communication between the computer and the smart probe controller for the OAP. A data verification sequence first initializes the communication between the two devices. Data is then acquired at a maximum rate of one sample per second in the following manner. Each set of data is first modified as it is acquired to reflect the number of droplets which would have passed through the light beam because the OAP is incapable of registering each particle that passes through the sampling region. In fact the actual sampling area (aperture) of the probe is a function of particle size. The sampling area for each particle size bin is the product of the depth of field and the effective array width for that bin. Depth of field represents the distance over which the probe can see, correctly size, and accept a particle of a given diameter. For all particles less than 156 µm the depth of field is limited by both the optics and electronics of the instrument, but is a constant 61 mm for larger particles as this is the physical distance between the two optical tubes. The photodiode array used by the OAP has 64 discrete elements. The two end elements (#1 and #64) are used to reject those particles larger than the available range. If either of these two elements is shadowed, no reading is taken. The effective array width is a measure of the available change in position, for a given size of particle, just short of being rejected by element #1 to the limit at the opposite end of the array just short of rejection by element #64.

The histogram in figure 3.6-3 illustrates how the aperture varies with particle size for the sixty-two bins. The imaging diagram in figure 3.6-4 illustrates the flow of air and particles through the sampling area. If it is assumed that the droplets are equally distributed through the light beam then the number of particles seen by the probe in each bin can be increased by the ratio of the actual sample area to the beam area (67.1 mm^2) to yield a corrected number of

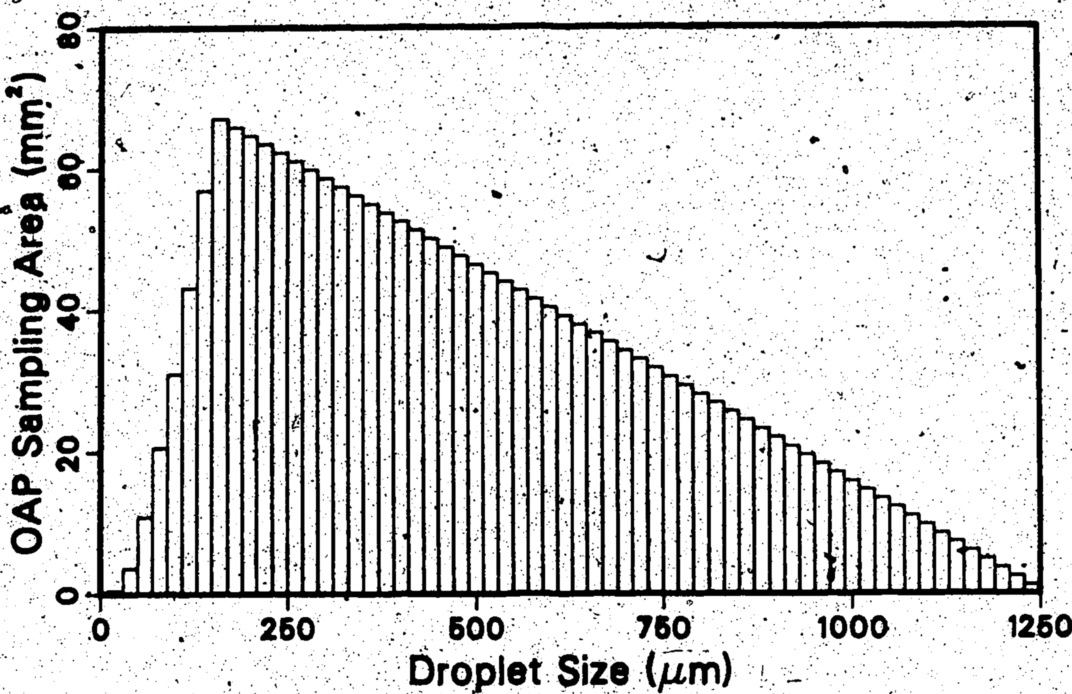

Figure 3.6-3 Histogram of actual sample area vs particle size for each of the OAP's 62 bins.

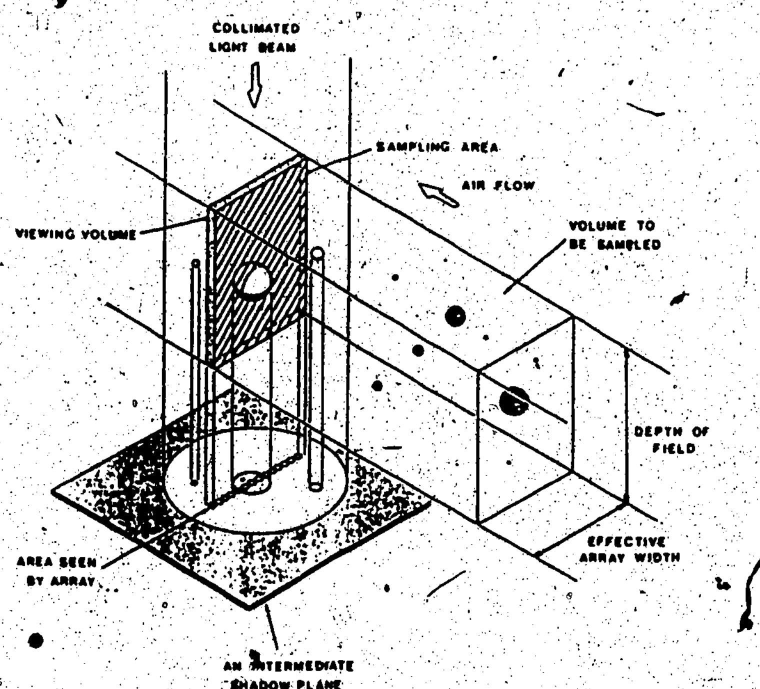

Figure 3.6-4 Imaging functional diagram for the optical array precipitation probe.

particles in each bin. This is a standard technique used by other researchers when dealing with this instrument. Normally this method does not distort the distribution significantly. However when the OAP detects a significant number of droplets in either the smallest or largest bin classifications the "corrected" distribution can be significantly skewed. An example of this can be seen in figure 3.6-5 which gives the raw data as it was obtained and a comparison of the droplet size distributions before and after the correction is made. The corrected distribution in this example is significantly skewed to the left which would indicate that there may in fact be a large number of droplets smaller than 10 μm not measured by the OAP. In order to get a complete description of this spray distribution an instrument capable of measuring these smaller droplets would be required. Fortunately droplets smaller than 10 μm do not tend to have as significant an effect on the ice accretion as do larger droplets if there are any.

The median volume diameter (mvd) is then calculated using the corrected distribution. This is done by determining the total volume of water represented by the droplets in each bin and normalizing it with respect to the total volume of water contained in the distribution. The mvd is then defined as the droplet size where half of the total water in the distribution is in droplets smaller and the other half in droplets larger. This interpolation is attained by fitting a cubic spline through the data. The technique is well illustrated by the graph in figure 3.6-6.

Liquid water content is estimated by calculating the mass of water represented by the droplet distribution (based on the total volume

TIME OF DAY 00:00:15.
INTERVAL(SECS) 15.0

260	612	1193	1915	2354	2590	2603	2571	2179	2128	2067	1936	1746	1832	1680	1531
1163	1304	1278	1182	1069	1001	961	867	735	723	692	695	567	567	477	507
318	399	376	347	332	277	268	258	220	196	175	175	137	110	88	105
87	76	53	56	54	43	41	29	13	19	10	5	5	3	0	0

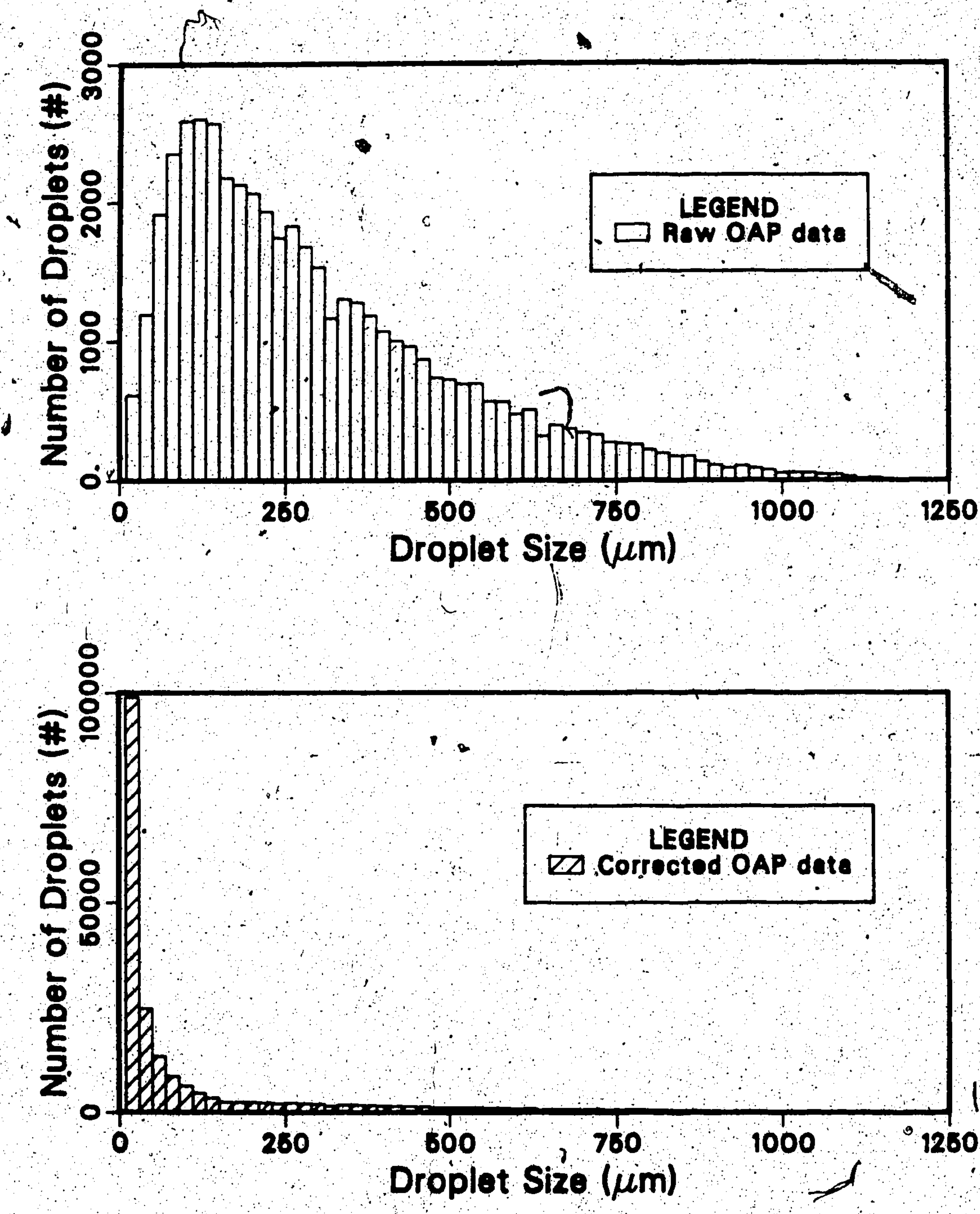

Figure 3.6-5 Comparison of a droplet size distribution before and after applying the sampling area correction.

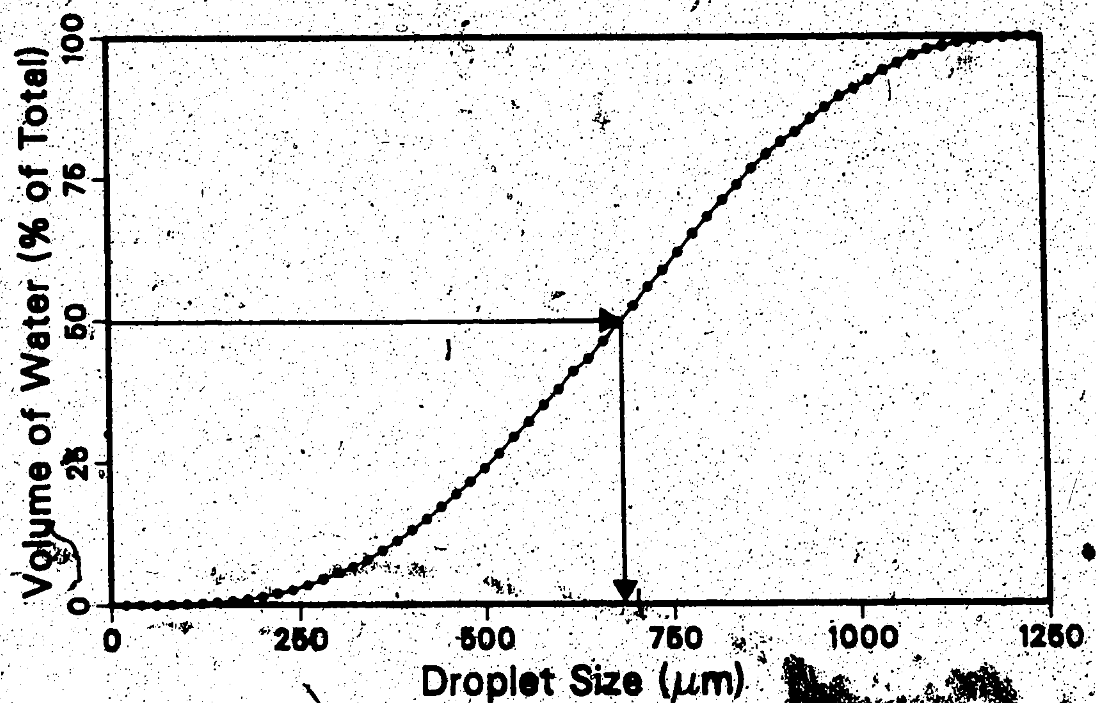

Figure 3.6-6 Method of calculation of median volume diameter (mvd) based on the total volume of water in each bin of the droplet size distribution, (corrected data).

above) and dividing it by the volume of air estimated to have passed through the light beam during the sample interval. The volume of air sampled during a given interval is assumed to be the product of the beam area, the current wind speed and the sampling time for that interval. The imaging functional diagram for the OAP in figure 3.6-4 is useful in visualizing this quantity.

The computer is capable of performing these calculations as often as once every second. At the end of the test interval, when all of the desired samples have been taken, the program will then plot both the median volume diameter and the liquid water content as functions of time.

4. Performance

4.1. Temperature

The operating temperature range of the tunnel was evaluated by running the facility at a variety of stable conditions. Two parameters, wind speed and refrigerant pressure, were varied in order to explore the entire working range. Refrigerant pressure is of course used to control the amount of heat removed by the refrigeration system while variations in wind speed affect the amount of heat generated by the fan. Four wind speeds were used for each of nine different pressures. The details of these tests are summarized in table 4.1-1. From the standard deviation results it can be seen that the air temperature fluctuation was well within a tolerance of ±0.5 degrees Celsius and often within ±0.17 degrees Celsius. From an operations perspective the most important result of these experiments is that the refrigerant pressure required to maintain a given temperature in the wind tunnel is a function of both the desired air temperature and wind speed. Close inspection of the data reveals that it appears to follow a polynomial relationship. It was possible to fit a simple surface corresponding to refrigerant pressure as a function of air temperature and wind speed through it using a series of polynomial expressions. This surface is given by the following relationship:

$$P = f(W,T) = a(W) + b(W) \times T + c(W) \times T^2$$

where:

$P = f(W,T)$ = Required Refrigerant Pressure [psi]

W = Desired Wind Speed [m/s]

T = Desired Air Temperature [C]

$a(W) = 61.793 - 0.55482 \times W + 0.025307 \times W^2 - 0.00039444 \times W^3$

$b(W) = 2.2962 - 0.072041 \times W + 0.0026307 \times W^2 - 0.000028061 \times W^3$

$c(W) = 0.024802 - 0.0013794 \times W + 0.000028672 \times W^2$

The graph in figure 4.1-1 illustrates how well this surface fits the experimental data. Of course at high wind speeds and low temperatures the relationship breaks down but as shown in figure 4.1-2 for most of the operating range it is a useful method of predicting the required refrigerant pressure for a desired air temperature and wind speed. Although the use of pounds per square inch as the unit of measure for refrigerant pressure is not customary it is a practical choice here because the pressure required is also measured in English units. In order to save the effort required to convert from metric to English the above correlation is given in pounds per square inch.

During the course of these tests it was also determined that the amount of time required to achieve a stable temperature when starting from an initial temperature of 20 degrees Celsius was on the order of 35 minutes. The initial cool down is typically less than 20 minutes but some additional time is required to achieve a more stable temperature. This is especially true of the lowest attainable temperatures which can typically take as long as 90 minutes to fully stabilize.

4.2. Airflow

It is also important to examine the behaviour of the air flow in the test section of the tunnel. The experiments performed include simple velocity profiles as well as attempts to characterize the turbulence. Velocity profiles were taken along a horizontal plane through the center of the test section using a pitot-static probe at

Test Number	Refrigerant Pressure [psi]	Wind Speed [m/s] Mean	Wind Speed [m/s] Std. Dev.	Temperature [° C] Mean	Temperature [° C] Std. Dev.
12	0.0	2.781	0.121	-40.581	0.027
11	0.0	10.093	0.156	-41.013	0.047
10	0.0	22.787	0.341	-36.539	0.062
41	0.0	33.528	0.363	-24.076	0.111
20	10.0	2.812	0.092	-38.664	0.125
36	10.0	10.336	0.117	-37.890	0.070
9	10.0	22.779	0.266	-34.902	0.098
28	10.0	32.165	0.339	-25.714	0.036
19	20.0	2.700	0.084	-25.014	0.020
35	20.0	10.626	0.111	-26.930	0.079
8	20.0	23.014	0.256	-27.249	0.395
27	20.0	32.670	0.319	-23.500	0.049
18	30.0	2.623	0.077	-17.870	0.030
34	30.0	10.712	0.115	-17.882	0.040
7	30.0	23.121	0.253	-17.315	0.364
26	30.0	32.833	0.339	-17.312	0.019
17	40.0	2.611	0.085	-10.264	0.234
33	40.0	10.726	0.117	-11.209	0.051
6	40.0	23.074	0.254	-10.486	0.274
25	40.0	33.624	0.356	-9.769	[illegible]176
16	50.0	2.811	0.073	-5.909	0.284
32	50.0	10.792	0.120	-4.551	0.147
38	50.0	22.507	0.246	-5.806	0.284
24	50.0	33.523	0.361	-4.077	0.232
15	60.0	2.790	0.068	0.306	0.047
31	60.0	10.888	0.117	0.449	0.117
40	60.0	23.609	0.249	1.594	0.536
23	60.0	34.244	0.358	1.979	0.120
14	70.0	2.811	0.067	4.075	0.072
30	70.0	10.876	0.121	6.617	0.045
39	70.0	23.496	0.254	6.835	0.193
22	70.0	34.542	0.363	6.909	0.091
13	80.0	2.760	0.061	8.355	0.027
29	80.0	10.926	0.117	11.884	0.035
37	80.0	23.130	0.254	12.899	0.053
21	80.0	34.786	0.348	12.493	0.086

Table 4.1-1 Summary of operating range performance test data.

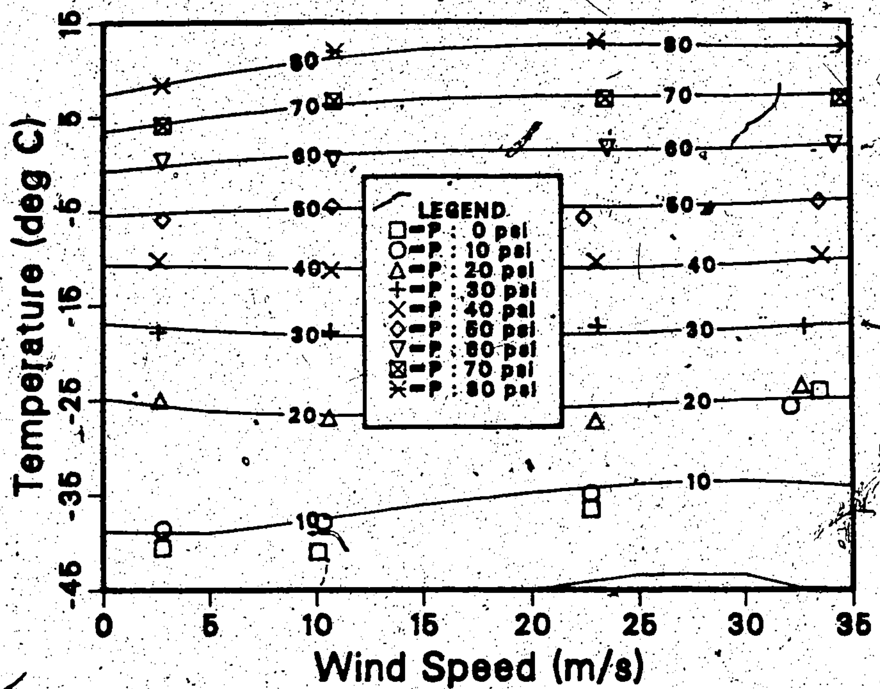

Figure 4.1-1 Operating temperature range data.
(Note: contour lines indicate P=f(W,T) surface)

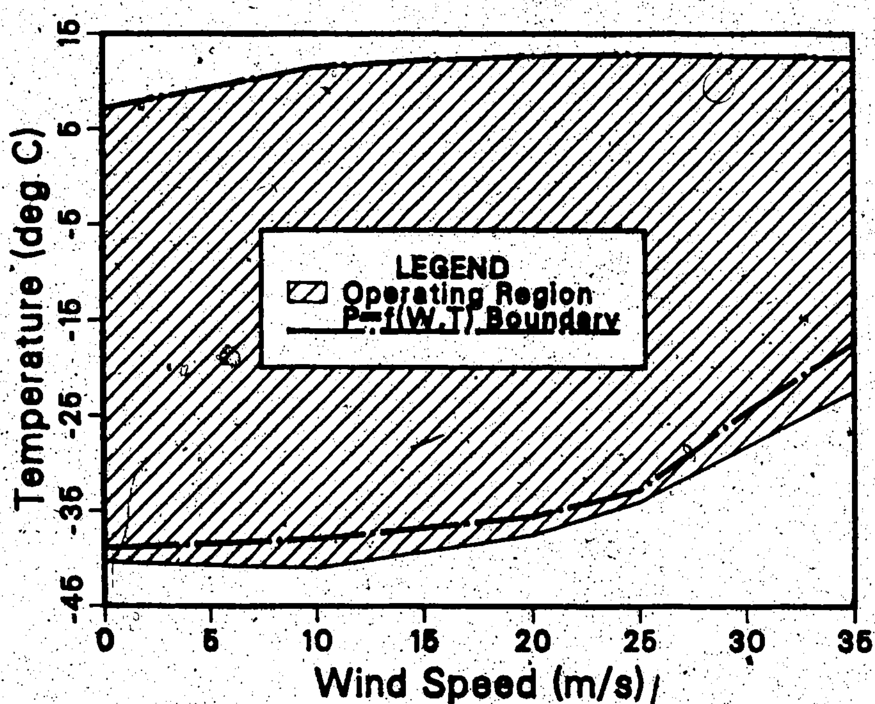

Figure 4.1-2 Overall operating range of Marine Icing Wind Tunnel with useful region of P=f(W,T) surface indicated.

three different wind speeds. These profiles each consisting of 217 individual measurements are displayed graphically in figures 4.2-1 to 4.2-3. It should be noted that no data points were taken in the corners of the test section primarily because the corners are difficult to access using a conventional pitot-static probe since the test section windows do not extend all the way to each wall. The most important thing to note from these results is how flat each of these profiles is over the entire range of wind speeds.

