An Improved Control Strategy for Wind-Powered

Refrigerated Storage of Apples,

by

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VI. NOMENCLATURE

C	Solenoid Valve
D,DEF	Defrost Mode
E	Quantity of electrical energy
E_{AUX}	Electrical energy delivered by the auxiliary power supply
$\hat{E}_{AUX}$	Electrical energy consumed by the auxiliary power supply
E_C	Electrical energy consumed by the compressor motor
E_W	Electrical energy delivered by the windmill
I_A	Armature current
I_G	Windmill generator current
I_m	Compressor motor current (armature + field)
IR	Infrared radiation
N_G	Angular speed of the windmill rotor (rev/min)
$\overline{P}$	Average power (2-minute)
$\overline{P}_{AUX}$	Average power delivered by the auxiliary power supply (2-minute)
$\hat{P}_{AUX}$	Average power consumed by the auxiliary power supply (2-minute)
p_C	Condenser pressure (psig)
$\overline{P}_C$	Average power consumed by the compressor motor (2-minute)
$\overline{P}_W$	Average power developed by the windmill (2-minute)
R,REF	Refrigeration Mode
R_B	Battery resistance (internal)
R_L	Load resistance

VI. NOMENCLATURE (Cont.)

s	Standard deviation
T	Temperature
Δt	Time interval
TEV	Thermostatic expansion valve
V	Voltage
$\overline{V}$	Average voltage (2-minute)
V_G	Windmill generator output voltage
$\overline{W}$	Average wind speed (2-minute)
$\overline{W}_{AVG}$	Average wind speed (Test Interval)
$\overline{W}_{CRMC}$	Cube root-mean cubed wind speed (Test Interval)

VII. INTRODUCTION

During the past one hundred years the economic development of the United States can be largely attributed to an abundance of inexpensive energy sources. These sources included vast, easily obtained deposits of coal, oil, and natural gas. The cost of many manufactured and agricultural products reflected the low cost of energy for much of this period.

Researchers noted more than twenty years ago that we were faced with finite, fossil fuel supplies. Many people ridiculed this notion, asserting that known fuel reserves would last for several hundred years with scientists solving the problem at some intermediate time. These people had certainly not anticipated seeing energy shortages in this country in their own lifetimes.

Recent energy shortages in the United States have been hastened by the actions of OPEC (Organization of Petroleum Exporting Countries), a cartel of oil-producing Arab states. OPEC's oil price increases and a scarcity of domestic petroleum-derived fuels have resulted in making the general public more aware of this country's growing dependence on imported oil.

The U.S. government's current souution has included allocation of gasoline supplies, partial de-regulation of oil prices, and the encouragement of voluntary energy conservation. Government-funded research programs have been expanded in the past few years to develop alternative energy sources including geothernal, solar, and wind energy.

Interest in renewable energy sources has been keen. These energy forms are generally attributed to the sun, directly or indirectly, and include solar energy, biomass conversion, and wind energy. This interest has developed because the energy from the sun is free to everyone. Acceptance of alternative energy systems has been slow, however, because of the high capital costs of equipment, system reliability problems, and the complexity of operation.

While alternative energy sources have been used by mankind for several thousand years, their usage has been largely restricted to agricultural processing on a limited basis. The sun has been used for drying crops and fish. Wind energy has been used for transportation (sailing vessels), milling of grains, and pumping water. These applications were on a small scale and were often replaced in developed countries by fossil fuel-powered machinery for reasons of convenience, economics, and increased productivity. The growing dependency on fossil fuels greatly slowed the technological development of these alternative energy sources.

The per capita consumption of energy has increased with our standard of living, and a desire to ensure a continued supply of energy has renewed an interest in the use of solar and wind energy. Technology in these areas must now be updated and extended since the previous technologies are now inadequate to meet our current needs.

The use of solar energy for heating and cooling has advanced rapidly as the necessary technology and materials have been, for the most part, readily available. The advanced technology required for medium and large-scale applications of wind energy do not exist for the majority of the intended uses. One exception to the latter was the development of the Grandpa's Knob project which ended in 1945 [1].

The current impetus in wind energy research has been toward the development of large-scale alplications (100 - 1000$^+$ kW). Many uses for wind energy exist for smaller uses, however, as pointed out by L.A. Liljedahl [2], particularly in rural and agricultural areas.

While large sums of money have been made available for the development and optimization of large-scale wind energy systems, similar needs exist for small-scale applications to insure the financial success where the investment of capital must be maintained at a minimal level. The intermittent availabliity of wind also makes the need for some form of energy storage necessary in most applications. Energy storage increases the complexity and cost of a wind energy system. Therefore, a great deal of attention must be given to optimize wind energy system design and to select control strategies to best utilize available wind energy. These subjects have been the basis for the research from which this dissertation developed.

It would be nearly impossible to attempt to develop optimal control strategies for every wind energy system. Attention has been focused on those wind energy systems which develop electrical power, employ a battery for energy storage, and have an auxiliary source of electrical power. The need for research in this area became apparent during the testing of a wind-powered, refrigeration system for apple storage at Virginia Polytechnic Institute and State University. The facility was constructed in 1977 and began operation in March 1978. A general description of this system is included.

The specific objective of the research on which this dissertation was based was to develop an improved control strategy for wind-powered, refrigerated apple storage systems. This objective was to be achieved by analysis of the performance of the total system and its components.

VIII. REVIEW OF THE LITERATURE

The study of operational control strategies in solar and wind energy systems is relatively new with most of the effort being directed to materials and system concept development. Control of these systems has been mostly an application of previous technology with the straightforward use of common control devices, e.g., differential thermostats.

However, Lissaman [3] felt that it was the consensus opinion that "the technology of small systems is satisfactory. It is fundamentally satisfactory in the sense that there are no outstanding areas of major ignorance or where there are inadequate data "and" that major technical improvements to small systems, if they involve extra complexity, extra costs, or more complicated operational features, would not find a ready acceptance among people who are building small systems and trying to sell them".

Raju [4] pointed out the need for low-cost, low-technology wind energy systems for use in the rural areas of India, precluding sophistication in design, construction, and operation. His point is made in light of that country's economic capability and the limited, available capital of those persons for whom small wind energy systems would be of benefit.

No literature, however, was found regarding the improvement in a system's cost benefit ratio with the addition of control equipment to increase the utilization of available wind energy.

Herczfeld et al [5] demonstrated the improvement in the utilization of available solar energy through continuous flow control by studying various operational strategies. Similarly, Pejsa et al [6] evaluated the control options that could be employed in solar energy systems for climate control. They also stated that the need for conventional back-up systems "introduces a multitude of control options that beg to be evaluated".

Savelyev [7] stated that higher fuel costs have increased the awareness of the need for conservation through operational strategy selection including: load shedding, duty cycle control, and demand control.

Although Liljedahl [2] has enumerated potential applications for small wind energy systems in agriculture, most of the wind energy development has focused on large scale applications.

No literature was found that dealt with the improvement of small wind energy system operation through improved control strategies. Pal [8], however, noted the inherent mis-match of windmill generators and loads and showed the advantage of automatic control of the generator through the use of a mechanically-driven variable transformer.

IX. DIRECT CURRENT WINDMILL SYSTEMS

A wind-powered, direct current (DC) electrical system consists of certain basic components regardless of that system's intended application. Additional components might be added as required for stable operation, necessity