In addition some attempt was made to estimate the amount of swirl there might be in the air flow at the test section. This could be created by the fan and would show up in the test section as a variation in the yaw angle of the velocity vector in the test section. Using a 3 tube yaw probe with the two outboard tubes chamfered at an angle of 45° it was determined that the maximum deviation of the flow in the test section from the vertical was less than 1°. It is possible to say then that the amount of swirl in the air flow once it reaches the test section is negligible.

In order to determine the turbulence characteristics it was necessary to use a flow sensor with a fast response and a data acquisition system capable of extremely high acquisition rates. The signal from a TSI hot film anemometer was taped on an FM recorder and played back into a PDP 11 at a digitizing rate of 20,000 samples per second. Using software developed by the Mechanical Engineering Department's combustion group the turbulence intensity, integral time scale and integral length scale were determined at a variety of wind

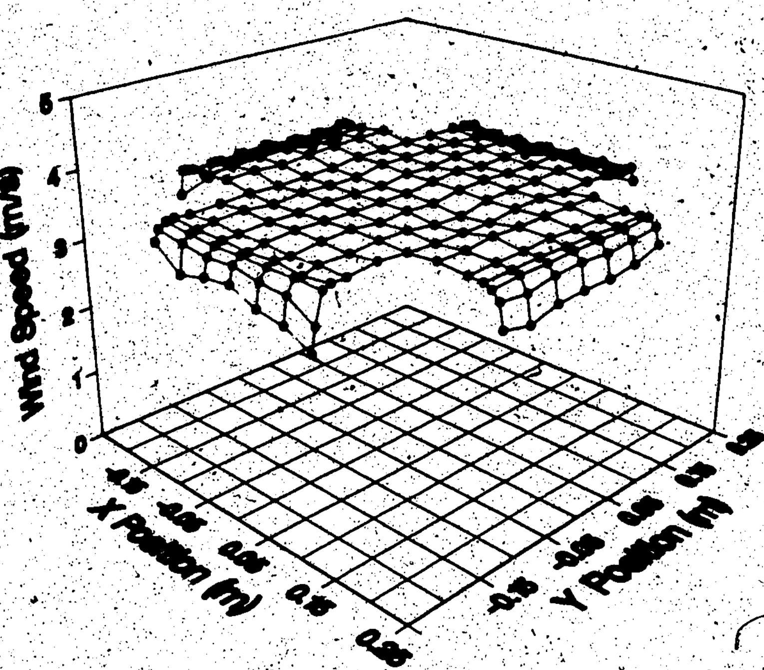

Figure 4.2-1 Wind speed as a function of position measured on a horizontal plane through the center of the test section. (Average wind speed = 3.6 m/s)

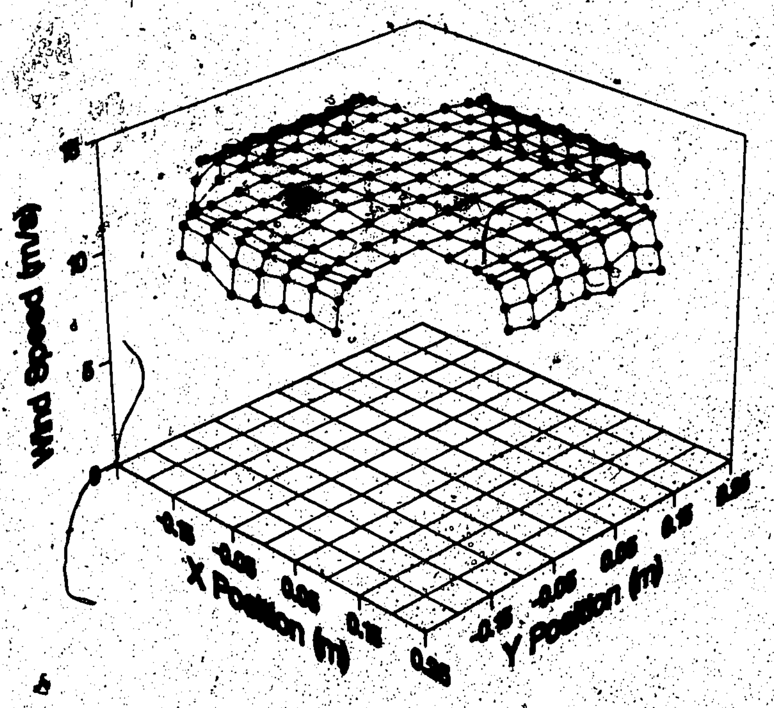

Figure 4.2-2 Wind speed as a function of position measured on a horizontal plane through the center of the test section. (Average wind speed = 13.3 m/s)

speeds from this data. For comparison purposes these experiments were duplicated in the FROST tunnel.

Turbulence intensity was calculated by first taking the average velocity for an entire set of data (26.6 seconds) and then determining the standard deviation of the data from that mean. The ratio of standard deviation to mean (turbulence intensity) is plotted as a percentage versus wind speed in figure 4.2-4. The results for the two wind tunnels are of the same order of magnitude but follow completely different behaviours. For the FROST tunnel which has a constant speed fan the intensity decreases with increasing wind speed. This would lead to the speculation that the amount of energy being dissipated is most likely constant in the FROST tunnel which is consistent with the constant amount of energy being supplied to drive the fan. However the MIWT intensities increase with increasing wind speed implying that the amount of energy being dissipated is increasing. Again this is consistent with the increasing amount of energy being supplied to the variable speed fan in the MIWT. It should be noted that these FROST tunnel results, which indicate an average intensity of the order of 2% are in direct contradiction with those obtained by Sroka [11] which were of the order of [illegible]. Although Sroka used a hot film sensor coupled with an rms [illegible]er to determine the turbulence intensity it is not clear what length of time was used in his tests. If too short a time period were used it would tend to reduce the measured intensity somewhat, but this is a significant discrepancy. Another factor must be involved. It has been 15 years since Sroka performed his experiments and it is possible that the configuration of the tunnel has changed enough to account for this difference. The spray bars which

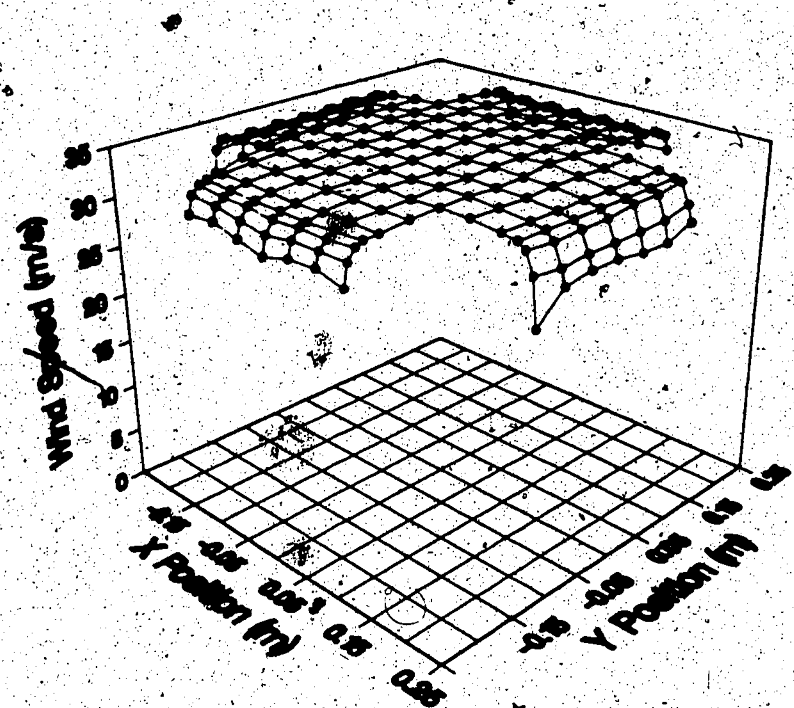

Figure 4.2-3 Wind speed as a function of position measured on a horizontal plane through the center of the test section. (Average wind speed = 34.4 m/s)

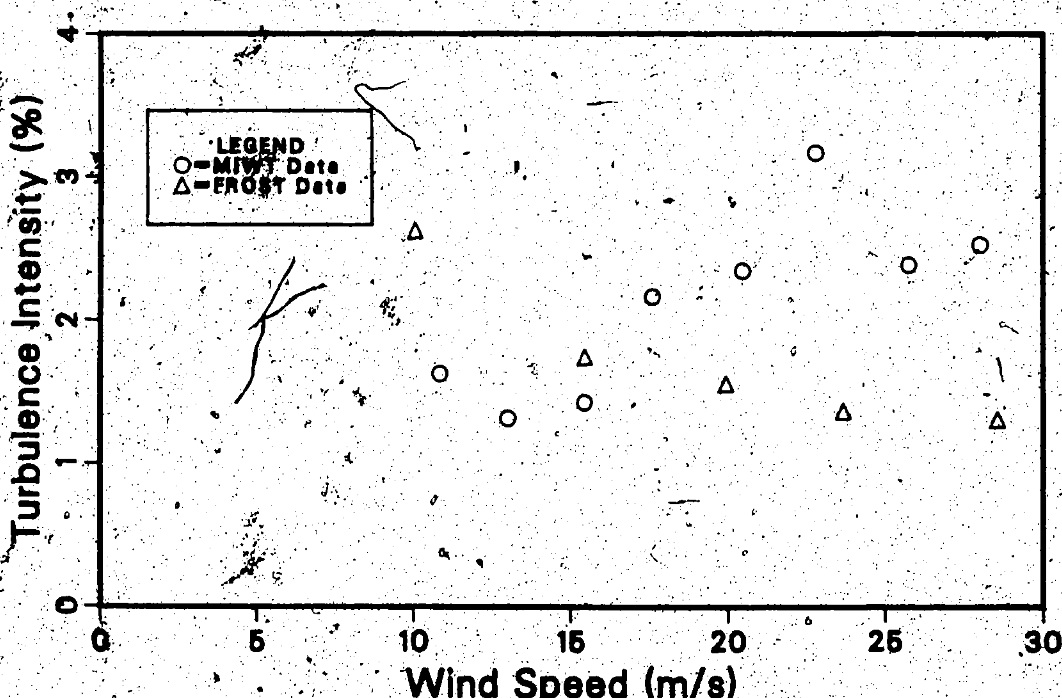

Figure 4.2-4 Turbulence intensity as a function of wind speed in the MIWT and FROST tunnels.

support the nozzles in the contraction as well as the flow conditioning screens have undoubtedly been changed in this time.

Explanation of the differing turbulence scale results is less obvious. The integral time scale was determined by extrapolating the power spectrum back to zero frequency in the manner described by Hinze (pg. 66 in [12]). The corresponding length scale is simply the calculated time scale multiplied by the mean velocity. These two quantities are plotted versus velocity in figures 4.2-5 and 4.2-6. Again the FROST tunnel data appear to follow expected trends. The time scale decreases with increasing velocity which enables the length scale to be independent of velocity and remain constant at approximately 20 mm. This is the expected result for a wind tunnel where the fan speed is kept constant and there are no other variations in the flow conditions. The MIWT data does not follow the same behaviour. Both time and length scales increase with increasing wind speed. One explanation could be that the effect of the different fan speeds used to alter the flow velocity changes the very nature of the turbulence. In fact the length scales vary dramatically from 10 mm at 10 m/s to nearly 70 mm at 30 m/s. The major differences between these two facilities that should be noted are:

- there are screens in the FROST tunnel while the MIWT has none.
- the settling length in the FROST tunnel is considerably longer than that in the MIWT.
- fan speed remains constant for all wind speeds in the FROST tunnel, while fan speed varies with wind speed in the MIWT.

The most important conclusions to draw from these airflow experiments lie in the differences between the MIWT and the FROST tunnels. While the velocity profiles are uniform and there appears to be little swirl in the test section of the MIWT the turbulent

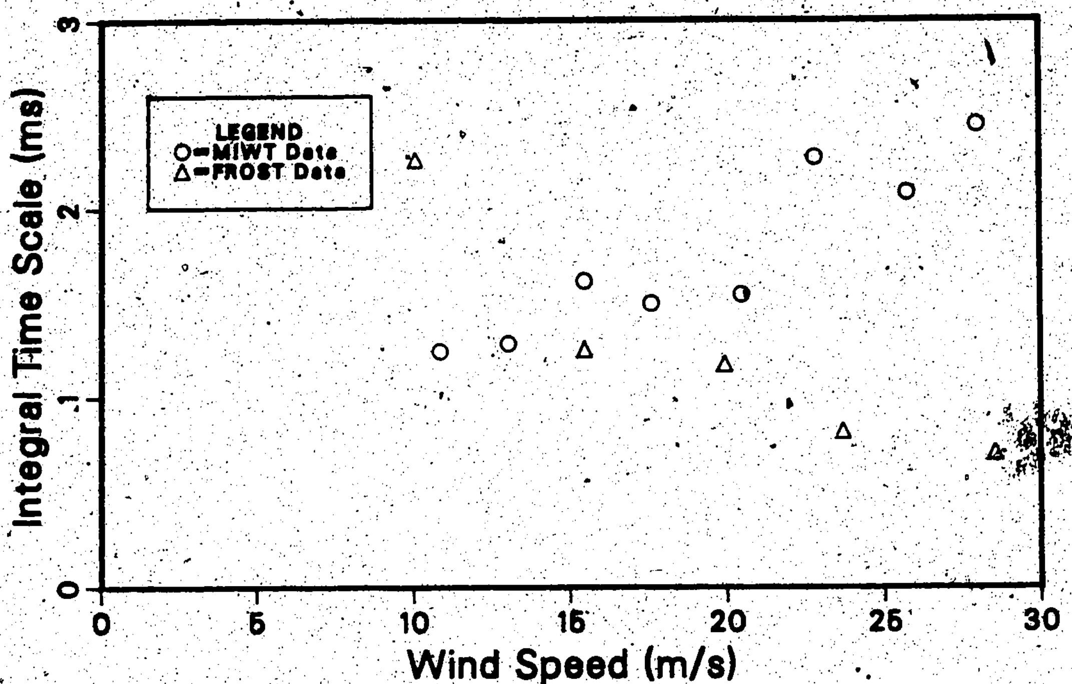

Figure 4.2-5 Integral time scale as a function of wind speed in the MIWT and FROST tunnels.

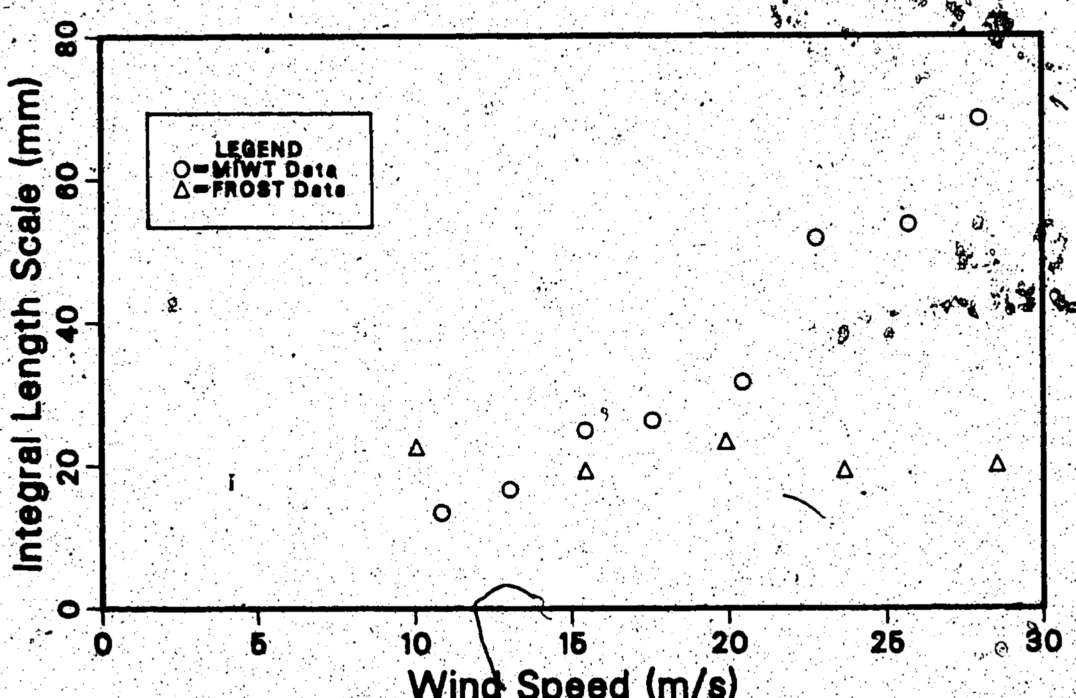

Figure 4.2-6 Integral length scale as a function of wind speed in the MIWT and FROST tunnels.

characteristics of the flow do not obey the same rules in this facility as they do in the FROST tunnel. This may affect any experimental work sensitive to the turbulent aspects of the flow such as convective heat transfer. Consequently it is an important aspect of their relative performance. It would be advisable to investigate the effect of these differing turbulence characteristics on ice accretion. One way to approach this might be to run parallel wet icing experiments in the two facilities.

4.3. Spray Characteristics

Another aspect of the tunnel which has been investigated is the performance of the spray system. Particular attention has been payed to its response time in reproducing pulsed sprays. The purpose of the pulsing system is to model the periodic nature of brine spray generated by ship-wave interaction. As mentioned earlier pulsed sprays are generated using a system of solenoid valves. In order to evaluate the performance of this system the liquid water content and median volume diameter of the spray have been measured as a function of time. Figures 4.3-1 and 4.3-2 illustrate these fluctuations for two pulse cycles. These tests were performed using an array of 8 Danfoss spray nozzles (rated at 1.5 gal/hr each) at room temperature with a wind speed of 10 m/s. The spray generated by these 8 nozzles supplies a uniform distribution to an oval shaped area with major and minor axes on the order of 0.3 m and 0.1 m respectively. Each measurement represents a one second time average while the sprays were pulsed on for 20.1 seconds and off for 37.7 seconds during each cycle. The solid line in each graph indicates the pulse duration and the average liquid water content and median volume diameter measured for each cycle. The

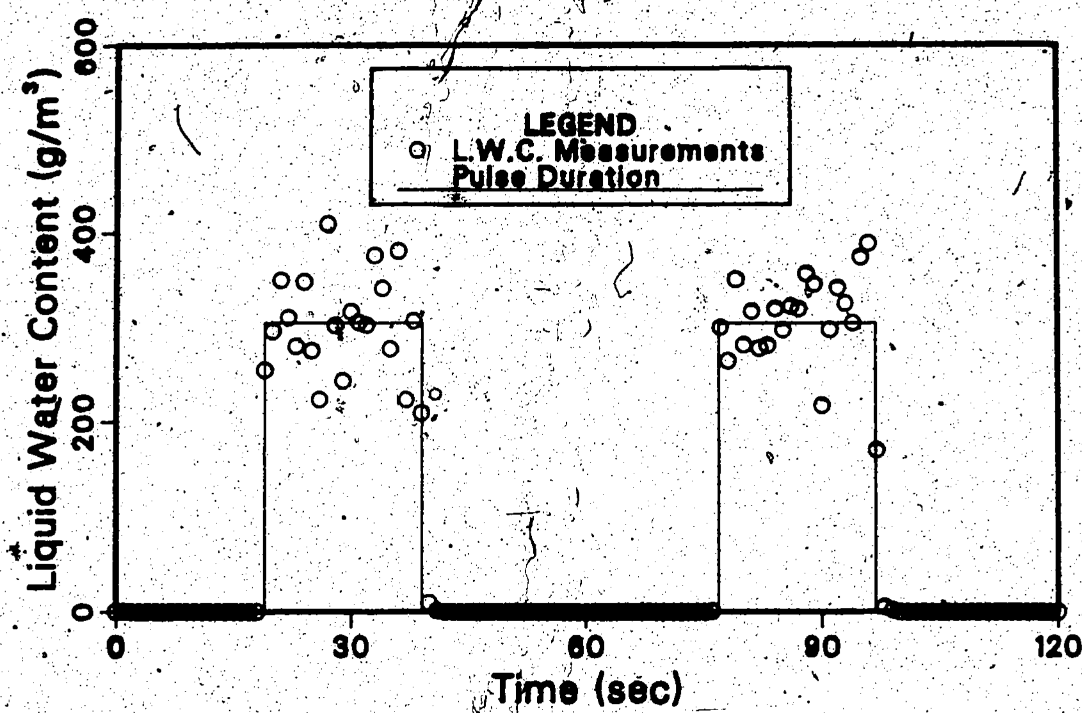

Figure 4.3-1 Pulsed spray test showing liquid water content as a function of time: On Time = 20.1 sec. Cycle Time = 57.8 sec.

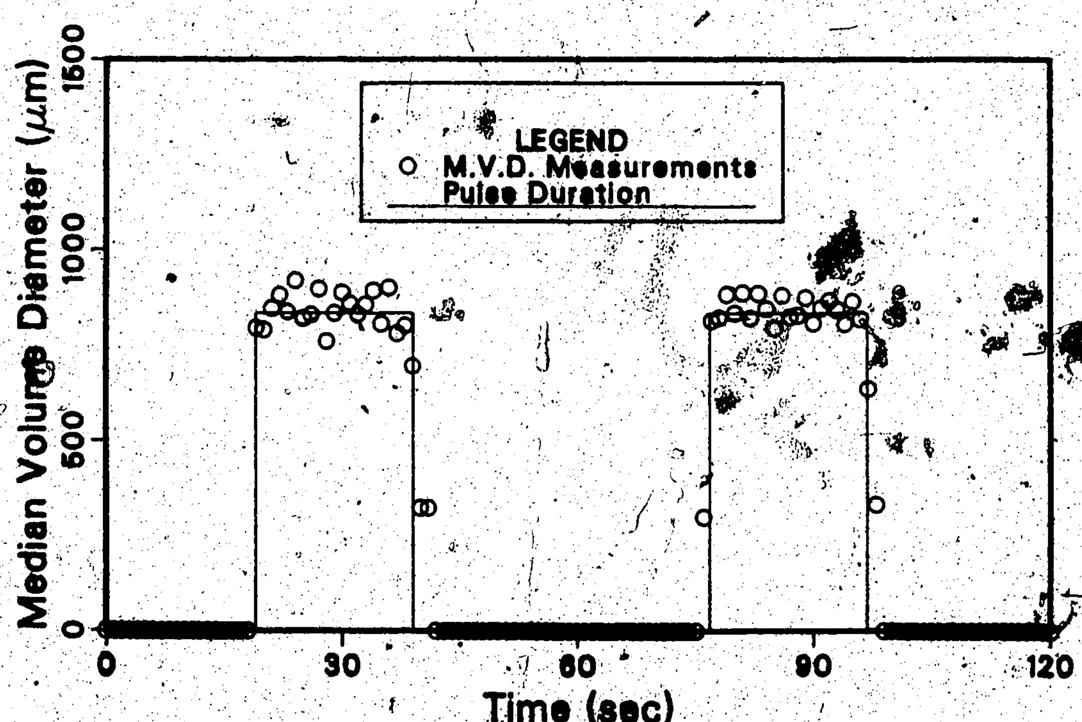

Figure 4.3-2 Pulsed spray test showing median volume diameter as a function of time: On Time = 20.1 sec. Cycle Time = 57.8 sec.

liquid water content tends to fluctuate considerably while the sprays are on but the median volume diameter is more consistent. This would indicate that while the total volume of water measured by the probe is varying from one sample to the next, the droplet distribution itself remains unchanged. The most important thing to note here is the fast response of the system both in turning on and off the sprays. This is possible because the solenoid controlling the flow to the spray nozzles is located immediately upstream of the nozzle manifold.

4.4. Maintenance

During the course of these performance experiments it was determined that in order to ensure that the tunnel will continue to perform well there are a number of important maintenance recommendations which must be followed. These suggestions apply to both the tunnel itself and the instruments being used in the facility which are subjected to brine spray.

The refrigeration system should be serviced at least once per year. At this time the dryers should be replaced and the oil and refrigerant levels checked. This level of maintenance is the minimum required and it may be necessary to service the system as often as once per quarter during periods of heavy use. All valves in the system should be closed and all electrical power "locked out" if it is anticipated that the facility will not be used for a period of six months or longer. This will reduce the chance of a refrigerant leak resulting in a loss of the system charge.

It is impossible for the settling chamber to collect all of the brine spray especially if the filter becomes fouled with salt. For this reason the settling chamber and fan must be thoroughly cleaned and flushed once for every 20 hours of operation or on the order of once per week during periods of normal use. The nozzles too will be vulnerable to the corrosive effects of brine and must be flushed with fresh water daily and removed weekly for a more thorough ultrasonic cleaning.

The instrumentation, particularly the OAP and its sensitive optics should also be checked weekly for signs of salt degradation. This is most likely to appear in the form of salt and water deposits on the mirrors and exposed lenses. Any contamination of these surfaces will dramatically reduce the intensity and form of the light source.) In an effort to minimize the need to continually clean the optics of the OAP an air purge should be used to maintain a slight positive pressure on the probe at all times. Without this air purge it is possible for all of the probe's optical surfaces, including the end mirror of the laser itself, to be contaminated.

Proper maintenance will be an important factor in determining the useful life of this facility. If at any time the facility is to remain idle for longer than a week it is important that the settling chamber, fan, nozzles and instruments be thoroughly cleaned. All of the internal surfaces of the ductwork should be cleaned at least once per quarter with particular attention to the evaporators.

5. Experimental Potential

Experiments have been performed by Dr. Paul Zakrzewski which involved the accretion of ice on rotating cylinders. The results of two of these tests are illustrated by the photographs in figures 5-1 and 5-2.

This facility's use need not be limited to simulation of the marine environment. The flexible design of the wind tunnel enables many different types of experiments to be performed, including:

- simulation of atmospheric icing conditions,
- hail growth and other cloud physics studies,
- fundamental and applied cold regions heat transfer research,
- testing of anti-icing and ice monitoring equipment,
- and inter-comparison or calibration of meteorological and icing instruments.

Atmospheric icing conditions could be reproduced by spraying fresh water into the airstream. It would also be desirable to use nozzles capable of producing smaller droplets. One advantage of using this facility to simulate atmospheric icing is the vertical orientation of the test section. This orientation makes it possible for the differential settling of large water droplets to be eliminated.

Hail growth simulation requires that both the location and orientation of the test section within the loop be altered. By inverting the test section and its accompanying contraction and diffuser, and interchanging it with the vertical contraction at the opposite end of the tunnel as illustrated in figure 5-3 hail studies and other cloud physics investigations can be performed. In the hail mode air flow is still clockwise resulting in air movement up through the test section. With the spray introduced lower down in the contraction an artificial hailstone can be suspended in the resulting

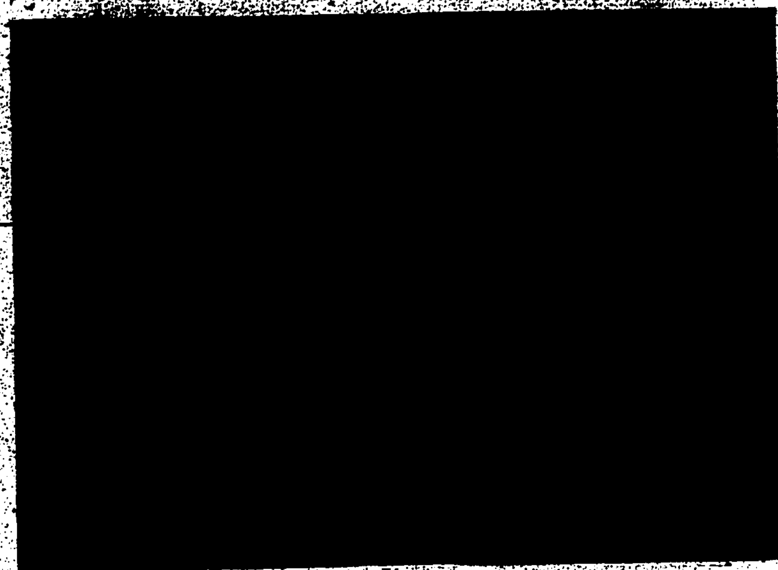

Figure 5-1 Ten minute ice accumulation on a 25.4 mm diameter rotating steel cylinder. (V_a=15m/s, T_a=-10°C, LWC=285g/m^3, MVD=690μm)

Figure 5-2 Ten minute ice accumulation on a 25.4 mm diameter stationary steel cylinder. (V_a=15m/s, T_a=-10°C, LWC=285g/m^3, MVD=690μm)

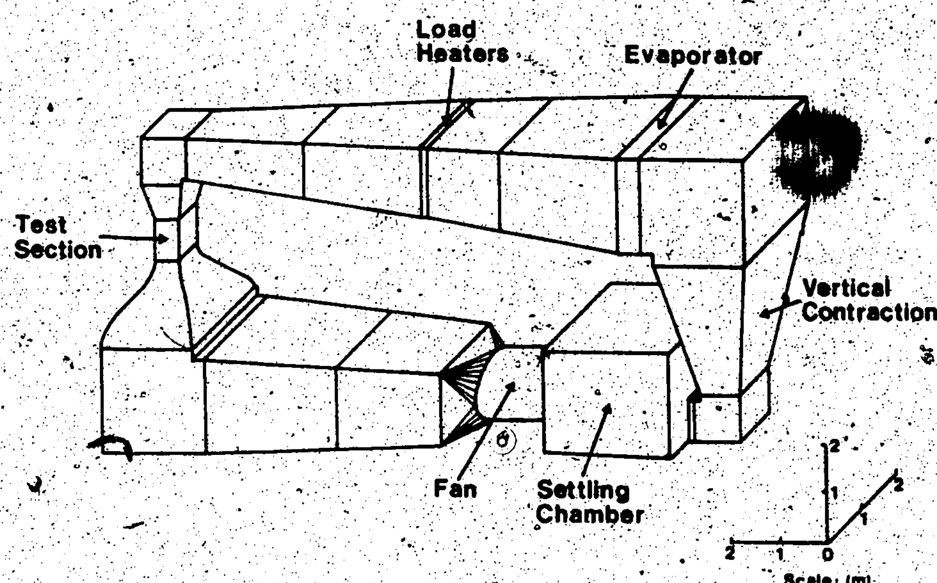

Figure 5-3 Oblique view of the MIWT in its hail simulation configuration.

upward moving cloud. It should be noted though that unlike some other facilities designed specifically for hail growth it is not possible to lower the air pressure within the test section in order to simulate high altitude conditions.

Cold regions heat transfer research is another area of possible use for this facility. Fundamental experiments such as those relating to the heat transfer between a warm surface and the cold airstream could readily be performed. In addition other applied experiments such as an investigation into the performance of thermosyphons using the cold air as a heat sink are possible.

Depending on the size of the equipment full or model scale investigations of anti-icing and ice monitoring apparatus are well within the scope of this facility. Icing and meteorological instruments such as those described in chapter 3 have already been used in this facility and some inter-comparisons have been made. It is of course a great advantage to make use of a controlled environment when attempting to compare different instruments or measuring techniques.

6. Summary and Recommendations

The main innovations in the design of the MIWT are:

- its ability to use brine sprays.
- the vertical orientation of its test section which will eliminate the problems caused by differential settling of large water droplets and thereby contribute to the uniformity of the spray distribution.
- its innovative construction technique which makes use of insulation as a major structural element.

The instrumentation and data acquisition system will contribute to this facility being a powerful research tool. It will dramatically reduce the time required for researchers to make comparisons between model predictions and experimental results. Also, it will make it possible to exercise tighter control over the experimental conditions by measuring those conditions quickly and accurately.

The performance of the facility meets or exceeds the design requirements:

- temperature control to at least ±0.5 degrees Celsius over the entire operating range of +15° to -40 degrees Celsius has been achieved.
- wind speeds as high as 32 m/s are attainable, with uniform velocity profiles and turbulence intensities in the primary flow direction of the order of 2%.
- the spray system is capable of reproducing pulsed sprays.

In order for this facility to maintain its high level of performance it will be important to pay proper attention to maintenance.

Finally, in addition to work already achieved there are several recommendations with respect to areas which require further work. One of these areas is the performance of the instrumentation. The weakest link in the instrumentation "chain" at this point is the characterization of the brine spray. Although its measurement of droplet size has been checked against a mono-disperse group of glass beads of known size a detailed comparison of the OAP's liquid water content predictions with some known standard has yet to be performed. In addition, if any experimental work being performed in the future is sensitive to the turbulent characteristics of the air flow extreme caution should be exercised. As noted in the chapter on performance, turbulence in the MIWT does not behave in the same manner as some other wind tunnels because of the fact that the fan speed changes with each new wind speed setting. Another important area for further study is the characterization of natural marine icing incidents through field experiments. This is currently being addressed by Dr. P. Zakrzewski and Mr. R. Blackmore of the division of meteorology.

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Appendix A

Design Calculations.

Appendix A

Design Calculations:

The majority of the preliminary design work for the MIWT facility was performed prior to the author's involvement with the project. However, in the interests of making this document as complete as possible a review of these design calculations is included in this appendix.

Pressure Losses

The sizing of the fan and its motor required that some estimation of the total expected pressure loss be made. This was achieved by estimating the friction loss coefficient due to each of the elements in the ductwork as related to the wind speed in the test section. These losses are summarized in table A-1.

Duct Element	Friction Loss Coefficient (K)
Skin friction	0.046840
Diffusers	0.133000
Corners	0.258030
Coils	0.124970
Honeycombs	0.007483
Screens	0.027837
Tested Model	0.200000
Settling Chamber	0.095300
Total	0.893440

Table A-1: Summary of Friction Loss Coefficients for MIWT.

Based on this total friction loss coefficient the total pressure drop through the ductwork will be given by:

$$P = \frac{1}{2} K \rho V^2$$

Assuming : K = Total frictional loss coefficient = 0.893440
ρ = Density of air = 1.45 kg/m^3
V = Maximum wind speed in the test section = 50 m/s

Thus the total estimated pressure drop for a wind speed of 50 m/s was 1.619 kPa. This wind speed corresponds to an air flow rate requirement of 12.5 m^3/s from the fan. Using this information it was possible to select the fan and motor for the MIWT. The fan was selected based on the required flow rate and pressure drop. The chosen fan was an axial flow design with a centrifugal impeller manufactured by Northern Blower Inc., (specifically a Design 80 Centri-Foil fan, size 365). Using the chosen fan's performance characteristics it was possible to determine the amount of power that it would require. This was found to be on the order of 30 kW (40 hp). In order to account for belt drive and other losses a 37 kW (50 hp) variable speed DC motor was selected.

Refrigeration Losses

In order to choose an effective refrigeration system it was necessary to estimate the total amount of heat which would act against the refrigeration system in the facility. This was the only calculation required for the refrigeration system by the original designers of this facility because all of the detailed design work was contracted out to the supplier. The total anticipated heat load was based on a number of major contributors as indicated in table A-2.

Heat Contributor	Based on V=40m/s, T=-30°C	Estimated Heat (Q)
Fan heating	Entrained air, frict. losses.	30 kW
Sprayed water	LWC of 5 g/m^3 in test section.	22 kW
Conduction	Through the tunnel walls.	5 kW
Heaters	To limit turning vane icing.	2 kW
Total		59 kW

Table A-2: Summary of Total Heat Load for MIWT.

A large majority of the refrigeration system's components were obtained as surplus equipment from the Student's Union Building curling rinks. In fact the only new component was the evaporator which was built according to the supplier's (CIMCO Thermo Design) specifications. The anticipated total heat load was used by the supplier in the design process to insure that the surplus equipment would be capable of meeting the needs of the facility.

Appendix B

Data Acquisition Software

MIWT_LOG_2.01

```
10 ! MIWT_LOG_2.01
20 !**********************************************************************
30 !*                                                                    *
40 !* Program : MIWT_LOG_2.01                 Written : June, 1987       *
50 !*                                         Revised : October, 1987    *
60 !*                                                                    *
70 !*          A data acquisition program for use in the Marine Icing    *
80 !*          Wind Tunnel.  Up to 19 channels of information can be    *
90 !*          read in simultaneously and displayed on the screen.      *
100 !*         The raw voltage data can be converted into temperature    *
110 !*         or velocity.  Each channel of data can then be plotted    *
120 !*         versus time.                                              *
130 !*                                                                   *
140 !* Hardware : HP 9000  - model 520 computer.                         *
150 !*            HP 3497A - data acquisition unit.                      *
160 !*            HP 2934A - external printer, (Unit 401).               *
170 !*                                                                   *
180 !* Subroutines : Logdat    - performs the data acquisition.          *
190 !*               Initscrn  - used by Logdat to initialize display.   *
200 !*               Initvar   - initializes Logdat's variables.         *
210 !*               Printdata - prints data to screen during acquisition. *
220 !*               Printres  - prints final results of test to printer. *
230 !*               Tcconv    - converts thermocouple voltage to temp.  *
240 !*               Pitot     - converts pitot tube voltage to velocity. *
250 !*               Plotit    - plots results from one channel vs time. *
260 !*                                                                   *
270 !**********************************************************************
280 !
290 ! Variable      Description                 Units              Range
300 !----------------------------------------------------------------------
310 ! Internally Generated
320 !---------------------
330 ! Dt            Data acquisition rate.      [seconds/sample]   Dt>=2
340 ! Tim           Total time of test.         [seconds]          Tim<=1400*Dt
350 ! Pbar          Barometric pressure.        [mm Hg]            ------------
360 ! Y(*)          Data vector (for plots).    [m/s,deg C,etc.]   ------------
370 ! X$            X axis label for plots.     ---------------    max 18 chrs.
380 ! Ttime         Total time of test.         [seconds]          ------------
390 ! Miny          Minimum Y value plotted.    ---------------    ------------
400 ! Maxy          Maximum Y value plotted.    ---------------    ------------
410 !----------------------------------------------------------------------
420 ! Generated by Subroutines
430 !-------------------------
440 ! Nchan         Total # of channels.        ---------------    Nchan<=19
450 ! Nplot         # of plotted channels.      ---------------    Nplot<=Nchan
460 ! Cp(*)         Channel pointer.            ---------------    0<=Cp<=19
470 ! Tcp(*)        Temp. channel pointer.      ---------------    0<=Tcp<=19
480 ! Pcp(*)        Plotted channel pointer.    ---------------    0<=Pcp<=19
490 ! Cntr          Number of points taken.     ---------------    Cntr<=1400
500 ! T(*)          Time vector.                [seconds]          ------------
510 ! Dat(*)        Data array.                 [m/s,deg C,etc.]   ------------
520 ! Sdat(*)       Sum of data vector.         [m/s,deg C,etc.]   ------------
530 ! Ssdat(*)      Sum of sqrs. of data.       [(m/s) 2,etc.]     ------------
540 ! Mean(*)       Mean vector.                [m/s,deg C,etc.]   ------------
550 ! Sdev(*)       Standard dev. vector.       [m/s,deg C,etc.]   ------------
560 ! Comment$(*)   Channel descriptions.       ---------------    max 40 chrs.
570 ! Unit$(*)      Units of each channel.      ---------------    max 10 chrs.
580 ! Y$(*)         Axis labels (for plots).    ---------------    max 30 chrs.
```

```
590 ! Titles(*)      Titles (for plots).     ----------------- max 30 chrs.
600 ! T$             Time of day for test.    [Hrs:Mins:Secs]  ------------
610 ! D$             Date of test.            [Day Month Year]  -----------
620 !---------------------------------------------------------------------------
630 !
640 ! Initialize default data logging parameters.
650   Dt=2         ! A sample will be taken once every 2 seconds.
660   Tim=360      ! The total time of the test will be 360 seconds.
670   Pbar=700     ! Barometric Pressure [mm Hg]
680 !
690 ! Declare all variables.
700   DIM [illegible](19),Tcp(19),Pcp(19),Comment$(19)[40],Unit$(19)[10]
710   DIM Y$(19)[30],Titles(19)[30]
720   DIM T(1400),Dat(19,1400),Y(1400)
730   DIM Sdat(19),Ssdat(19),Mean(19),Sdev(19)
740 !
750 ! Set up logging menu.
760 Menu: !
770   PRINTER IS CRT
780   PRINT PAGE
790   PRINT "Acq. Rate - Used to change the data acquisition interval."
800   PRINT "             Currently : ";Dt;" secs./sample"
810   PRINT "Test Time - Used to specify the total test time."
820   PRINT "             Currently : ";Tim;" seconds."
830   PRINT "Bar Press - Used to enter desired barometric pressure."
840   PRINT "             Currently : ";Pbar;" mm Hg."
850   PRINT "Start     - Starts data acquisition procedure."
860   PRINT "Quit      - Stops program execution."
870   OFF KEY
880   ON KEY 0 LABEL "Acq. Rate    SFK 0" GOTO Rate
890   ON KEY 1 LABEL "Test Time    SFK 1" GOTO Testtim
900   ON KEY 2 LABEL "Bar Press    SFK 2" GOTO Barp
910   ON KEY 6 LABEL "Start        SFK 6" GOTO Start
920   ON KEY 7 LABEL "Quit         SFK 7" GOTO Quit
930   WAIT
940 Rate: !
950   PRINTER IS CRT
960   PRINT PAGE
970   PRINT "Current data acquisition interval : ";Dt;" secs./sample"
980   PRINT "Available range => Dt >=2 "
990   INPUT "Enter new data acquisition interval [secs./sample].",Dtt
1000  IF Dtt<2 THEN
1010              PRINT PAGE
1020              PRINT "Requested interval too short."
1030              PRINT "Dt must be greater than 2 secs."
1040              PRINT
1050              GOTO 970
1060          ELSE
1070              Dt=Dtt
1080  END IF
1090  GOTO Menu
1100 Testtim: !
1110  PRINTER IS CRT
1120  PRINT PAGE
1130  PRINT "Current total test time : ";Tim;" seconds"
1140  PRINT "Available range => Tim <= Dt*1400"
1150  INPUT "Enter new test time, [seconds].",Timt
1160  IF Timt>Dt*1400 THEN
1170                    PRINT PAGE
1180                    PRINT "Requested time too large."
```

```
1190                   PRINT "For this sampling rate Tim must not exceed
";Dt*1400;" secs."
1200                   PRINT
1210                   GOTO 1130
1220                 ELSE
1230                   Tim=Timt
1240    END IF
1250    GOTO Menu
1260 Barp: !
1270    PRINTER IS CRT
1280    PRINT PAGE
1290    PRINT "Current barometric pressure : ";Pbar;" mm Hg"
1300    INPUT "Enter new barometric pressure, [mm Hg].",Pbar
1310    GOTO Menu
1320 Start: !
1330    OFF KEY
1340    CALL Logdat(Dt,Tim,Pbar,Nchan,Nplot,Cp(*),Tcp(*),Pcp(*),Cntr,T(*),Dat(*
),Sdat(*),Ssdat(*),Comment$(*),Unit$(*),Y$(*),Title$(*),T$,D$)
1350 !
1360 Stop: !
1370 ! Reset the screen and display status message.
1380    PRINTER IS CRT
1390    PRINT PAGE
1400    DISP "
1410    PRINT "Data Sampling Terminated."
1420 !
1430 ! Calculation of Mean and Standard Deviation.
1440    FOR I=1 TO Nchan
1450      Mean(Cp(I))=Sdat(Cp(I))/Cntr
1460      Sdev(Cp(I))=SQR((Ssdat(Cp(I))-Cntr*(Mean(Cp(I))^2))/(Cntr-1))
1470    NEXT I
1480 !
1490 ! Print results out to external printer, (Unit 401).
1500    PRINTER IS 401
1510    CALL Printres(Nplot,Pcp(*),Cntr,Mean(*),Sdev(*),Comment$(*),Unit$(*),T$
,D$)
1520 !
1530 ! Plot the results from those channels specified.
1540    REDIM Y(Cntr)
1550    X$="Time [sec]"
1560    FOR I=1 TO Nplot
1570      K=Pcp(I)
1580      FOR J=1 TO Cntr
1590        Y(J)=Dat(K,J)
1600      NEXT J
1610      Y(0)=Mean(K)
1620      Miny=MIN(Y(*))
1630      Maxy=MAX(Y(*))
1640      Ttime=T(Cntr)
1650 !    First plot to the screen,
1660      CALL Plotit(X$,Y$(K),Title$(K),T(*),Y(*),Ttime,Cntr,Miny,Maxy)
1670 !    Then dump plot to external printer, (Unit 401).
1680      DUMP GRAPHICS  TO 401
1690    NEXT I
1700 !
1710 Quit: !
1720 ! Reset the screen and display status message.
1730    PRINTER IS CRT
1740    PRINT PAGE
1750    GRAPHICS OFF
```

```
1760   PRINT "Program Execution Terminated"
1770 !
1780 ! End of program.
1790   END
```

```
1800 !************************************************************************
1810    SUB Logdat(Dt,Tim,Pbar,Nchan,Nplot,Cp(*),Tcp(*),Pcp(*),Cntr,T(*),Dat(*)
,Sdat(*),Ssdat(*),Comment$(*),Unit$(*),Y$(*),Title$(*),T$,D$)
1820 !************************************************************************
1830 !*                                                                      *
1840 !* Subroutine: Logdat                          Written : June, 1987     *
1850 !*                                             Revised : October, 1987  *
1860 !*                                                                      *
1870 !*            A data acquisition routine for use with the HP 3497A      *
1880 !*            data acquisition unit.  Up to 19 channels of information  *
1890 !*            can be read in simultaneously and displayed on the screen.*
1900 !*            The raw voltage data can be converted into temperature    *
1910 !*            or velocity.                                              *
1920 !*                                                                      *
1930 !* Hardware : HP 9000   - model 520 computer.                           *
1940 !*            HP 3497A  - data acquisition unit.                        *
1950 !*                                                                      *
1960 !* Subroutines : Initscrn  - used to initialize display.                *
1970 !*               Initvar   - initializes Logdat's variables.           *
1980 !*               Printdata - prints data to screen during acquisition. *
1990 !*               Tcconv    - converts thermocouple voltage to temp.    *
2000 !*               Pitot     - converts pitot tube voltage to velocity.  *
2010 !*                                                                      *
2020 !************************************************************************
2030 !
2040 ! Variable      Description              Units              Range
2050 !------------------------------------------------------------------------
2060 ! Input
2070 !-------
2080 ! Dt            Data acquisition rate.   [seconds/sample]   Dt>=2
2090 ! Tim           Total time of test.      [seconds]          Tim<=1400*Dt
2100 ! Pbar          Barometric pressure.     [mm Hg]            ------------
2110 !------------------------------------------------------------------------
2120 ! Output
2130 !--------
2140 ! Nchan         Total # of channels.     ----------------   Nchan<=19
2150 ! Nplot         # of plotted channels.   ----------------   Nplot<=Nchan
2160 ! Cp(*)         Channel pointer.         ----------------   0<=Cp<=19
2170 ! Tcp(*)        Temp. channel pointer.   ----------------   0<=Tcp<=19
2180 ! Pcp(*)        Plotted channel pointer. ----------------   0<=Pcp<=19
2190 ! Cntr          Number of points taken.  ----------------   Cntr<=1400
2200 ! T(*)          Time vector.             [seconds]          ------------
2210 ! Dat(*)        Data array.              [m/s,deg C,etc.]   ------------
2220 ! Sdat(*)       Sum of data vector.      [m/s,deg C,etc.]   ------------
2230 ! Ssdat(*)      Sum of sqrs. of data.    [(m/s) 2,etc.]     ------------
2240 ! Comment$(*)   Channel descriptions.    ----------------   max 40 chrs.
2250 ! Unit$(*)      Units of each channel.   ----------------   max 10 chrs.
2260 ! Y$(*)         Axis labels (for plots). ----------------   max 30 chrs.
2270 ! Title$(*)     Titles (for plots).      ----------------   max 30 chrs.
2280 ! T$            Time of day for test.    [Hrs:Mins:Secs]    ------------
2290 ! D$            Date of test.            [Day Month Year]   ------------
2300 !------------------------------------------------------------------------
2310 ! Internal
2320 !----------
2330 ! Tchan         # of Temp. channels.     ----------------   Tchan<=9
2340 ! V(*)          Raw voltage data.        [volts]            ------------
2350 ! R(*)          T type T/C coeff.        Temp. -> Voltage   ------------
2360 ! P(*)          T type T/C coeff.        Voltage -> Temp.   ------------
```

```
2370 ! Ctime          Current time.            [seconds]          ------------
2380 !------------------------------------------------------------------------------
2390 !
2400 !      Declare all local variables.
2410        DIM V(19)
2420        DIM R(3),P(10)
2430 !
2440 !      Initialize all Variables
2450        CALL Initvar(Nchan,Tchan,Nplot,Cp(*),Tcp(*),Pcp(*),R(*),P(*),Commen
t$(*),Unit$(*),Y$(*),Title$(*))
2460 !
2470 !      Initialize the screen to display output
2480        CALL Initscrn(Nchan,Cp(*),Comment$(*),Unit$(*))
2490 !
2500 !      Initialize the HP 3497A to take data.
2510        Idt=INT(Dt)
2520        Dt$=IVAL$(Idt,10)
2530        CLEAR 409
2540        ON INTR 4 GOSUB Intrtn
2550        ENABLE INTR 4;4096   ! Enable Bit 12 of Interrupt Mask Register, SRQ
2560        OUTPUT 409;"VT4 VD5 SD0 VA0 SE1 AF0 AL19 VN20 VT2 VS1 AC0 AE1"
2570        OUTPUT 409;"TI"&Dt$
2580        T$=TIME$(TIMEDATE)
2590        D$=DATE$(TIMEDATE)
2600 !
2610 !      Enable the stop function.
2620        DISP "         Stop        - Stops data acquisition procedure."
2630        ON KEY 6 LABEL "Stop          SFK 6" GOTO Exit
2640 !
2650        Flag=0
2660        Cntr=0
2670 Main:  ! Do nothing loop while wating for data.
2680        IF Flag THEN
2690 !              If data is read then record it.
2700                Ctime=Cntr*Dt
2710                Cntr=Cntr+1
2720                CALL Tcconv(Tchan,Tcp(*),R(*),P(*),V(*))
2730                CALL Pitot(1,10,Pbar,V(*))
2740                CALL Printdata(Nchan,Cp(*),V(*),Ctime)
2750                FOR I=0 TO 19
2760                  Dat(I,Cntr)=V(I)
2770                  Sdat(I)=Sdat(I)+V(I)
2780                  Ssdat(I)=Ssdat(I)+(V(I)^2)
2790                NEXT I
2800                T(Cntr)=Ctime
2810                IF Ctime>=Tim THEN  GOTO Exit
2820                Flag=0
2830        END IF
2840        GOTO Main
2850 !
2860 Intrtn: ! Interrupt Routine
2870        P=SPOLL(409)
2880        IF P<>65 THEN  GOTO Main
2890        OUTPUT 409;"VT4 AE0 VS"
2900        FOR I=0 TO 19
2910          ENTER 409 USING "#,K";V(I)
2920        NEXT I
2930        Flag=1
2940        ENABLE INTR 4;4096   ! Enable Bit 12 of Interrupt Mask Register, SRQ
2950        OUTPUT 409;"VT2 AE1"
```

```
2960        RETURN
2970 Exit: !
2980 !      Reset HP 3497A data acquisition unit.
2990        CLEAR 409
3000        OUTPUT 409;"AR"   ! Analog Reset
3010    SUBEND
```

```
3020 !*********************************************************************
3030   SUB Initscrn(Nchan,Cp(*),Comment$(*),Unit$(*))
3040 !*********************************************************************
3050 !*                                                                   *
3060 !* Subroutine: Initscrn                      Written : June, 1987    *
3070 !*                                           Revised : October, 1987 *
3080 !*                                                                   *
3090 !*             A routine used to initialize the screen for output. It *
3100 !*             prepares the screen in a format compatible with the  *
3110 !*             subroutine Printdata.                                 *
3120 !*                                                                   *
3130 !* Hardware : HP 9000   - model 520 computer.                        *
3140 !*                                                                   *
3150 !*********************************************************************
3160 !
3170 ! Variable    Description                 Units              Range
3180 !---------------------------------------------------------------------
3190 ! Input
3200 !-------
3210 ! Nchan       Total # of channels.     ----------------   Nchan<=19
3220 ! Cp(*)       Channel pointer.         ----------------   0<=Cp<=19
3230 ! Comment$(*) Channel descriptions.    ----------------   max 40 chrs.
3240 ! Unit$(*)    Units of each channel.   ----------------   max 10 chrs.
3250 !---------------------------------------------------------------------
3260 !
3270 !      Set up the screen with a display of the channels in use.
3280 !      First print the header.
3290       PRINTER IS CRT
3300       PRINT PAGE
3310 !     PRINT USING "K,2X,K,35X,K,7X,K";"Channel","Description","Reading","
Units"
3320 !     PRINT USING "3X,K";"#"
3330 !     Then print the channel number, description, and units.
3340       FOR I=1 TO 19
3350         PRINT TABXY(0,I)
3360         PRINT USING "2X,DD,5X,K,20X,K";I-1,Comment$(I-1),Unit$(I-1)
3370       NEXT I
3380       PRINT TABXY(0,20)
3390       PRINT USING "9X,K,20X,K";Comment$(19),Unit$(19)
3400   SUBEND
```

```
3410 !**************************************************************************
3420   SUB Printdata(Nchan,Cp(*),V(*),Ctime)
3430 !**************************************************************************
3440 !*                                                                        *
3450 !* Subroutine: Printdata                          Written : June, 1987    *
3460 !*                                                Revised : October, 1987 *
3470 !*                                                                        *
3480 !*           A routine used to display data to the screen as it is       *
3490 !*           obtained from the data acquisition unit.  Note that the     *
3500 !*           screen should be initialized using the Initscrn routine.    *
3510 !*                                                                        *
3520 !* Hardware : HP 9000  - model 520 computer.                              *
3530 !*                                                                        *
3540 !**************************************************************************
3550 !
3560 ! Variable     Description                Units              Range
3570 !---------------------------------------------------------------------------
3580 ! Input
3590 !-------
3600 ! Nchan       Total # of channels.       ----------------   Nchan<=19
3610 ! Cp(*)       Channel pointer.           ----------------   0<=Cp<=19
3620 ! V(*)        Raw voltage data.          [volts]            -----------
3630 ! Ctime       Current time.              [seconds]          -----------
3640 !---------------------------------------------------------------------------
3650 !
3660 !     Display the new reading for each channel monitored.
3670      FOR I=1 TO Nchan
3680        V(Cp(I))=INT(V(Cp(I))*1000+.5)/1000
3690        PRINT TABXY(53,Cp(I)+1),V(Cp(I))
3700      NEXT I
3710 !    Also display the current time.
3720      PRINT TABXY(53,20),Ctime
3730   SUBEND
```

```
3740 !*************************************************************************
3750   SUB Initvar(Nchan,Tchan,Nplot,Cp(*),Tcp(*),Pcp(*),R(*),P(*),Comment$(*)
,Unit$(*),Y$(*),Title$(*))
3760 !*************************************************************************
3770 !*                                                                       *
3780 !* Subroutine: Initvar                           Written : June, 1987    *
3790 !*                                               Revised : October, 1987 *
3800 !*                                                                       *
3810 !*                An initialization routine used by Logdat to set up all *
3820 !*                initial values.                                        *
3830 !*                                                                       *
3840 !* Hardware : HP 9000  - model 520 computer.                             *
3850 !*                                                                       *
3860 !*************************************************************************
3870 !
3880 ! Variable     Description                 Units              Range
3890 !--------------------------------------------------------------------------
3900 ! Output
3910 !--------
3920 ! Nchan        Total # of channels.        ----------------   Nchan<=19
3930 ! Tchan        # of Temp. channels.        ----------------   Tchan<=9
3940 ! Nplot        # of plotted channels.      ----------------   Nplot<=Nchan
3950 ! Cp(*)        Channel pointer.            ----------------   0<=Cp<=19
3960 ! Tcp(*)       Temp. channel pointer.      ----------------   0<=Tcp<=19
3970 ! Pcp(*)       Plotted channel pointer..   ----------------   0<=Pcp<=19
3980 ! R(*)         T type T/C coeff.           Temp. -> Voltage   ------------
3990 ! P(*)         T type T/C coeff.           Voltage -> Temp.   ------------
4000 ! Comment$(*)  Channel descriptions.       ----------------   max 40 chrs.
4010 ! Unit$(*)     Units of each channel.      ----------------   max 10 chrs.
4020 ! Y$(*)        Axis labels (for plots).    ----------------   max 30 chrs.
4030 ! Title$(*)    Titles (for plots).         ----------------   max 30 chrs.
4040 !--------------------------------------------------------------------------
4050 !
4060 !      First set up the channel #'s and pointers.
4070       Nchan=6                           ! Total of 6 channels.
4080       Tchan=4                           ! 4 of the 6 are designated for T/C's.
4090       Nplot=2                           ! 2 of the 6 will be plotted.
4100       Cp(1)=0                           ! Channel  0: Printed.
4110       Cp(2)=Pcp(1)=1                    ! Channel  1: Printed, Plotted.
4120       Cp(3)=Tcp(1)=Pcp(2)=10            ! Channel 10: Printed, T/C, Plotted.
4130       Cp(4)=Tcp(2)=11                   ! Channel 11: Printed, T/C.
4140       Cp(5)=Tcp(3)=12                   ! Channel 12: Printed, T/C.
4150       Cp(6)=Tcp(4)=13                   ! Channel 13: Printed, T/C.
4160 !
4170 !     Also set up a description and units for each channel.
4180       Comment$(0)="Wind Speed (Validyne Output) ..........."
4190       Unit$(0)="[volts]"
4200       Comment$(1)="Wind Speed from Pitot-Tube ............."
4210       Unit$(1)="[m/s]"
4220       Comment$(2)="........................................"
4230       Unit$(2)="....."
4240       Comment$(3)="........................................"
4250       Unit$(3)="....."
4260       Comment$(4)="........................................"
4270       Unit$(4)="....."
4280       Comment$(5)="........................................"
4290       Unit$(5)="....."
4300       Comment$(6)="........................................"
```

```
4310    Unit$(6)="....."
4320    Comment$(7)="........................................"
4330    Unit$(7)="....."
4340    Comment$(8)="........................................"
4350    Unit$(8)="....."
4360    Comment$(9)="........................................"
4370    Unit$(9)="....."
4380    Comment$(10)="Air Temperature ......................."
4390    Unit$(10)="[deg C]"
4400    Comment$(11)="Circulating Water Temperature .........."
4410    Unit$(11)="[deg C]"
4420    Comment$(12)="Spraying Water Temperature ............."
4430    Unit$(12)="[deg C]"
4440    Comment$(13)="Nozzle Manifold Temperature ............"
4450    Unit$(13)="[deg C]"
4460    Comment$(14)="........................................"
4470    Unit$(14)="......."
4480    Comment$(15)="........................................"
4490    Unit$(15)="......."
4500    Comment$(16)="........................................"
4510    Unit$(16)="......."
4520    Comment$(17)="........................................"
4530    Unit$(17)="......."
4540    Comment$(18)="........................................"
4550    Unit$(18)="......."
4560    Comment$(19)="Elapsed Time ..........................."
4570    Unit$(19)="[sec]"
4580 !
4590 !  For those channels plotted include a description for each plot.
4600    Y$(1)="Windspeed [m/s]"
4610    Title$(1)="Windspeed vs Time"
4620    Y$(10)="Air Temperature [deg C]"
4630    Title$(10)="Air Temperature vs Time"
4640 !
4650 !  Also initialize R(*) and P(*) for use by the routine Tcconv.
4660    R(0)=5.257929840E-7
4670    R(1)=3.860071243E-5
4680    R(2)=4.186486602E-8
4690    P(0)=1.238117795E-1
4700    P(1)=2.686117637E4
4710    P(2)=-8.964942880E5
4720    P(3)=-4.648926088E7
4730    P(4)=1.244114245E10
4740    P(5)=2.275304922E12
4750    P(6)=-6.399496867E14
4760    P(7)=5.435757807E16
4770    P(8)=-2.023615370E18
4780    P(9)=2.830121167E19
4790 !
4800  SUBEND
```

```
4810 !***********************************************************************
4820   SUB Tcconv(Tchan,Tcp(*),R(*),P(*),V(*))
4830 !***********************************************************************
4840 !*                                                                     *
4850 !* Subroutine: Tcconv                          Written : June, 1987    *
4860 !*                                             Revised : October, 1987 *
4870 !*                                                                     *
4880 !*             A conversion routine used by Logdat to convert raw      *
4890 !*             voltage readings to temperatures. Note that the values  *
4900 !*             in the vector V(*) corresponding to the Tcp(*) channels *
4910 !*             will be altered by this routine.                        *
4920 !*                                                                     *
4930 !* Hardware : HP 9000   - model 520 computer.                          *
4940 !*                                                                     *
4950 !***********************************************************************
4960 !
4970 ! Variable     Description                  Units               Range
4980 !------------------------------------------------------------------------
4990 ! Input
5000 !-------
5010 ! Tchan        # of Temp. channels.         ----------------   Tchan<=9
5020 ! Tcp(*)       Temp. channel pointer.       ----------------   0<=Tcp<=19
5030 ! R(*)         T type T/C coeff.            Temp. -> Voltage   ------------
5040 ! P(*)         T type T/C coeff.            Voltage -> Temp.   ------------
5050 ! V(*)         Raw voltage data.            [volts]            ------------
5060 !------------------------------------------------------------------------
5070 ! Output
5080 !--------
5090 ! V(*)         Modified data.               [deg C]            ------------
5100 !------------------------------------------------------------------------
5110 !
5120      Tref=V(19)=10*V(19)
5130      Vref=R(0)+Tref*(R(1)+Tref*R(2))
5140      FOR I=1 TO Tchan
5150        Vt=V(Tcp(I))+Vref
5160        V(Tcp(I))=P(0)+Vt*(P(1)+Vt*(P(2)+Vt*(P(3)+Vt*(P(4)+Vt*(P(5)+Vt*(P
(6)+Vt*(P(7)+Vt*(P(8)+Vt*P(9)))))))))
5170      NEXT I
5180   SUBEND
```

```
5190 !************************************************************************
5200   SUB Pitot(Vchan,Tchan,Pbar,V(*))
5210 !************************************************************************
5220 !*                                                                      *
5230 !* Subroutine: Pitot                          Written : June, 1987      *
5240 !*                                            Revised : October, 1987   *
5250 !*                                                                      *
5260 !*          A conversion routine used by Logdat to convert raw          *
5270 !*          voltage readings to velocities.  Note that the value        *
5280 !*          in the vector V(*) corresponding to Vchan will be altered   *
5290 !*          by this routine.                                            *
5300 !*                                                                      *
5310 !* Hardware : HP 9000 - model 520 computer.                             *
5320 !*                                                                      *
5330 !************************************************************************
5340 !
5350 ! Variable    Description                    Units          Range
5360 !------------------------------------------------------------------------
5370 ! Input
5380 !-------
5390 ! Vchan       Channel being modified.        -------------  0<=Vchan<=19
5400 ! Tchan       Air temperature channel.       -------------  0<=Tchan<=19
5410 ! Pbar        Barometric pressure.           [mm Hg]        ------------
5420 ! V(*)        Raw voltage data.              [volts]        ------------
5430 !------------------------------------------------------------------------
5440 ! Output
5450 !--------
5460 ! V(*)        Modified data.                 [m/s]          ------------
5470 !------------------------------------------------------------------------
5480 !
5490 !      Perform conversion from voltage to velocity.
5500       IF V(Vchan)<0 THEN V(Vchan)=0        ! No negative voltages allowed.
5510       V(Vchan)=32.42624*SQR((V(Vchan)/3)*(V(Tchan)+273.15)/Pbar)
5520 !
5530   SUBEND
```

```
5540 !************************************************************************
5550   SUB Printres(Nprt,Pt(*),Cntr,Mean(*),Sdev(*),Comment$(*),Unit$(*),T$,D$
)
5560 !************************************************************************
5570 !*                                                                      *
5580 !* Subroutine: Printres                          Written : June, 1987    *
5590 !*                                               Revised : October, 1987 *
5600 !*                                                                      *
5610 !*              A printing routine used to print out the results of a   *
5620 !*              set of channels to the external printer, (Unit 401).    *
5630 !*                                                                      *
5640 !* Hardware : HP 9000   - model 520 computer.                           *
5650 !*            HP 2934A  - external printer, (Unit 401).                 *
5660 !*                                                                      *
5670 !************************************************************************
5680 !
5690 ! Variable      Description                 Units             Range
5700 !------------------------------------------------------------------------
5710 ! Input
5720 !-------
5730 ! Nprt          # of channels to print.     ---------------   Nprt<=19
5740 ! Pt(*)         Print channel pointer.      ---------------   0<=Pt<=19
5750 ! Cntr          Number of points taken.     ---------------   Cntr<=1400
5760 ! Mean(*)       Mean vector.                [m/s,deg C,etc.]  ------------
5770 ! Sdev(*)       Standard dev. vector.       [m/s,deg C,etc.]  ------------
5780 ! Comment$(*)   Channel descriptions.       ---------------   max 40 chrs.
5790 ! Unit$(*)      Units of each channel.      ---------------   max 10 chrs.
5800 ! T$            Time of day for test.       [Hrs:Mins:Secs]   ------------
5810 ! D$            Date of test.               [Day Month Year]  ------------
5820 !------------------------------------------------------------------------
5830 !
5840 !       Print header for table.
5850        PRINT USING "K,2X,K,32X,K,3X,K,6X,K";"Channel","Description","Avera
ge","Std Dev","Units"
5860        PRINT USING "3X,K";"#"
5870        PRINT
5880 !
5890 !       Print results for each channel specified by Nprt in Pt(*).
5900        FOR I=1 TO Nprt
5910          PRINT USING "2X,DD,5X,K,2X,DDDD.DDD,2X,DDDD.DDD,4X,K";Pt(I),Comme
nt$(Pt(I)),Mean(Pt(I)),Sdev(Pt(I)),Unit$(Pt(I))
5920        NEXT I
5930        PRINT
5940 !
5950 !       Also print; number of points, test time, time of day and date.
5960        PRINT USING "9X,K,1X,DDDDD,20X,K,2X,K";"Number of Data Points :",Cn
tr,"Date:",D$
5970        PRINT USING "9X,K,1X,DDDDD,1X,K,15X,K,2X,K";"Total Time of Test
:",(Cntr-1)*2,"sec.","Time:",T$
5980 !
5990   SUBEND
```

```
6000 !**********************************************************************
6010   SUB Plotit(X$,Y$,Title$,X(*),Y(*),Maxx,Size,Miny,Maxy)
6020 !**********************************************************************
6030 !*                                                                    *
6040 !* Subroutine: Plotit                        Written : June, 1987    *
6050 !*                                           Revised : October, 1987 *
6060 !*                                                                    *
6070 !*           A plotting routine used to plot the results from one    *
6080 !*           channel as a function of time to the screen.            *
6090 !*                                                                    *
6100 !* Hardware : HP 9000   - model 520 computer.                        *
6110 !*                                                                    *
6120 !**********************************************************************
6130 !
6140 ! Variable    Description               Units              Range
6150 !-----------------------------------------------------------------------
6160 ! Input
6170 !-------
6180 ! X$          X axis label.             ----------------   max 18 chrs.
6190 ! Y$          Y axis label.             ----------------   max 30 chrs.
6200 ! Title$      Title of plot.            ----------------   max 30 chrs.
6210 ! X(*)        X data vector.            [seconds]          ------------
6220 ! Y(*)        Y data vector.            [m/s,deg C,etc.]   ------------
6230 ! Maxx        Maximum X value.          [seconds]          ------------
6240 ! Size        Number of points.         ----------------   Size<=1400
6250 ! Miny        Minimum Y value.          [m/s,deg C,etc.]   ------------
6260 ! Maxy        Maximum Y value.          [m/s,deg C,etc.]   ------------
6270 !-----------------------------------------------------------------------
6280 !
6290 !      First determine the range to be used on the Y axis.
6300       IF PROUND(Miny,0)<=Miny THEN
6310                            Lowerlim=PROUND(Miny,0)
6320                            ELSE
6330                            Lowerlim=PROUND(Miny,0)-1
6340       END IF
6350       IF PROUND(Maxy,0)>Maxy THEN
6360                           Upperlim=PROUND(Maxy,0)
6370                           ELSE
6380                           Upperlim=PROUND(Maxy,0)+1
6390       END IF
6400 !     Then determine the range to be used on the X axis.
6410       IF PROUND(Maxx,1)>Maxx THEN
6420                           Utime=PROUND(Maxx,1)
6430                           ELSE
6440                           Utime=PROUND(Maxx,1)+10
6450       END IF
6460 !
6470 !      Set up the plot parameters.
6480       GINIT
6490       GCLEAR
6500       PLOTTER IS "GRAPHICS"
6510       GRAPHICS ON
6520       PEN 3
6530       VIEWPORT 20,100,20,90
6540       WINDOW 0,Utime,Lowerlim,Upperlim
6550       LAXES Utime/10,(Upperlim-Lowerlim)/10,0,Lowerlim
6560 !
6570 !     Plot the data.
```

```
6580        MOVE 0,0
6590        PEN 5
6600        PLOT X(1),Y(1),-2
6610        FOR I=2 TO Size
6620          PLOT X(I),Y(I),-1
6630        NEXT I
6640  !
6650  !     Reset the window in order to plot the labels.
6660        PEN 1
6670        VIEWPORT 0,100,0,90
6680        WINDOW -2,10,-4,45
6690  !     Label X axis.
6700        MOVE 4,-1
6710        LABEL X$
6720  !     Label Y axis.
6730        MOVE -1,10
6740        DEG
6750        LDIR 90
6760        LABEL Y$
6770  !     Label the title.
6780        MOVE 3,47
6790        LDIR 0
6800        LABEL Title$
6810  !
6820    SUBEND
```

Appendix C

Data Acquisition Software

KING_LWC_2.01

```
10 ! KING_LWC_2.01
20 !************************************************************************
30 !*                                                                      *
40 !* Program : KING_LWC_2.01                    Written : June, 1987      *
50 !*                                            Revised : October, 1987   *
60 !*                                                                      *
70 !*              A data acquisition program used to acquire information  *
80 !*              from the C.S.I.R.O. King liquid water content probe.    *
90 !*                                                                      *
100 !* Hardware : HP 9000    - model 520 computer.                          *
110 !*            HP 3497A   - data acquisition unit.                       *
120 !*            HP 2934A   - external printer, (Unit 401)                 *
130 !*            PMS        - C.S.I.R.O. King liquid water content probe.  *
140 !*                                                                      *
150 !* Blocks : Init  - Initialization procedures.                          *
160 !*          Main  - Main menu set up and control.                       *
170 !*          Dryp  - Dry power measurements.                             *
180 !*                  Startdry - Start of dry measurements.               *
190 !*                  Stopdry  - End of dry measurements.                 *
200 !*                  Ratedry  - Dry measurement rate control.            *
210 !*          Wetp  - Wet power measurements.                             *
220 !*                  Startwet - Start of wet measurements.               *
230 !*                  Stopwet  - End of wet measurements.                 *
240 !*                  Ratewet  - Wet measurement rate control.            *
250 !*          Plot  - Plotting and printing of results.                   *
260 !*                  Plotdata - Plot of L.W.C. vs time.                  *
270 !*                  Plotfreq - Plot of frequency vs L.W.C..             *
280 !*                  Dumpplot - Transfers data plot to printer.          *
290 !*                  Dumprint - Prints results to external printer.      *
300 !*                  Nextplot - Transfers freq. plot to printer.         *
310 !*                  Setrange - Controls the range plotted.              *
320 !*          Quit  - Program termination.                                *
330 !*                                                                      *
340 !* Subroutines : Plotit - used to plot results.                         *
350 !*                                                                      *
360 !************************************************************************
370 !
380 ! Variable     Description                  Units               Range
390 !-------------------------------------------------------------------------
400 ! Input
410 !-------
420 ! Testnum      Test number.                 ---------------     -----------
430 ! Vel          Air velocity.                [m/s]               -----------
440 ! Temp         Air temperature.             [deg C]             -----------
450 ! Dryrate      Data acq. rate (Dry).        [samples/sec.]      Dryrate<=40
460 ! Perioddry    1/Dryrate.                   [100 micro-sec.]    -----------
470 ! Vdrytot      Sum of dry voltages.         [volts]             -----------
480 ! Vdry         Dry voltage reading.         [volts]             -----------
490 ! Startdry     Start time of dry meas.      [seconds]           -----------
500 ! Elapseddry   Elapsed time.                [seconds]           -----------
510 ! Actdryrate   True dry data acq. rate.     [samples/sec.]      -----------
520 ! Wetrate      Data acq. rate (Wet).        [samples/sec.]      Wetrate<=40
530 ! Periodwet    1/Wetrate.                   [100 micro-sec.]    -----------
540 ! Vwet         Wet voltage reading.         [volts]             -----------
550 ! Constant     Conversion constant.         Volts -> LWC        -----------
560 ! Lwc(*)       L.W.C. data vector.          [g/m 3]             -----------
570 ! Lwctot       Sum of LWC measurements.     [g/m 3]             -----------
580 ! Lwc2tot      Sum of sqrs of LWC meas.     [(g/m 3) 2]         -----------
```

```
590 ! Numpoints      Number of LWC meas.         ----------------  ------------
600 ! Lwc            Mean LWC measured.          [g/m 3]           ------------
610 ! Sdevlwc        Std. dev. of LWC meas.      [g/m 3]           ------------
620 ! Startwet       Start time of wet meas.     [seconds]         ------------
630 ! Elapsedwet     Elapsed time.               [seconds]         ------------
640 ! Actwetrate     True wet data acq. rate.    [samples/sec.]    ------------
650 ! Tempx(*)       X axis plotting vector.     ----------------  ------------
660 ! Tempy(*)       Y axis plotting vector.     ----------------  ------------
670 ! Temppen(*)     Pen control for plots.      ----------------  ------------
680 ! X$             X axis label.               ----------------  max 18 chrs.
690 ! Y$             Y axis label.               ----------------  max 18 chrs.
700 ! Title$         Used for plot titles.       ----------------  max 25 chrs.
710 ! Duration       Test time (rounded up).     [seconds]         ------------
720 ! Xmin           Min. LWC in freq. plot.     [g/m 3]           Xmin>=0
730 ! Xmax           Max. LWC in freq. plot.     [g/m 3]           Xmax>Xmin
740 ! Ymin           Minimum LWC value used.     [g/m 3]           ------------
750 ! Ymax           Maximum LWC value used.     [g/m 3]           Ymax>Ymin
760 ! Xtic           X axis tick marks.          ----------------  ------------
770 ! Ytic           Y axis tick marks.          ----------------  ------------
780 ! Numbins        # of bins in freq. plot.    ----------------  Numbins>=0
790 ! Binsize        Size of each bin.           [g/m 3]           ------------
800 ! Db             Binsize/2                   [g/m 3]           ------------
810 ! Freqmin        Min. freq. of LWC value.    ----------------  Freqmin>=0
820 ! Freqmax        Max. freq. of LWC value.    ----------------  Freqmax>Freqmin
830 ! Dumpflag       Indicates print status.     ----------------  0 or 1
840 !-------------------------------------------------------------------------
850 !
860 Init: ! Initialization procedures.
870         DIM Lwc(1:4000),Tempx(1:4000),Tempy(1:4000),Tempen(1:4000),Title$[2
5]
880         Dryrate=40
890         Perioddry=10000/Dryrate
900         Wetrate=40
910         Periodwet=10000/Wetrate
920 E_init: !
930 Main: !
940         OFF KEY
950         PRINTER IS CRT
960         PRINT PAGE ! Clear the screen
970         PRINT "               C.S.I.R.O. King Probe L.W.C. Measurement Progr
am"
980         PRINT
990         PRINT "Dry Power - measures the dry power, (baseline voltage)."
1000        PRINT "Wet Power - measures the wet and dry power as a function
 of time."
1010        PRINT "Plot LWC  - plots the L.W.C. as a function of time."
1020        PRINT "Main Menu - returns control to this menu."
1030        PRINT "Quit      - stops the program."
1040        ON KEY 3 LABEL "Dry Power   SFK 3" GOTO Dryp
1050        ON KEY 4 LABEL "Wet Power   SFK 4" GOTO Wetp
1060        ON KEY 5 LABEL "Plot LWC    SFK 5" GOTO Plot
1070        ON KEY 6 LABEL "Main Menu   SFK 6" GOTO Main
1080        ON KEY 7 LABEL "Quit        SFK 7" GOTO Quit
1090        INPUT "Please enter test number.",Testnum
1100        Testnum=Testnum-1
1110        INPUT "Wind velocity ? (m/s]",Vel
1120        INPUT "Air temperature ? (degrees C]",Temp
1130        GOTO Dryp
1140 E_main: !
```

```
1150 Dryp: !
1160      O[illegible]
1170      PR[illegible] CRT
1180      PR[illegible]E ! Clear the screen
1190      PR[illegible]              Dry Power (baseline voltage) Measurement"
1200      PRI[illegible]
1210      PRINT "Start     - starts the dry power measurement."
1220      PRINT "Stop      - stops the dry power masurement."
1230      PRINT "Rate      - to change the sampling rate, currently: ";Dry
rate;" measurements/sec."
1240      ON KEY 0 LABEL "Start       SFK 0" GOTO Startdry
1250      ON KEY 1 LABEL "Stop        SFK 1" GOTO Stopdry
1260      ON KEY 2 LABEL "Rate        SFK 2" GOTO Ratedry
1270      ON KEY 6 LABEL "Main Menu   SFK 6" GOTO Main
1280      ON KEY 7 LABEL "Quit        SFK 7" GOTO Quit
1290      WAIT
1300 Startdry: !
1310          PRINT PAGE
1320          Vdrytot=0
1330          CLEAR 409
1340          OUTPUT 409;"VF1 SD0 AC00 VA0 VR5 VD3 VT4 TO";Perioddry
1350          OUTPUT 409;"VT2"
1360          Startdry=TIMEDATE
1370          FOR I=1 TO 4000
1380            ENTER 409;Vdry
1390            Vdry=-Vdry
1400            DISP USING "#,K,DDD.DDD,K,/";"The dry voltage reading is: ";V
dry;" volts"
1410            Vdrytot=Vdrytot+Vdry
1420          NEXT I
1430 E_startdry: !
1440 Stopdry: !
1450         Elapseddry=TIMEDATE-Startdry
1460         CLEAR 409
1470         Vdry=Vdrytot/I
1480         DISP "
1490         PRINT USING "#,K,DDDD,K,DDD.DDD,K";"The average dry voltage over
";I;" readings is: ";Vdry;" volts"
1500         PRINT
1510         Actdryrate=I/Elapseddry
1520         PRINT USING "#,K,DDD.DD,K";"The actual sampling rate was ";Actdr
yrate;" measurements/sec."
1530         WAIT 5
1540         DISP "
"
1550         GOTO Wetp
1560 E_stopdry: !
1570 Ratedry: !
1580         PRINT PAGE
1590         INPUT "What sampling rate do you want ? [2-49 measurements/sec]"
,Dryrate
1600         Perioddry=10000/Dryrate
1610         GOTO Dryp
1620 E_ratedry: !
1630 E_dryp: !
```

```
1640 Wetp: !
1650        OFF KEY
1660        Ymin=0
1670        Ymax=6
1680        PRINTER IS CRT
1690        PRINT PAGE ! Clear the screen
1700        PRINT "          Wet and Dry Power Measurement"
1710        [illegible]
1720        PRINT "Start    - starts the wet and dry power measurement."
1730        PRINT "Stop     - stops the wet and dry power measurement."
1740        PRINT "Rate     - to change the sampling rate, currently: ";Wet
rate;" measurement/sec."
1750        ON KEY 0 LABEL "Start        SFK 0" GOTO Startwet
1760        ON KEY 1 LABEL "Stop         SFK 1" GOTO Stopwet
1770        ON KEY 2 LABEL "Rate         SFK 2" GOTO Ratewet
1780        ON KEY 6 LABEL "Main Menu    SFK 6" GOTO Main
1790        ON KEY 7 LABEL "Quit         SFK 7" GOTO Quit
1800        WAIT
1810 Startwet: !
1820             PRINT PAGE
1830             Lwctot=0
1840             Lwc2tot=0
1850             Constant=10/(3.74E-5*Vel*(2256+4.1868*(90-Temp)))
1860             CLEAR 409
1870             OUTPUT 409;"VF1 SD0 AC00 VA0 VR5 VD3 VT4 TO";Periodwet
1880             OUTPUT 409;"VT2"
1890             Startwet=TIMEDATE
1900             FOR I=1 TO 4000
1910               ENTER 409;Vwet
1920               Vwet=-Vwet
1930               Lwc(I)=Constant*(Vwet-Vdry)
1940               DISP USING "#,K,DDD.DDD,K,/";"The L.W.C. reading is: ";Lwc(I)
;" grams/m 3"
1950               Lwctot=Lwctot+Lwc(I)
1960               Lwc2tot=Lwc2tot+(Lwc(I) 2)
1970             NEXT I
1980 E_startwet: !
1990 Stopwet: !
2000            Elapsedwet=TIMEDATE-Startwet
2010            CLEAR 409
2020            DISP "
2030            Numpoints=I
2040            Lwc=Lwctot/I
2050            Sdevlwc=SQR(((Numpoints*Lwc2tot)-(Lwctot 2))/(Numpoints*(Numpoin
ts-1)))
2060            PRINT USING "#,K,DDDDD,K,DDD.DDD,K";"The average L.W.C. over ";N
umpoints;" readings is: ";Lwc;" grams/m 3"
2070            PRINT
2080            Actwetrate=Numpoints/Elapsedwet
2090            PRINT USING "#,K,DDD.DD,K";"The actual sampling rate was ";Actwe
trate;" measurements/sec"
2100            WAIT 5
2110            PRINT PAGE
2120            Testnum=Testnum+1
2130            GOTO Plot
2140 E_stopwet: !
2150 Ratewet: !
2160            PRINT PAGE
```

```
2170          INPUT "What sampling rate do you want ? [2-49 measurements/sec]"
,Wetrate
2180          Periodwet=10000/Wetrate
2190          GOTO Wetp
2200 E_ratewet: !
2210 E_wetp: !
```

```
2220 Plot: !
2230      OFF KEY
2240      PRINTER IS CRT
2250      PRINT PAGE ! Clear the screen
2260      PRINT "           Plot of L.W.C. Versus Time"
2270      PRINT
2280      PRINT "Plot Data - plots the L.W.C. data versus time."
2290      PRINT "Plot Freq - plots the frequency distribution of L.W.C."
2300      PRINT "Dump Plot - dumps plots to printer."
2310      PRINT "Alter Rng - alter the range of L.W.C. data plotted."
2320      ON KEY 0 LABEL "Plot Data   SFK 0" GOTO Plotdata
2330      ON KEY 1 LABEL "Plot Freq   SFK 1" GOTO Plotfreq
2340      ON KEY 2 LABEL "Dump Plot   SFK 2" GOTO Dumplot
2350      ON KEY 3 LABEL "Alter Rng   SFK 3" GOTO Setrange
2360      ON KEY 6 LABEL "Main Menu   SFK 6" GOTO Main
2370      ON KEY 7 LABEL "Quit        SFK 7" GOTO Quit
2380      WAIT
2390 Plotdata: !
2400           PRINTER IS CRT
2410           FOR I=1 TO Numpoints
2420             Tempx(I)=PROUND((I-1)/Actwetrate,-3)
2430             Tempy(I)=PROUND(Lwc(I),-2)
2440             IF I=1 OR I=Numpoints THEN
2450                     Tempen(I)=-2
2460                     ELSE
2470                     Tempen(I)=-1
2480                     END IF
2490           NEXT I
2500           PRINT PAGE
2510           GINIT
2520           GCLEAR
2530           GRAPHICS ON
2540           IF PROUND(Tempx(Numpoints),1)<Tempx(Numpoints) THEN
2550                                                      Duration=PROUND(T
empx(Numpoints),1)+10
2560                                                      ELSE
2570                                                      Duration=PROUND(T
empx(Numpoints),1)
2580           END IF
2590           X$="Time [sec]"
2600           Y$="L.W.C. [grams/m 3]"
2610           Title$="L.W.C. versus Time"
2620           Xtic=PROUND((Duration)/10,0)
2630           IF (Ymax-Ymin)<=1 THEN
2640                          Ytic=PROUND((Ymax-Ymin)/(10*Ymax),-1)
2650                          ELSE
2660                          Ytic=PROUND((Ymax-Ymin)/Ymax,0)
2670                          END IF
2680           CALL Plot(Tempx(*),Tempy(*),Tempen(*),0,Duration,Ymin,Ymax,Xtic
,Ytic,Numpoints,X$,Y$,Title$)
2690           IF Dumpflag=1 THEN  GOTO Nextplot
2700           PRINT TABXY(-.4,0);"PRESS"
2710           PRINT "CONTINUE"
2720           PRINT "TO"
2730           PRINT "PROCEED"
2740           PAUSE
2750           GRAPHICS OFF
2760           GOTO Plot
```

```
2770 E_plotdata: !
2780 Plotfreq: !
2790          PRINTER IS CRT
2800          Numbins=(Ymax-Ymin)*10
2810          Binsize=.1
2820          Db=Binsize/2
2830          Xmin=Ymin
2840          Xmax=Ymax
2850          Freqmin=0
2860          FOR I=1 TO Numbins
2870            Tempx(I)=Binsize*(I-.5)
2880            Tempy(I)=0
2890            FOR J=1 TO Numpoints
2900              IF Lwc(J)<Tempx(I)+Db AND Lwc(J)>Tempx(I)-Db THEN
2910                                                               Tempy(I)=Tempy
(I)+1
2920              END IF
2930            NEXT J
2940            PRINT Tempy(I)
2950            IF I=1 THEN
2960                   Tempen(I)=-2
2970                   Freqmax=Tempy(I)
2980                   ELSE
2990                   Tempen(I)=-1
3000                   Freqmax=MAX(Tempy(I),Freqmax)
3010            END IF
3020          NEXT I
3030          PRINT PAGE
3040          GINIT
3050          GCLEAR
3060          GRAPHICS ON
3070          X$="L.W.C. [grams/m 3]"
3080          Y$="Frequency [#]"
3090          Title$="Frequency versus L.W.C."
3100          IF PROUND(Freqmax,2)<Freqmax THEN
3110                                          Freqmax=PROUND(Freqmax,2)+100
3120                                          ELSE
3130                                          Freqmax=PROUND(Freqmax,2)
3140                                          END IF
3150          IF (Ymax-Ymin)<=1 THEN
3160                                Xtic=PROUND((Ymax-Ymin)/(10*Ymax),-1)
3170                                ELSE
3180                                Xtic=PROUND((Ymax-Ymin)/Ymax,0)
3190                                END IF
3200          Ytic=PROUND((Freqmax-Freqmin)/(Freqmax/100),2)
3210          CALL Plot(Tempx(*),Tempy(*),Tempen(*),Xmin,Xmax,Freqmin,Freqmax
,Xtic,Ytic,Numbins,X$,Y$,Title$)
3220          IF Dumpflag=1 THEN  GOTO Dumprint
3230          PRINT TABXY(-.4,0);"PRESS"
3240          PRINT "CONTINUE"
3250          PRINT "TO"
3260          PRINT "PROCEED"
3270          PAUSE
3280          GRAPHICS OFF
3290          GOTO Plot
3300 E_plotfreq: !
3310 Dumplot: !
3320          Dumpflag=1
3330          PRINTER IS 401
3340          PRINT "L.W.C. Results Using King Probe"
```

```
3350          PRINT "Test number ";Testnum
3360          GOTO Plotdata
3370 E_dumplot: !
3380 Nextplot: !
3390           GRAPHICS OFF
3400           PRINTER IS CRT
3410           PRINT PAGE
3420           PRINT "L.W.C. versus Time graph currently being printed."
3430           PRINT "                                          Please Wait"
3440           DUMP GRAPHICS  TO 401
3450           GOTO Plotfreq
3460 E_nextplot: !
3470 Dumprint: !
3480           GRAPHICS OFF
3490           PRINTER IS CRT
3500           PRINT PAGE
3510           PRINT "Freq. versus L.W.C. graph currently being printed."
3520           PRINT "                                          Please Wait"
3530           PRINTER IS 401
3540           DUMP GRAPHICS  TO 401
3550           PRINT
3560           PRINT USING "#,K,DDDD,K,DDD.DDD,K,/";"Mean L.W.C. over ";Numpoi
nts;" readings = ";Lwc;" grams/m 3"
3570           PRINT USING "#,K,DDD.DDD,K,/";"Standard deviation of L.W.C. =";
Sdlwc;" grams/m 3"
3580           PRINT PAGE;
3590           PRINTER IS CRT
3600           Dumpflag=0
3610           GOTO Plot
3620 E_dumprint: !
3630 Setrange: !
3640           PRINT PAGE
3650           PRINT "The current LWC range being plotted is :";Ymin;"-";Ymax
3660           INPUT "Enter a new range or Return to leave unchanged (min,ma
x)",Ymin,Ymax
3670           GOTO Plot
3680 E_setrange: !
3690 E_plot: !

3700 Quit: !
3710        PRINTER IS CRT
3720        PRINT PAGE
3730        PRINT "Program execution terminated."
3740        END
3750 E_quit: !
```

```
3760 !*************************************************************************
3770  SUB Plot(X(*),Y(*),Pen(*),Xmin,Xmax,Ymin,Ymax,Xtic,Ytic,Size,Xlab$,Ylab$
,Title$)
3780 !*************************************************************************
3790 !*                                                                        *
3800 !* Subroutine: Plot                          Written : June, 1987         *
3810 !*                                           Revised : October, 1987      *
3820 !*                                                                        *
3830 !*              A plotting routine used to plot the results obtained      *
3840 !*              from the King probe to the screen.                        *
3850 !*                                                                        *
3860 !* Hardware : HP 9000   - model 520 computer.                             *
3870 !*                                                                        *
3880 !*************************************************************************
3890 !
3900 ! Variable     Description                    Units            Range
3910 !-------------------------------------------------------------------------
3920 ! Input
3930 !-------
3940 ! X(*)         X data vector.                 ---------------  -----------
3950 ! Y(*)         Y data vector.                 ---------------  -----------
3960 ! Pen(*)       Pen control vector.            ---------------  -----------
3970 ! Xmin         Min. X value.                  ---------------  -----------
3980 ! Xmax         Max. X value.                  ---------------  Xmax>Xmin
3990 ! Ymin         Min. Y value.                  ---------------  -----------
4000 ! Ymax         Max. Y value.                  ---------------  Ymax>Ymin
4010 ! Xtic         X axis tick marks.             ---------------  -----------
4020 ! Ytic         Y axis tick marks.             ---------------  -----------
4030 ! Size         Number of ponts to plot.       ---------------  -----------
4040 ! Xlab$        X axis label.                  ---------------  max 18 chrs.
4050 ! Ylab$        Y axis label.                  ---------------  max 18 chrs.
4060 ! Title$       Title of plot.                 ---------------  max 25 chrs.
4070 !-------------------------------------------------------------------------
4080 !
4090      GINIT
4100      PEN 3
4110      VIEWPORT 25,100,20,90
4120      WINDOW Xmin,Xmax,Ymin,Ymax
4130      LAXES Xtic,Ytic,Xmin,Ymin
4140      MOVE 0,0
4150      PEN 5
4160      PLOT X(1:Size),Y(1:Size),Pen(1:Size)
4170      PEN 1
4180      VIEWPORT 0,100,0,90
4190      WINDOW -2,10,-4,45
4200      MOVE 3,48
4210      LABEL Title$
4220      MOVE [illegible],-1
4230      LABEL Xlab$
4240      MOVE -1,15
4250      DEG
4260      LDIR 90
4270      LABEL Ylab$
4280      SUBEND
```

Appendix D

Data Acquisition Software

OAP_DRIVER_2.01

```
10 ! OAP_DRIVER_2.01
20 !*************************************************************************
30 !*                                                                       *
40 !* Program : OAP_DRIVER_2.01                  Written : July, 1987       *
50 !*                                            Revised : October, 1987    *
60 !*                                                                       *
70 !*         A data acquisition and analysis program for use with          *
80 !*         the PMS optical array precipitation probe.                    *
90 !*                                                                       *
100 !* Hardware : HP [illegible] - [illegible] 520 computer.                 *
110 !*            [illegible] - external printer, (Unit 401).                *
120 !*            PMS OAP-200X - optical array precipitation probe.          *
130 !*            [illegible] - stand alone smart probe.                     *
140 !*                                                                       *
150 !* Blocks : Startdata   - initialization of OAP for data acquisition.    *
160 !*          Stopdata    - output of final results.                       *
170 !*          Starttaking - data checking, acquisition and analysis.       *
180 !*                        Checkdata - Checks are made to insure data     *
190 !*                                    communication is correct.         *
200 !*                        Takingdata - data acquisition.                 *
210 !*                        Analysis   - data analysis.                    *
220 !*          Quit        - end of main program.                           *
230 !*                                                                       *
240 !* Subroutines : Oapinit - initializes OAP for proprer communication.    *
250 !*               Calc    - calculates LWC and MVD for a set of data.     *
260 !*               Spline  - cubic spline (used in MVD calculation).       *
270 !*               Oapvar  - initializes the OAP variables (bin size...).  *
280 !*               Plotit  - plots final results.                          *
290 !*                                                                       *
300 !*************************************************************************
310 !
320 ! Variable      Description               Units            Range
330 !-------------------------------------------------------------------------
340 ! Oapdata$(*)   Serial data from OAP.     ---------------  max 80 chrs.
350 ! Ti$           Actual time interval.     ---------------  max 80 chrs.
360 ! N(*)          # of drops/bin (raw).     [#]              -----------
370 ! Nc(*)         # of drops/bin (cor).     [#]              -----------
380 ! D(*)          Drop size for each bin.   [microns]        -----------
390 ! Sa(*)         Sampling area.            [mm 2]           -----------
400 ! Binl(*)       Left edge of each bin.    [microns]        -----------
410 ! Binr(*)       Right edge of each bin.   [microns]        -----------
420 ! Lwc(*)        LWC for each time T.      [g/m 3]          -----------
430 ! Mvd(*)        MVD for each time T.      [microns]        -----------
440 ! Tim(*)        Time T.                   [seconds]        -----------
450 ! X$            X axis label.             ---------------  max 40 chrs.
460 ! Y$            Y axis label.             ---------------  max 40 chrs.
470 ! Title$        Title of plot.            ---------------  max 40 chrs.
480 ! Rho           Density of water.         [Kg/m 3]         -----------
490 ! Windspeed     Wind speed in test sect.  [m/s]            -----------
500 ! Tsamp         Sample interval.          [seconds]        Tsamp>=1
510 ! Ttot          Total sample time.        [minutes]        -----------
520 ! Digit         # of digits used by OAP.  Digit=4          Do not alter.
530 ! Sat           Total sample area.        75.64 mm 2       Do not alter.
540 ! Numbins       Number of bins.           Numbins=62       Do not alter.
550 !-------------------------------------------------------------------------
560 !
570 !
580 !
```

```
590 ! Dimension all Variables.
600   DIM Oapdata$(24)[80],Ti$[80],N(63),Nc(62)
610   DIM X$[40],Y$[40],Title$[40]
620   DIM D(62),Sa(62),Binl(64),Binr(62)
630   DIM Lwc(1000),Mvd(1000),Tim(1000)
640 !
650 ! Initialize all Variables.
660   CALL Oapvar(D(*),Sa(*),Binl(*),Binr(*))
670   Rho=999.8                ! Density of Water [kg/m 3]
680   Windspeed=10             ! [m/s].
690   Tsamp=1
700   Digit=4
710   Sat=61*1.24
720   Numbins=62
730 !
740 ! Input Sample Time and Windspeed.
750   INPUT "Current Windspeed ? [m/s]",Windspeed
760   INPUT "Sample Interval ? [sec]",Tsamp
770   INPUT "Total Sample Time ? [min]",Ttot
780   Ttot=Ttot*60
790   Ttot=Ttot-1
800 !
810 ! Display Menu for Controling OAP.
820    PRINTER IS CRT
830    PRINT PAGE
840    GINIT
850    GCLEAR
860    GRAPHICS ON
870    OFF KEY
880    ON KEY 0 LABEL "Start       SFK 0" GOTO Startdata
890    WAIT
900 !
910 Startdata: !
920    T=0
930    CALL Oapinit(Tsamp)
940    Stime=TIMEDATE
950    OFF KEY
960    ON KEY 0 LABEL "Stop        SFK 0" GOTO Stopdata
970    First=1
980    GOTO Starttaking
990 !
1000 Stopdata: !
1010   OUTPUT 3;"ES"          ! End Sampling Data.
1020   DISABLE INTR 3
1030   OFF INTR
1040   OFF KEY
1050 !
1060 ! Calculate statistics for LWC and MVD data.
1070   Lwctot=Mvdtot=0
1080   Lwc2=Mvd2=0
1090   Cmvd=0
1100   FOR I=1 TO Cntr
1110     Lwctot=Lwctot+Lwc(I)
1120     Lwc2=Lwc2+Lwc(I) 2
1130     IF Mvd(I)=0 THEN  GOTO 1170
1140     Cmvd=Cmvd+1
1150     Mvdtot=Mvdtot+Mvd(I)
1160     Mvd2=Mvd2+Mvd(I) 2
1170   NEXT I
1180   Lwc=Lwctot/Cntr
```

```
1190    Mvd=Mvdtot/Cmvd
1200    Lwcdev=SQR((Lwc2-Cntr*(Lwc^2))/(Cntr-1))
1210    Mvddev=SQR((Mvd2-Cmvd*(Mvd^2))/(Cmvd-1))
1220  !
1230  ! Print out mean and std. dev. for LWC and MVD.
1240    PRINTER IS 401
1250    PRINT USING "6X,K,K,6X,K,K";"Date : ";DATE$(Stime);"Time : ";TIME$(Sti
me)
1260    PRINT
1270    PRINT USING "30X,K,5X,K,5X,K";"Mean";"Std. Dev.";"Units"
1280    PRINT USING "K,DDDDDD.DD,5X,DDDDDD.DD,4X,K";"Liquid Water Content  :
";Lwc;Lwcdev;" g/m^3"
1290    PRINT USING "K,DDDDDD.DD,5X,DDDDDD.DD,4X,K";"Median Volume Diameter :
";Mvd;Mvddev;" um"
1300    PRINT
1310    PRINT
1320    PRINT
1330    PRINTER IS CRT
1340  !
1350  ! Plot LWC vs Time.
1360    X$="Time [sec]"
1370    Y$="Liquid Water Content [g/m^3]"
1380    Title$="L.W.C. vs Time"
1390    Maxlwc=MAX(Lwc(*))
1400    CALL Plotit(1,X$,Y$,Title$,Tim(*),Lwc(*),Tim(Cntr),Cntr,0,Maxlwc)
1410    DUMP GRAPHICS  TO 401
1420  !
1430  ! Plot MVD vs Time.
1440    Y$="Median Volume Diameter [um]"
1450    Title$="M.V.D. vs Time"
1460    Maxmvd=MAX(Mvd(*))
1470    CALL Plotit(2,X$,Y$,Title$,Tim(*),Mvd(*),Tim(Cntr),Cntr,0,Maxmvd)
1480    DUMP GRAPHICS  TO 401
1490  !
1500    GOTO Quit
1510 Starttaking: !
1520  ! Read Data From Serial Port as it is Received.
1530    Cntr=0
1540    Checking=1
1550    I=1
1560    WHILE Checking
1570      Oapdata$(I)=""
1580      ENTER 3;Oapdata$(I)
1590      PRINT Oapdata$(I)
1600      IF Oapdata$(I)="" AND I>=7 THEN  GOSUB Checkdata
1610      I=I+1
1620    END WHILE
1630    Ndat=I-1
1640    GOTO Analysis
1650 Checkdata: ! To insure that OAP communication is correct.
1660    Ti$=Oapdata$(I-5)
1670    Ti=VAL(Ti$[15,80])
1680    IF Ti=Tsamp THEN Checking=0
1690    RETURN
1700 Takingdata: !
1710    FOR I=1 TO 7
1720      ENTER 3;Oapdata$(I)
1730    NEXT I
1740    Ndat=I-1
1750 Analysis: !
```

```
1760 ! Convert Data String into Numerical Values.
1770   Total=0
1780   FOR I=Ndat-4 TO Ndat-1
1790     K=I-(Ndat-4)+3
1800       FOR J=1 TO 16
1810         IF ((K*16-49)+J)=63 THEN  GOTO 1850
1820         Temp$=Oapdata$(I)[(J*Digit)+(J-1)-3,(J*Digit)+(J-1)]
1830         N((K*16-49)+J)=VAL(Temp$)
1840         Total=Total+N((K*16-49)+J)
1850       NEXT J
1860     NEXT I
1870     Total=Total-N(0)-N(1)
1880     Ti$=Oapdata$(Ndat-5)[15,80]
1890     Ti=VAL(Ti$)
1900     T=T+Ti
1910     PRINT Total
1920   ! Statistical Correction of Droplet Totals in each Bin.
1930     FOR I=1 TO Numbins
1940       Nc(I)=(N(I)/Sa(I))*Sat
1950     NEXT I
1960     CALL Calc(Total,Numbins,Nc(*),D(*),Sat,Rho,Windspeed,Ti,Lwc,Mvd)
1970     PRINT T
1980     PRINT USING "K,DDDDDD.DD,K";"Liquid Water Content = ";Lwc;" g/m 3"
1990     PRINT USING "K,DDDDDD.DD,K";"Median Volume Diameter = ";Mvd;" um"
2000     Cntr=Cntr+1
2010     Lwc(Cntr)=Lwc
2020     Mvd(Cntr)=Mvd
2030     Tim(Cntr)=T
2040     IF Tim(Cnt[illegible]tot THEN  GOTO Stopdata
2050     GOTO Takingdata
2060 Quit: !
2070     STOP
2080     END
```

```
10000  SUB Oapinit(Tsamp)
10010    ! Setup Serial Port for OAP Communication.
10020      Handshake=IVAL("01100010",2)
10030      Enableshake=IVAL("10000000",2)
10040      Bitsperchar=7          ! 7 bits per character.
10050      Check=2                ! Even parity.
10060      Stopbits=1             ! 1 stop bits.
10070      RESET 3                ! Sets Serial Port to Power On Condition.
10080      ASSIGN @D TO 3;DRIVER "SERIAL"
10090      CONTROL @D,526;1                          ! Host Enq/Ack
10100      CONTROL @D,527;Bitsperchar-5              ! Set Bits per Character
10110      CONTROL @D,529;Check                      ! Set Parity
10120      CONTROL @D,528;Stopbits*2-2               ! Set # of Stop Bits
10130      CONTROL @D,562;1                          ! Flush Buffer
10140      CONTROL @D,505;1                          ! Set RTS
10150      CONTROL @D,506;1                          ! Set DTR
10160      CONTROL @D,560;2                          ! Transmission Mode
10170    !
10180    ! Initialize OAP Control Variables.
10190      Curtime$=TIME$(TIMEDATE)
10200      Oaptime$=Curtime$[1,2]&Curtime$[4,5]&Curtime$[7,8]
10210      Sampint$=VAL$(Tsamp)
10220      Digit=4
10230      Digits$=VAL$(Digit)
10240      OUTPUT 3;"ES"
10250      CONTROL @D,562;3
10260      OUTPUT 3;"BD 000000"       ! Synchronize OAP with HP Current Time.
10270      OUTPUT 3;"SI "&Sampint$    ! Sample Interval.
10280      OUTPUT 3;"MN "&Digits$     ! Maximum Number of Digits.
10290      ASSIGN @D TO *
10300  SUBEND
```

```
11000 SUB Calc(Total,Numbins,Nc(*),D(*),Sat,Rho,Windspeed,Samptime,Lwc,Mvd)
11010     DIM Cumvw(62),Bs(62),Cs(62),Ds(62),X(62),Y(62)
11020   ! Calculation of Lwc
11030     Vwtot=0.
11040     FOR I=1 TO Numbins
11050       Vw=Nc(I)*(PI/6)*(D(I) 3)
11060       Vwtot=Vwtot+Vw
11070       Cumvw(I)=Vwtot
11080     NEXT I
11090     Va=Sat*Windspeed*Samptime
11100     Lwc=(10 (-9))*(Rho*Vwtot)/Va
11110     IF Total<=20 THEN
11120                 Mvd=0
11130                 GOTO 11310
11140     END IF
11150   !
11160   ! Calculation of Median Volume Diameter
11170     FOR I=1 TO Numbins
11180       Cumvw(I)=100*(Cumvw(I)/Vwtot)
11190     NEXT I
11200     Cnum=0
11210     FOR I=1 TO Numbins
11220       IF Cumvw(I)<=40 OR Cumvw(I)>=60 THEN  GOTO 11280
11230       Cnum=Cnum+1
11240       X(Cnum)=Cumvw(I)
11250       Y(Cnum)=D(I)
11260       IF Cnum=1 THEN  GOTO 11280
11270       IF X(Cnum)=X(Cnum-1) THEN  GOTO 11310
11280     NEXT I
11290     CALL Spline(Cnum,X(*),Y(*),Bs(*),Cs(*),Ds(*))
11300     Mvd=FNSeval(Cnum,50,X(*),Y(*),Bs(*),Cs(*),Ds(*))
11310 SUBEND
```

```
12000  SUB Spline(N,X(*),Y(*),B(*),C(*),D(*))
12010       Nm1=N-1
12020       IF N<2 THEN  GOTO 12460
12030       IF N<3 THEN  GOTO 12400
12040       D(1)=X(2)-X(1)
12050       C(2)=(Y(2)-Y(1))/D(1)
12060       FOR I=2 TO Nm1
12070         D(I)=X(I+1)-X(I)
12080         B(I)=2*(D(I-1)+D(I))
12090         C(I+1)=(Y(I+1)-Y(I))/D(I)
12100         C(I)=C(I+1)-C(I)
12110       NEXT I
12120       B(1)=-D(1)
12130       B(N)=-D(N-1)
12140       C(1)=0
12150       C(N)=0
12160       IF N=3 THEN  GOTO 12210
12170       C(1)=C(3)/(X(4)-X(2))-C(2)/(X(3)-X(1))
12180       C(N)=C(N-1)/(X(N)-X(N-2))-C(N-2)/(X(N-1)-X(N-3))
12190       C(1)=C(1)*D(1) 2/(X(4)-X(1))
12200       C(N)=-C(N)*D(N-1) 2/(X(N)-X(N-3))
12210       FOR I=2 TO N
12220         T=D(I-1)/B(I-1)
12230         B(I)=B(I)-T*D(I-1)
12240         C(I)=C(I)-T*C(I-1)
12250       NEXT I
12260       C(N)=C(N)/B(N)
12270       FOR Ib=1 TO Nm1
12280         I=N-Ib
12290         C(I)=(C(I)-D(I)*C(I+1))/B(I)
12300       NEXT Ib
12310       B(N)=(Y(N)-Y(Nm1))/D(Nm1)+D(Nm1)*(C(Nm1)+2*C(N))
12320       FOR I=1 TO Nm1
12330         B(I)=(Y(I+1)-Y(I))/D(I)-D(I)*(C(I+1)+2*C(I))
12340         D(I)=(C(I+1)-C(I))/D(I)
12350         C(I)=3*C(I)
12360       NEXT I
12370       C(N)=3*C(N)
12380       D(N)=D(N-1)
12390       GOTO 12460
12400       B(1)=(Y(2)-Y(1))/(X(2)-X(1))
12410       C(1)=0
12420       D(1)=0
12430       B(2)=B(1)
12440       C(2)=0
12450       D(2)=0
12460  SUBEND
```

```
13000 DEF FNSeval(N,U,X(*),Y(*),B(*),C(*),D(*))
13010     I=1
13020     IF I>=N THEN I=1
13030     IF U<X(I) THEN  GOTO 13050
13040     IF U<=X(I+1) THEN  GOTO 13110
13050     I=1
13060     J=N+1
13070     K=(I+J)/2
13080     IF U<X(K) THEN J=K
13090     IF U>=X(K) THEN I=K
13100     IF J>I+1 THEN  GOTO 13070
13110     Dx=U-X(I)
13120     Seval=Y(I)+Dx*(B(I)+Dx*(C(I)+Dx*D(I)))
13130     Deriv=B(I)+Dx*(2*C(I)+Dx*(3*D(I)))
13140     RETURN Seval
13150 FNEND
14000 DEF FNDeriv(N,U,X(*),Y(*),B(*),C(*),D(*))
14010     I=1
14020     IF I>=N THEN I=1
14030     IF U<X(I) THEN  GOTO 14050
14040     IF U<=X(I+1) THEN  GOTO 14110
14050     I=1
14060     J=N+1
14070     K=(I+J)/2
14080     IF U<X(K) THEN J=K
14090     IF U>=X(K) THEN I=K
14100     IF J>I+1 THEN  GOTO 14070
14110     Dx=U-X(I)
14120     Seval=Y(I)+Dx*(B(I)+Dx*(C(I)+Dx*D(I)))
14130     Deriv=B(I)+Dx*(2*C(I)+Dx*(3*D(I)))
14140     RETURN Deriv
14150 FNEND
```

```
15000     SUB Oapvar(D(*),Sa(*),Binl(*),Binr(*))
15010       FOR I=1 TO 62
15020         READ Binl(I),D(I),Binr(I),Sa(I)
15030       NEXT I
15040       DATA   14.20,   24.10,   34.00,  0.468
15050       DATA   34.00,   43.50,   53.80,  3.644
15060       DATA   53.80,   63.70,   73.50, 10.834
15070       DATA   73.50,   83.50,   93.40, 20.568
15080       DATA   93.40,  103.30,  113.20, 30.946
15090       DATA  113.20,  123.00,  132.80, 43.118
15100       DATA  132.80,  142.60,  152.40, 56.937
15110       DATA  152.40,  162.30,  172.20, 67.100
15120       DATA  172.20,  182.90,  193.60, 65.880
15130       DATA  193.60,  202.70,  211.80, 64.660
15140       DATA  211.80,  221.50,  231.20, 63.440
15150       DATA  231.20,  241.10,  251.00, 62.220
15160       DATA  251.00,  260.80,  270.60, 61.000
15170       DATA  270.60,  280.50,  290.40, 59.780
15180       DATA  290.40,  300.20,  310.00, 58.560
15190       DATA  310.00,  320.00,  330.00, 57.340
15200       DATA  330.00,  340.00,  350.00, 56.120
15210       DATA  350.00,  360.00,  370.00, 54.900
15220       DATA  370.00,  380.00,  390.00, 53.680
15230       DATA  390.00,  400.00,  410.00, 52.460
15240       DATA  410.00,  420.00,  430.00, 51.240
15250       DATA  430.00,  440.00,  450.00, 50.020
15260       DATA  450.00,  460.00,  470.00, 48.800
15270       DATA  470.00,  480.00,  490.00, 47.580
15280       DATA  490.00,  500.00,  510.00, 46.360
15290       DATA  510.00,  520.00,  530.00, 45.140
15300       DATA  530.00,  540.00,  550.00, 43.920
15310       DATA  550.00,  560.00,  570.00, 42.700
15320       DATA  570.00,  580.00,  590.00, 41.480
15330       DATA  590.00,  600.00,  610.00, 40.260
15340       DATA  610.00,  620.00,  630.00, 39.040
15350       DATA  630.00,  640.00,  650.00, 37.820
15360       DATA  650.00,  660.00,  670.00, 36.000
15370       DATA  670.00,  680.00,  690.00, 35.380
15380       DATA  690.00,  700.00,  710.00, 34.160
15390       DATA  710.00,  720.00,  730.00, 32.940
15400       DATA  730.00,  740.00,  750.00, 31.720
15410       DATA  750.00,  760.00,  770.00, 30.500
15420       DATA  770.00,  780.00,  790.00, 29.280
15430       DATA  790.00,  800.00,  810.00, 28.060
15440       DATA  810.00,  820.00,  830.00, 26.840
15450       DATA  830.00,  840.00,  850.00, 25.620
15460       DATA  850.00,  860.00,  870.00, 24.400
15470       DATA  870.00,  880.00,  890.00, 23.180
15480       DATA  890.00,  900.00,  910.00, 21.960
15490       DATA  910.00,  920.00,  930.00, 20.740
15500       DATA  930.00,  940.00,  950.00, 19.520
15510       DATA  950.00,  960.00,  970.00, 18.300
15520       DATA  970.00,  980.00,  990.00, 17.080
15530       DATA  990.00, 1000.00, 1010.00, 15.860
15540       DATA 1010.00, 1020.00, 1030.00, 14.640
15550       DATA 1030.00, 1040.00, 1050.00, 13.420
15560       DATA 1050.00, 1060.00, 1070.00, 12.200
15570       DATA 1070.00, 1080.00, 1090.00, 10.980
```

```
15580      DATA 1090.00, 1100.00, 1110.00,  9.760
15590      DATA 1110.00, 1120.00, 1130.00,  8.540
15600      DATA 1130.00, 1140.00, 1150.00,  7.320
15610      DATA 1150.00, 1160.00, 1170.00,  6.100
15620      DATA 1170.00, 1180.00, 1190.00,  4.880
15630      DATA 1190.00, 1200.00, 1210.00,  3.660
15640      DATA 1210.00, 1220.00, 1230.00,  2.440
15650      DATA 1230.00, 1240.00, 1250.00,  1.220
15660   SUBEND
```

```
16000  SUB Plotit(R,X$,Y$,Title$,X(*),Y(*),Ttime,Size,Miny,Maxy)
16010    IF PROUND(Miny,R)<=Miny THEN
16020                        Lowerlim=PROUND(Miny,R)
16030                        ELSE
16040                        Lowerlim=PROUND(Miny,R)-10 R
16050                        END IF
16060    IF PROUND(Maxy,R)>Maxy THEN
16070                       Upperlim=PROUND(Maxy,R)
16080                       ELSE
16090                       Upperlim=PROUND(Maxy,R)+10 R
16100                       END IF
16110    IF PROUND(Ttime,1)>Ttime THEN
16120                         Utime=PROUND(Ttime,1)
16130                         ELSE
16140                         Utime=PROUND(Ttime,1)+10
16150    END IF
16160    GINIT
16170    GCLEAR
16180    PLOTTER IS "GRAPHICS"
16190    GRAPHICS ON
16200    PEN 3
16210    VIEWPORT 20,100,20,90
16220    WINDOW 0,Utime,Lowerlim,Upperlim
16230    LAXES Utime/10,(Upperlim-Lowerlim)/10,0,Lowerlim
16240    MOVE 0,0
16250    PEN 5
16260    PLOT X(1),Y(1),-2
16270    FOR I=2 TO Size
16280      PLOT X(I),Y(I),-1
16290    NEXT I
16300    PEN 1
16310    VIEWPORT 0,100,0,90
16320    WINDOW -2,10,-4,45
16330    MOVE 4,-1
16340    LABEL X$
16350    MOVE -1,10
16360    DEG
16370    LDIR 90
16380    LABEL Y$
16390    MOVE 3,47
16400    LDIR 0
16410    LABEL Title$
16420  SUBEND
```

Appendix E

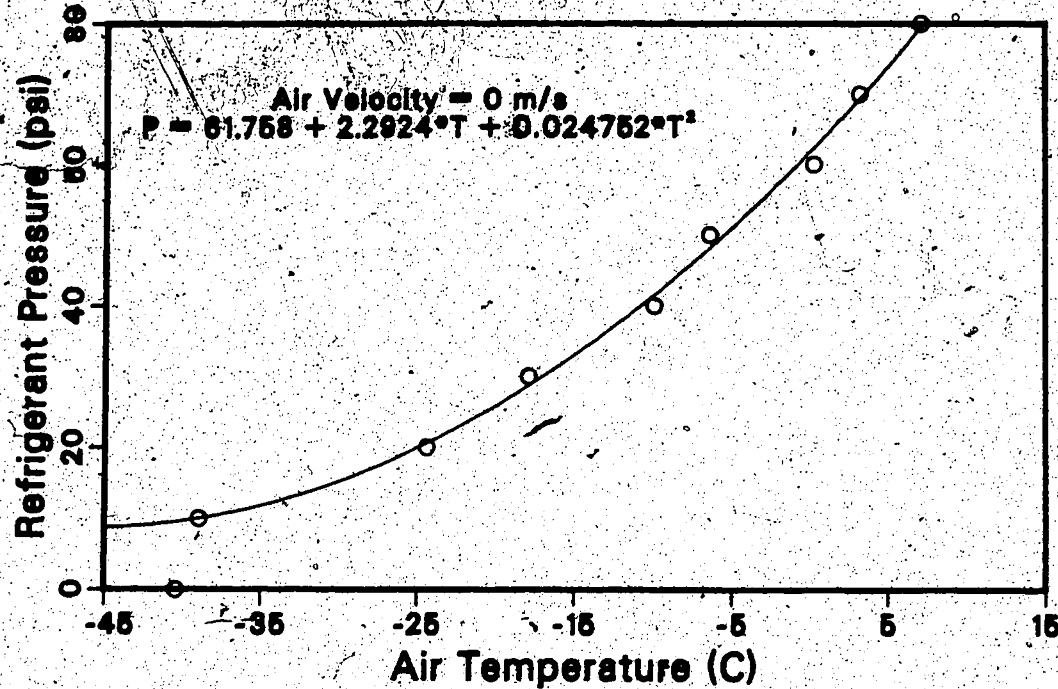
Performance Calculations

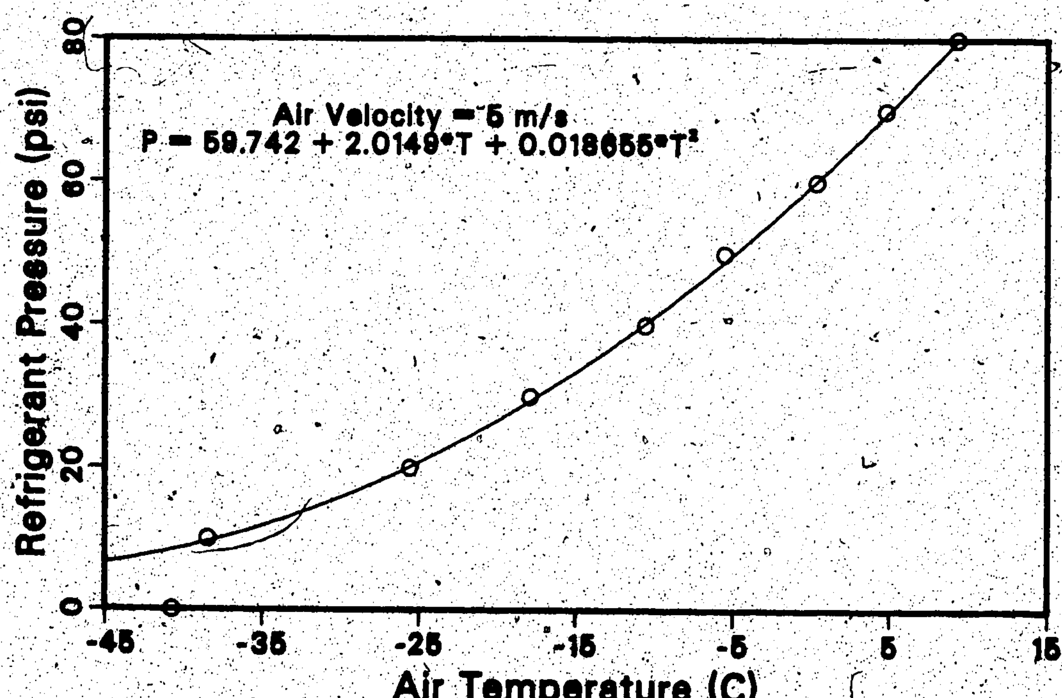
Temperature

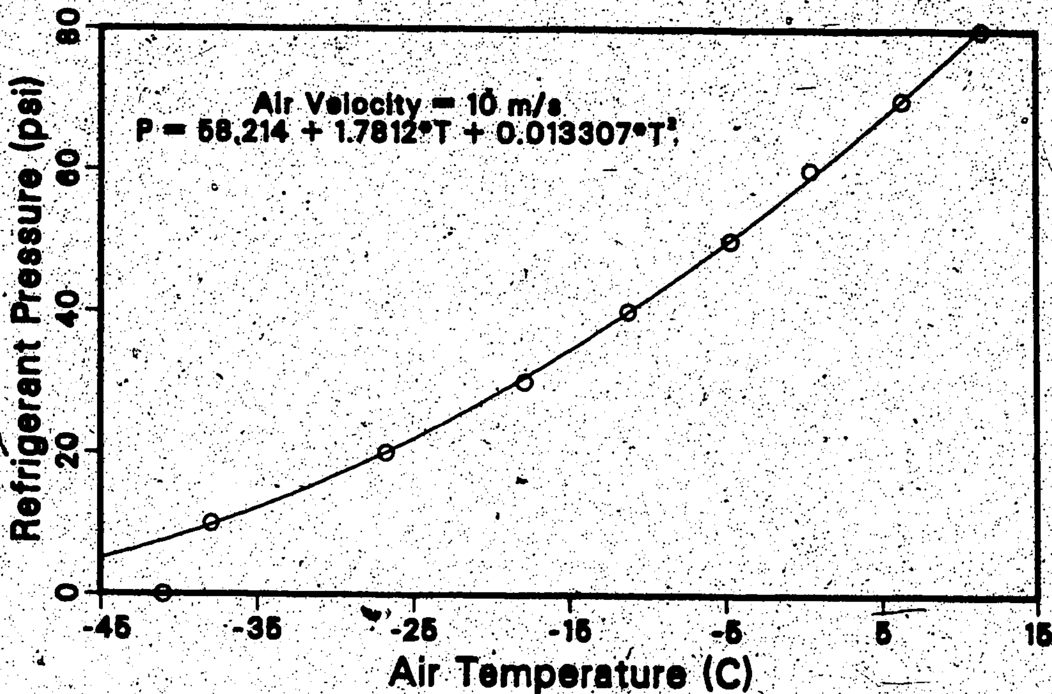
Appendix E

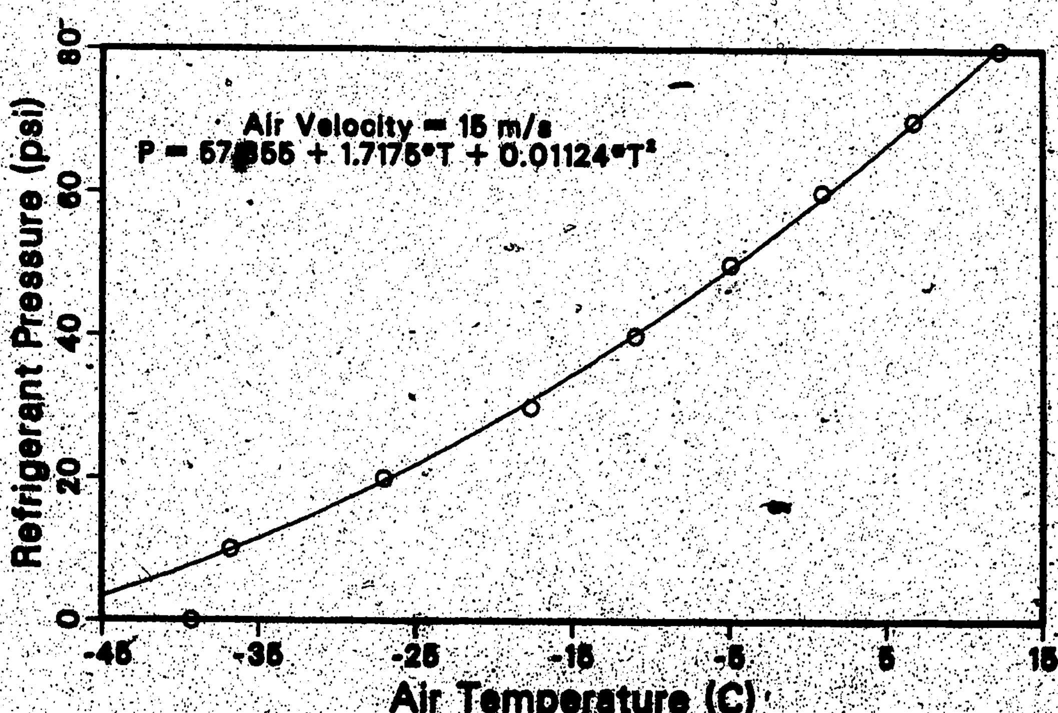
Temperature Performance Calculations:

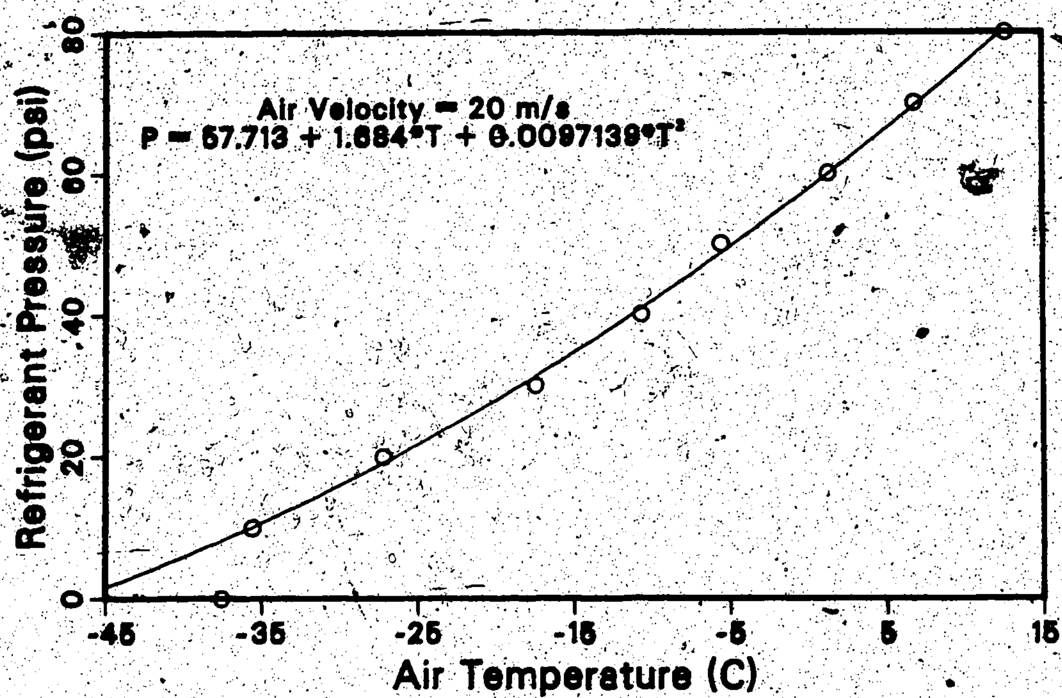
A function which relates refrigerant pressure to air temperature and wind speed was developed by fitting simple polynomials to the operating range performance test results in table 4.1-1. Since this data does not fall along lines of constant wind speed some linear interpolation was used to first obtain a set of data corresponding to pressure as a function of temperature along lines of constant wind speed. The figures on pages 112 to 115 illustrate the manner in which a second order polynomial (pressure as a function of temperature) was fit through this data at 8 wind speeds ranging from 0 to 35 m/s. The coefficients from these 8 second order polynomials were then fit as both second and third order functions of wind speed as shown in the following three figures (pages 116 and 117). The final result is of course the general expression for refrigerant pressure as a function of wind speed and temperature given in section 4.1.

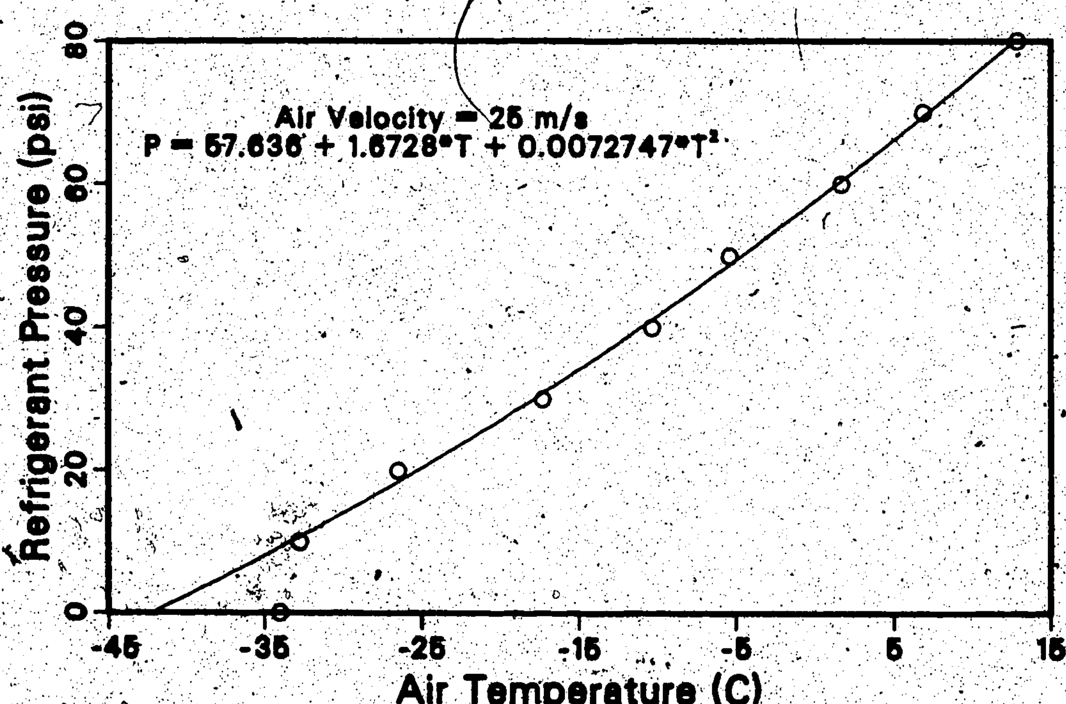

Air Velocity = 0 m/s
P = 61.758 + 2.2924*T + 0.024752*T²
Refrigerant Pressure (psi)
0
20
40
60
80
-45
-35
-25
-15
-5
5
15
Air Temperature (C)

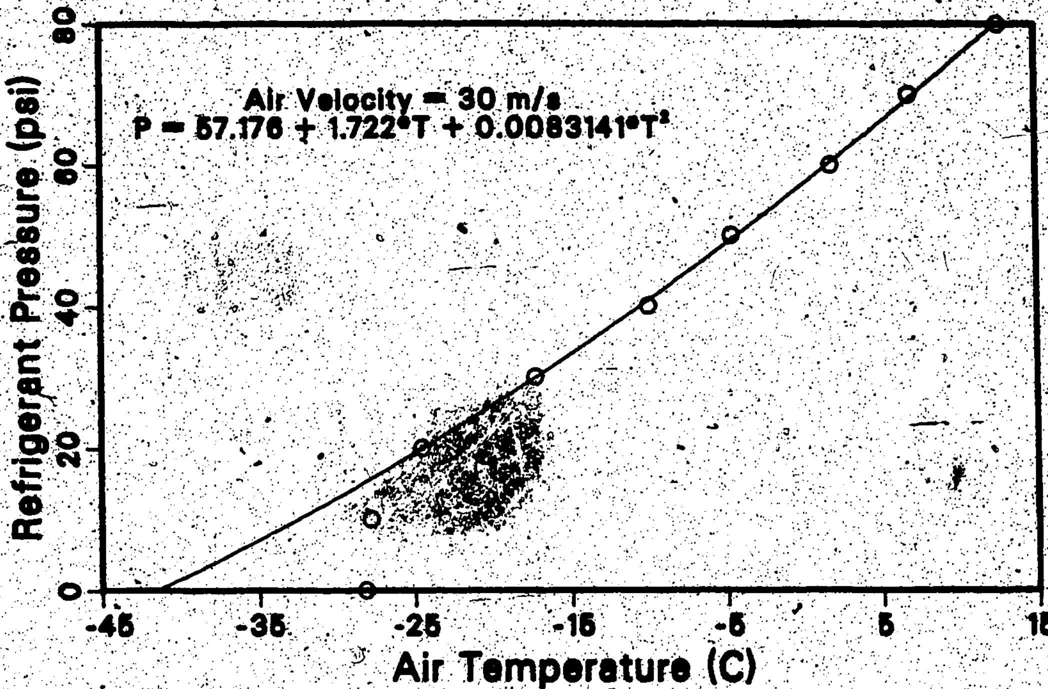

Air Velocity = 5 m/s
P = 59.742 + 2.0149*T + 0.018655*T²
Refrigerant Pressure (psi)
0
20
40
60
80
-45
-35
-25
-15
-5
5
15
Air Temperature (C)

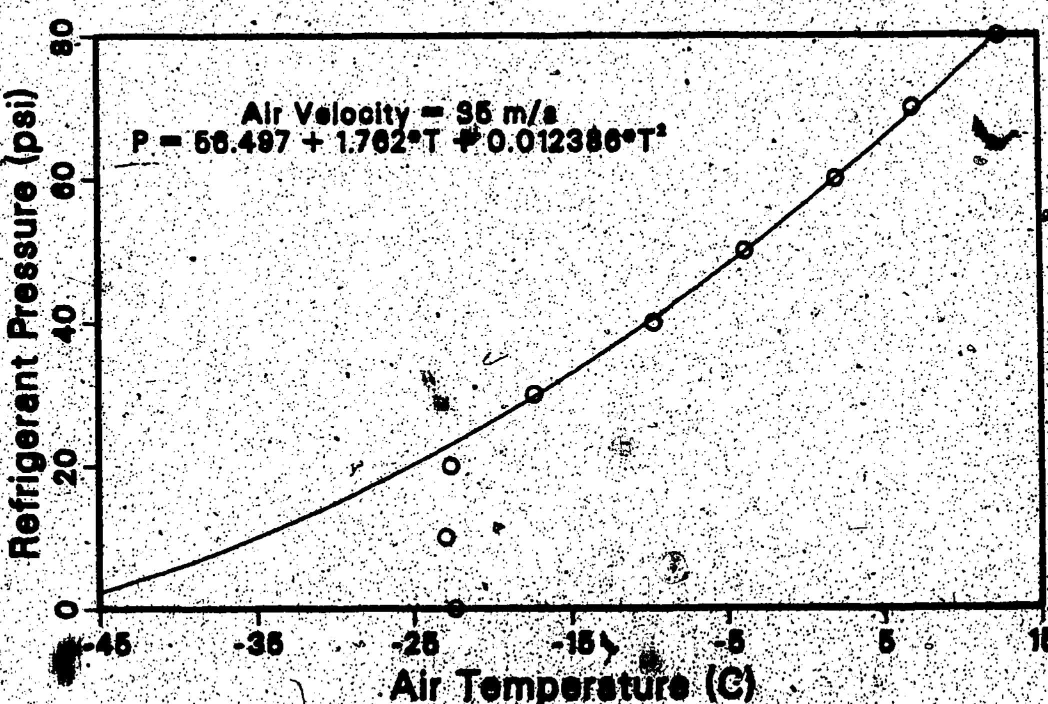

Air Velocity = 10 m/s
P = 58.214 + 1.7812*T + 0.013307*T²
Refrigerant Pressure (psi)
0
20
40
60
80
-45
-35
-25
-15
-5
5
15
Air Temperature (C)

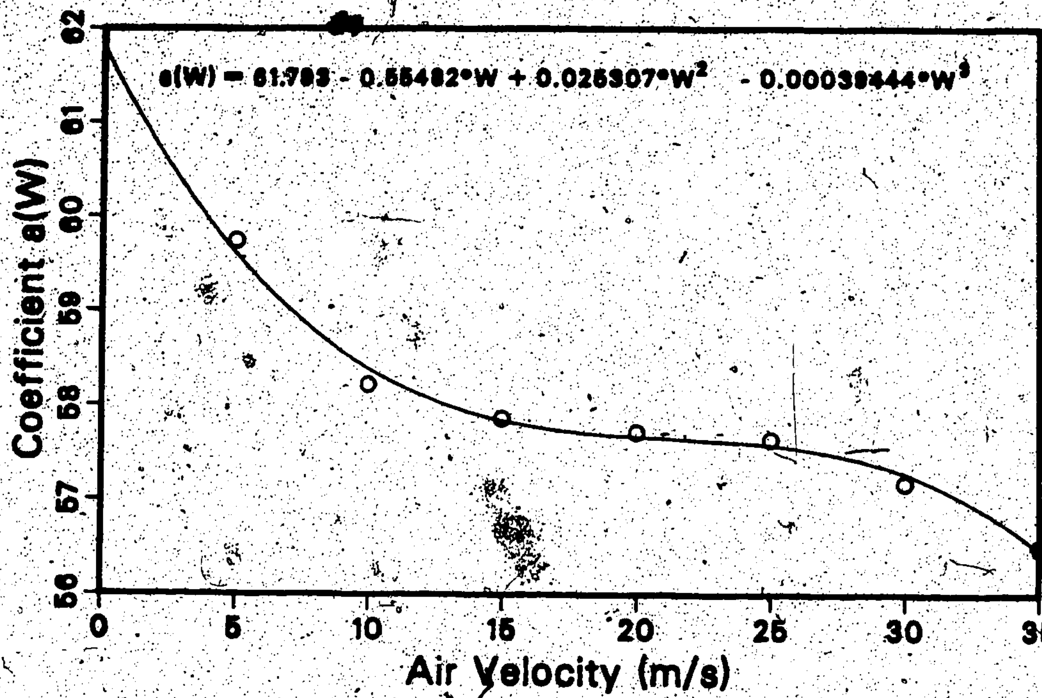

Air Velocity = 15 m/s
Refrigerant Pressure (psi)
0
20
40
60
80
-45
-35
-25
-15
-5
5
15
Air Temperature (C)

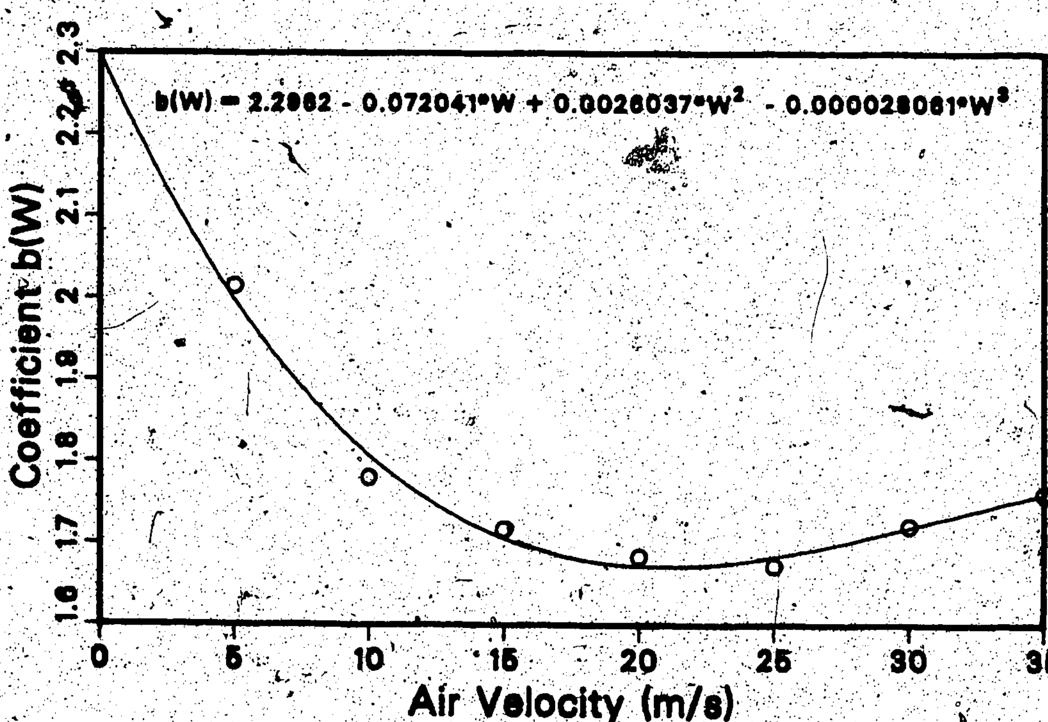

Air Velocity = 20 m/s
P = 57.713 + 1.684*T + 0.0097139*T²
Refrigerant Pressure (psi)
0
20
40
60
80
-45
-35
-25
-15
-5
5
15
Air Temperature (C)

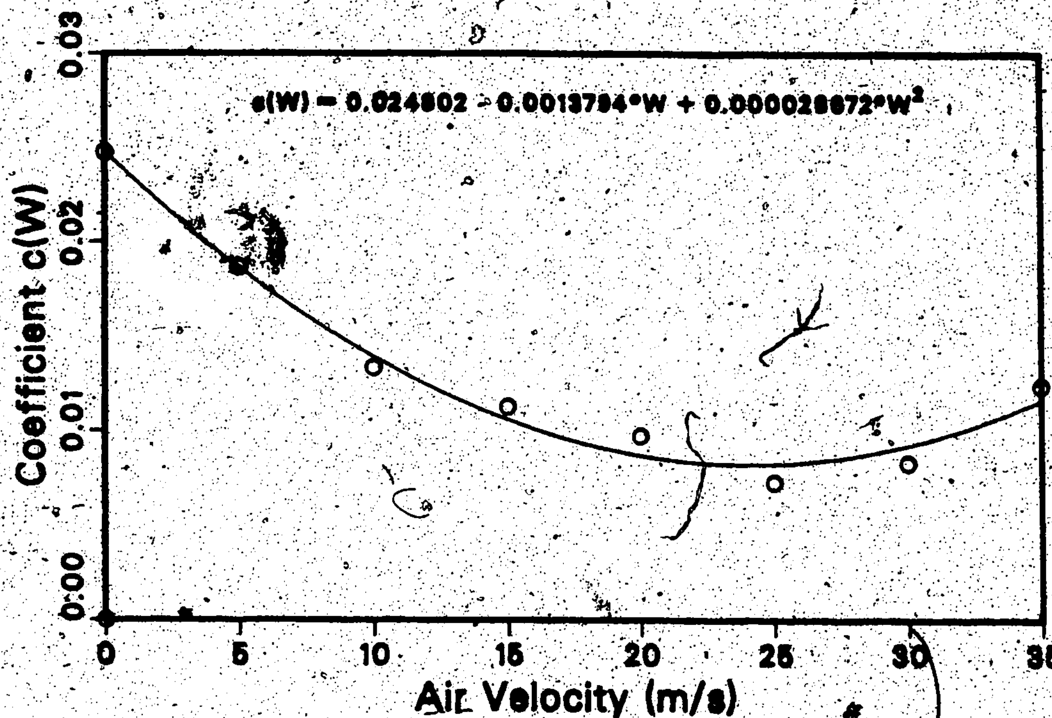

Air Velocity = 25 m/s
P = 57.636 + 1.6728*T + 0.0072747*T²
Refrigerant Pressure (psi)
0
20
40
60
80
-45
-35
-25
-15
-5
5
15
Air Temperature (C)


Air Velocity = 30 m/s
P = 57.176 + 1.722*T + 0.0083141*T²
Refrigerant Pressure (psi)
0
20
40
60
80
-45
-35
-25
-15
-5
5
15
Air Temperature (C)


Air Velocity = 35 m/s
P = 56.497 + 1.762*T + 0.012386*T²
Refrigerant Pressure (psi)
0
20
40
60
80
-45
-35
-25
-15
-5
5
15
Air Temperature (C)


a(W) = 61.783 - 0.55482*W + 0.025307*W^2 - 0.00038444*W^3
Coefficient a(W)
62
61
60
59
58
57
56
0
5
10
15
20
25
30
35
Air Velocity (m/s)


b(W) = 2.2982 - 0.072041*W + 0.0026037*W^2 - 0.000028061*W^3
Coefficient b(W)
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
0
5
10
15
20
25
30
35
Air Velocity (m/s)


c(W) = 0.024802 - 0.0013794*W + 0.000028672*W^2
Coefficient c(W)
0.00
0.01
0.02
0.03
0
5
10
15
20
25
30
35
Air Velocity (m/s)

Appendix F

Performance Data

Wind Speed

Appendix F

Wind Speed Performance Data:

The following table summarizes the wind speed data taken to develop the velocity profiles depicted in figures 4.2-1 to 4.2-3. Three different profiles were considered at average wind speeds of 3.6, 13.3 and 34.4 m/s. Each profile represents 217 individual measurements taken at distinct X - Y positions on a horizontal plane through the center of the test section. The measurements were made by measuring the pressure difference from a pitot-static tube using a variable reluctance pressure transducer. The voltage output from the transducer was sampled at 40 Hz for a period of 10 seconds for each measurement.

Position X	Position Y	Average Speed 3.6 m/s		Average Speed 13.3 m/s		Average Speed 34.4 m/s	
[mm]	[mm]	Avg [m/s]	Sd Dev [m/s]	Avg [m/s]	Sd Dev [m/s]	Avg [m/s]	Sd Dev [m/s]
-120	-245	3.4037	0.0863	11.4167	0.3112	31.1606	0.7333
-80	-245	3.1063	0.1173	11.4319	0.4490	31.4637	0.6474
-40	-245	3.2149	0.1180	10.6973	0.5455	30.7461	1.0407
0	-245	3.2715	0.0760	10.8179	0.4608	30.1320	0.8497
40	-245	3.1077	0.0797	11.1322	0.4500	30.9328	0.7534
80	-245	3.0580	0.0817	11.2647	0.4043	31.1214	0.6418
120	-245	2.8594	0.0587	11.1769	0.3967	30.3771	0.7957
-120	-240	3.5619	0.0343	12.6361	0.3290	32.9232	0.7035
-80	-240	3.5103	0.0334	12.5773	0.2383	32.7800	0.5283
-40	-240	3.4663	0.0690	11.9887	0.4373	32.3374	0.6784
0	-240	3.5039	0.0304	12.0826	0.4127	31.9686	0.7363
40	-240	3.4381	0.0619	12.3405	0.3405	32.4569	0.5242
80	-240	3.4188	0.0663	12.4526	0.2263	32.5054	0.5818
120	-240	3.1889	0.0679	12.4360	0.2932	32.4992	0.5411
-120	-230	3.6338	0.0165	12.9993	0.0843	33.6640	0.3381
-80	-230	3.6032	0.0187	12.9515	0.1285	33.3609	0.3094
-40	-230	3.5831	0.0182	12.8241	0.1817	33.3957	0.3718
0	-230	3.5913	0.0414	12.7391	0.1921	33.1179	0.3772
40	-230	3.5920	0.0333	12.8250	0.1524	33.3299	0.4011
80	-230	3.6054	0.0209	12.8472	0.1575	33.2566	0.3306
120	-230	3.5992	0.0525	12.9294	0.1185	33.5418	0.3581

Position X [mm]	Position Y [mm]	Average Speed 3.6 m/s Avg [m/s]	Average Speed 3.6 m/s Sd Dev [m/s]	Average Speed 13.3 m/s Avg [m/s]	Average Speed 13.3 m/s Sd Dev [m/s]	Average Speed 34.4 m/s Avg [m/s]	Average Speed 34.4 m/s Sd Dev [m/s]
-120	-220	3.6539	0.0352	13.0243	0.1340	33.9298	0.3193
-80	-220	3.6279	0.0311	13.0297	0.1294	33.7819	0.3528
-40	-220	3.6223	0.0352	13.0883	0.1292	33.6987	0.3073
0	-220	3.6015	0.0182	12.9429	0.1612	33.6515	0.3384
40	-220	3.6380	0.0350	12.8792	0.1283	33.6089	0.3009
80	-220	3.5925	0.0259	12.9818	0.1286	33.7397	0.3897
120	-220	3.6496	0.0199	13.0632	0.1166	33.9049	0.3028
-120	-200	3.6351	0.0247	13.0462	0.1425	34.0447	0.3883
-80	-200	3.6660	0.0254	13.1106	0.1267	34.0561	0.3767
-40	-200	3.6344	0.0326	13.1269	0.1165	34.0079	0.3556
0	-200	3.6491	0.0311	13.0215	0.1323	33.9010	0.3507
40	-200	3.6241	0.0319	13.0822	0.1641	33.9892	0.3505
80	-200	3.6584	0.0312	13.0721	0.0972	34.0553	0.3714
120	-200	3.6486	0.0233	13.0629	0.1195	33.9706	0.3915
-120	-160	3.6469	0.0265	13.1508	0.1357	34.[illegible]650	0.3590
-80	-160	3.6843	0.0405	13.1233	0.1530	34.2325	0.3601
-40	-160	3.6580	0.0228	13.1858	0.1042	34.1898	0.2963
0	-160	3.6810	0.0412	13.1606	0.1377	34.1805	0.3245
40	-160	3.6689	0.0374	13.1860	0.1360	34.2217	0.3600
80	-160	3.6492	0.0247	13.1871	0.0969	34.1341	0.2764
120	-160	3.6941	0.0229	13.1369	0.1465	34.1798	0.3592
-245	-120	3.2486	0.1530	10.5535	0.4281	29.7716	0.8691
-240	-120	3.6287	0.0447	11.7700	0.3654	32.2494	0.6252
-230	-120	3.6657	0.0410	12.7876	0.1763	33.4690	0.3474
-220	-120	3.7053	0.0271	13.0005	0.1147	33.8102	0.4308
-200	-120	3.6901	0.0169	13.1420	0.1244	34.0484	0.3841
-160	-120	3.7334	0.0148	13.2612	0.1382	34.3062	0.3214
-120	-120	3.6633	0.0345	13.2448	0.1061	34.4389	0.3448
-80	-120	3.6365	0.0353	13.2891	0.1222	34.1297	0.3128
-40	-120	3.6455	0.0254	13.3414	0.1293	34.2204	0.3550
0	-120	3.6678	0.0388	13.3939	0.1667	34.1853	0.3065
40	-120	3.6892	0.0330	13.1906	0.1489	34.3148	0.3413
80	-120	3.6778	0.0183	13.1980	0.1139	34.1522	0.2922
120	-120	3.6588	0.0288	13.2400	0.1223	34.2864	0.3718
160	-120	3.6902	0.0228	13.1594	0.1942	34.2344	0.3476
200	-120	3.6525	0.0269	13.1571	0.1431	33.9414	0.3586
220	-120	3.6415	0.0168	13.0478	0.1268	33.7191	0.3787
230	-120	3.5893	0.0543	12.9082	0.1181	33.1413	0.5082
240	-120	3.4780	0.0675	12.0891	0.3801	31.1592	0.7785
245	-120	3.1400	0.0922	11.2227	0.3129	26.6297	0.8117
-245	-80	3.3825	0.1090	11.2850	0.3635	30.5662	0.9727
-240	-80	3.6098	0.0375	12.4431	0.2950	32.4467	0.5947
-230	-80	3.6691	0.0411	12.9002	[illegible]293	33.3638	0.[illegible]689
-220	-80	3.7068	0.0225	12.9718	0.[illegible]069	33.6223	0.3162
-200	-80	3.6816	0.0357	13.1362	0.1163	33.8827	0.3676

Position X	Y	Average Speed 3.6 m/s		Average Speed 13.3 m/s		Average Speed 34.4 m/s	
		Avg	Sd Dev	Avg	Sd Dev	Avg	Sd Dev
[mm]	[mm]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]
-160	-80	3.7416	0.0167	13.1388	0.1228	34.4402	0.4030
-120	-80	3.6405	0.0192	13.2195	0.1147	34.2747	0.4045
-80	-80	3.6703	0.0378	13.2274	0.1266	34.2687	0.2978
-40	-80	3.6642	0.0236	13.3140	0.1672	34.3282	0.3745
0	-80	3.6525	0.0197	13.3694	0.1569	34.2778	0.3463
40	-80	3.6377	0.0245	13.2949	0.1233	34.1924	0.3411
80	-80	3.6677	0.0313	13.2086	0.1448	34.3411	0.3615
120	-80	3.6296	0.0329	13.156[illegible]	0.1240	34.3647	0.3450
160	-80	3.6757	0.0181	13.227[illegible]	0.1194	34.1977	0.3053
200	-80	3.6677	0.0302	13.1248	0.1303	33.9307	0.3573
220	-80	3.6477	0.0197	13.0355	0.1346	33.6484	0.3626
230	-80	3.6176	0.0148	12.8610	0.1079	32.8492	0.5175
240	-80	3.4245	0.0878	11.9500	0.2790	30.7754	0.873[illegible]
245	-80	3.0388	0.1013	10.9073	0.2965	29.2355	0.8835
-245	-40	3.5222	0.0532	11.4441	0.3970	30.8412	0.7272
-240	-40	3.6352	0.0190	12.6176	0.1652	32.6203	0.5670
-230	-40	3.6729	0.0149	12.9063	0.1057	33.5001	0.3025
-220	-40	3.6821	0.0231	13.0165	0.1050	33.6856	0.3216
-200	-40	3.7055	0.0212	13.1445	0.1465	34.0259	0.3846
-160	-40	3.7088	0.0398	13.2550	0.1115	34.2193	0.3315
-120	-40	3.6481	0.0315	13.2505	0.1346	34.2039	0.3411
-80	-40	3.6464	0.0318	13.1877	0.1405	34.3403	0.3591
-40	-40	3.6467	0.0246	13.3222	0.1032	34.2931	0.2870
0	-40	3.6533	0.0353	13.3106	0.1259	34.2928	0.3463
40	-40	3.6623	0.0214	13.2480	0.1456	34.1290	0.3748
80	-40	3.6028	0.0300	13.2264	0.1043	34.2967	0.3640
120	-40	3.6283	0.0306	13.2074	0.1040	34.2034	0.3315
160	-40	3.7173	0.0266	13.2337	0.1006	34.1571	0.3604
200	-40	3.6638	0.0141	13.1808	0.1105	33.8872	0.3970
220	-40	3.6584	0.0229	12.9971	0.1406	33.5579	0.3795
230	-40	3.6157	0.0092	12.8738	0.1046	32.9053	0.4900
240	-40	3.4998	0.0524	12.1802	0.2360	30.9972	0.6867
245	-40	3.1506	0.1439	11.1702	0.3129	29.6253	0.7349
-245	0	3.4918	0.1137	11.6640	0.3212	31.2066	0.7281
-240	0	3.6556	0.0320	12.6435	0.1982	32.6718	0.4895
-230	0	3.6807	0.0226	12.8701	0.1342	33.4412	0.3649
-220	0	3.6893	0.0505	12.9306	0.1243	33.6625	0.3312
-200	0	3.7182	0.0198	13.1413	0.1448	33.9617	0.3410
-160	0	3.7351	0.0358	13.2321	0.1459	34.2651	0.3762
-120	0	3.6582	0.0235	13.1736	0.1486	34.[illegible]70	0.4055
-80	0	3.6377	0.0323	13.2555	0.1435	34.2906	0.3513
-40	0	3.6332	0.0262	13.2739	0.1442	34.2945	0.2935
0	0	3.64[illegible]	0.0287	13.2558	0.1209	[illegible].3470	0.3855
40	0	3.6[illegible]3	0.0335	13.2018	0.1278	[illegible].3009	0.3747
80	0	3.5803	0.0223	13.2635	0.1736	34.4640	0.3621
120	0	3.6223	0.[illegible]360	13.2544	0.1496	[illegible].3116	0.3821

Position X	Y	Average Speed 3.6 m/s		Average Speed 13.3 m/s		Average Speed 34.4 m/s	
		Avg	Sd Dev	Avg	Sd Dev	Avg	Sd Dev
[mm]	[mm]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]
160	0	3.7022	0.0284	13.2138	0.1534	34.2891	0.3549
200	0	3.6918	0.0294	13.0867	0.1074	33.9389	0.3149
220	0	3.6519	0.0236	13.0170	0.1055	33.5924	0.2954
230	0	3.6286	0.0210	12.8978	0.1059	32.8990	0.4107
240	0	3.5160	0.0514	12.0776	0.2654	30.9362	0.6[illegible]27
245	0	3.1670	0.0613	11.1161	0.2973	29.5882	0.6929
-245	40	3.4766	0.0986	11.4218	0.3413	31.3508	0.7458
-240	40	3.5954	0.0557	12.5133	0.2910	32.8442	0.4104
-230	40	3.6570	0.0425	12.8584	0.1394	33.4733	0.3401
-220	40	3.6815	0.0217	13.0191	0.1144	33.74[illegible]	0.3064
-200	40	3.7220	0.0281	13.0769	0.1402	33.9884	0.3103
-160	40	3.7545	0.0244	13.1038	0.0890	34.3832	0.2896
-120	40	3.6987	0.0223	13.2104	0.1309	34.4415	0.4170
-80	40	3.7064	0.0245	13.2616	0.1153	34.6142	0.3618
-40	40	3.6845	0.0300	13.2691	0.1365	34.4620	0.3209
0	40	3.6893	0.0300	13.3138	0.1668	34.5740	0.3907
40	40	3.6859	0.0338	13.2122	0.1253	34.5812	0.3258
80	40	3.6681	0.0254	13.2077	0.1273	34.4716	0.3311
120	40	3.6776	0.0258	13.2242	0.1524	34.6950	0.3724
160	40	3.7076	0.0486	13.1536	0.1225	34.2854	0.3482
200	40	3.6701	0.0374	13.1150	0.1525	33.8721	0.3413
220	40	3.6459	0.0250	13.0245	0.1310	33.5726	0.3183
230	40	3.6250	0.0183	12.8321	0.1442	33.2434	0.3111
240	40	3.4849	0.0413	11.7590	0.2371	30.9413	0.7044
245	40	3.1647	0.0480	10.7382	0.2752	29.1207	0.6887
-245	80	3.3978	0.1111	11.3493	0.3824	31.9731	0.7066
-240	80	3.5990	0.0322	12.3994	0.2916	33.2391	0.3590
-230	80	3.6491	0.0230	12.8027	0.1323	33.6093	0.3449
-220	80	3.6685	0.0175	12.9310	0.1319	33.7045	0.3059
-200	80	3.7148	0.0432	13.1319	0.1268	33.9618	0.2948
-160	80	3.7601	0.0228	13.2467	0.1248	34.2412	0.3271
-120	80	3.6891	0.0202	13.1900	0.1174	34.3789	0.3767
-80	80	3.6862	0.0204	13.2547	0.1258	34.5460	0.4026
-40	80	3.6688	0.0303	13.2204	0.1287	34.3994	0.3821
0	80	3.7128	0.0308	13.3355	0.1697	34.5503	0.3699
40	80	3.7046	0.0445	13.2857	0.1288	34.5074	0.3935
80	80	3.6833	0.0318	13.2242	0.1249	34.4578	0.3696
120	80	3.6910	0.0278	13.2389	0.1411	34.5428	0.3252
160	80	3.7121	0.0305	13.2601	0.1630	34.1816	0.2881
200	80	3.6657	0.0237	13.0713	0.1218	33.8849	0.3401
220	80	3.6309	0.0245	12.9788	0.0988	33.6011	0.3329
230	80	3.6284	0.0152	12.8328	0.1293	33.2263	0.4083
240	80	3.5149	0.0314	12.1058	0.2358	31.0300	0.5181
245	80	3.2129	0.0545	11.0207	0.2630	29.0001	0.6864
-245	120	3.4168	0.0976	11.4762	0.3076	31.5971	0.5495

Position X [mm]	Position Y [mm]	Average Speed 3.6 m/s Avg [m/s]	Average Speed 3.6 m/s Sd Dev [m/s]	Average Speed 13.3 m/s Avg [m/s]	Average Speed 13.3 m/s Sd Dev [m/s]	Average Speed 34.4 m/s Avg [m/s]	Average Speed 34.4 m/s Sd Dev [m/s]
-240	120	3.6484	0.0310	12.5769	0.1990	33.1051	0.3789
-230	120	3.6922	0.0397	12.9165	0.1411	33.6027	0.3735
-220	120	3.6864	0.0203	13.0829	0.1873	33.6897	0.3119
-200	120	3.6979	0.0316	13.1705	0.1122	34.1063	0.3208
-160	120	3.7581	0.0218	13.2332	0.1197	34.3653	0.3555
-120	120	3.6912	0.0254	13.2074	0.1257	34.4878	0.3813
-80	120	3.6912	0.0290	13.2614	0.1354	34.4701	0.3528
-40	120	3.6966	0.0161	13.2996	0.1792	34.5153	0.4002
0	120	3.6623	0.0204	13.3013	0.1142	34.4161	0.3682
40	120	3.6759	0.0216	13.2698	0.1323	34.3699	0.3187
80	120	3.6851	0.0162	13.2690	0.1277	34.4862	0.3070
120	120	3.6517	0.0371	13.2508	0.1190	34.3804	0.2978
160	120	3.7026	0.0341	13.1785	0.1688	34.2781	0.4202
200	120	3.6436	0.0406	13.1179	0.1335	33.9544	0.3430
220	120	3.6413	0.0112	13.0079	0.1161	33.6541	0.3155
230	120	3.6553	0.0224	12.8291	0.1790	33.5019	0.3484
240	120	3.5578	0.0201	11.6340	0.3431	31.5615	0.6388
245	120	3.3319	0.0484	10.6011	0.3190	29.9427	0.7241
-120	160	3.6788	0.0299	13.2150	0.1627	34.3394	0.3433
-80	160	3.6707	0.0235	13.1355	0.1210	34.3218	0.3168
-40	160	3.6929	0.0270	13.2024	0.1449	34.3608	0.3999
0	160	3.6820	0.0269	13.1599	0.1051	34.3528	0.4146
40	160	3.6723	0.0237	13.1150	0.1532	34.4042	0.3613
80	160	3.7151	0.0309	13.1196	0.1482	34.4439	0.3615
120	160	3.6690	0.0180	13.1080	0.1145	34.3723	0.3597
-120	200	3.6750	0.0377	13.0199	0.1441	34.2194	0.3258
-80	200	3.6413	0.0239	13.0372	0.1308	34.1952	0.3627
-40	200	3.6781	0.0181	13.0524	0.1447	34.0678	0.3754
0	200	3.6731	0.0390	13.0414	0.1252	34.1030	0.3949
40	200	3.6897	0.0259	12.9439	0.0960	34.1614	0.3297
80	200	3.6579	0.0280	12.9540	0.1664	34.2083	[illegible]
120	200	3.6449	0.0305	13.0276	0.1390	34.2368	0.3544
-120	220	3.6600	0.0325	12.8863	0.1688	33.9003	0.3217
-80	220	3.6358	0.0163	12.8630	0.1420	33.7822	0.3587
-40	220	3.6389	0.0175	12.8037	0.1285	33.7200	0.3411
0	220	3.6492	0.0300	12.8132	0.1185	33.7240	0.3164
40	220	3.6392	0.0153	12.9209	0.1188	33.7718	0.3248
80	220	3.6257	0.0222	12.8105	0.1191	33.7965	0.3226
120	220	3.6173	0.0468	12.8999	0.1415	34.0441	0.3694
-120	230	3.6321	0.0280	12.9116	0.1083	33.8468	0.2920
-80	230	3.6116	0.0332	12.7407	0.1150	[illegible]	0.3169
-40	230	3.6394	0.0193	[illegible]	[illegible]	[illegible]	0.3173
0	230	3.6176	0.0343	[illegible]	[illegible]	[illegible]	[illegible]
40	230	3.6245	0.0199	[illegible]	[illegible]	[illegible]	0.3142

Position X	Y	Average Speed 3.6 m/s Avg	Sd Dev	Average Speed 13.3 m/s Avg	Sd Dev	Average Speed 34.4 m/s Avg	Sd Dev
[mm]	[mm]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]
80	230	3.6063	0.0285	12.7912	0.0986	33.5423	0.2755
120	230	3.6318	0.0119	12.8919	0.1087	33.6793	0.2937
-120	240	3.6220	0.0210	12.3837	0.1964	33.1962	0.3899
-80	240	3.5672	0.0309	12.3435	0.1892	32.9561	0.3403
-40	240	3.5449	0.0209	12.2375	0.2155	33.1709	0.2916
0	240	3.5869	0.0344	12.4380	0.1958	32.8389	0.3860
40	240	3.6210	0.0312	12.4329	0.1951	33.1098	0.3814
80	240	3.6062	0.0223	12.2667	0.2261	33.0303	0.3471
120	240	3.6341	0.0257	12.3938	0.2426	33.2684	0.3799
-120	245	3.4533	0.0380	10.8397	0.2456	30.9529	0.5826
-80	245	3.4645	0.0483	10.7622	0.2621	30.951[illegible]	0.4945
-40	245	3.3499	0.0883	10.7574	0.2146	31.3517	0.4778
0	245	3.4730	0.0730	10.9307	0.2477	30.6793	0.6200
40	245	3.4434	0.0505	10.7871	0.2837	31.1903	0.4912
80	245	3.3803	0.0806	10.5810	0.2695	31.5553	0.6102
120	245	3.4169	0.0986	10.9336	0.3215	31.6878	0.6247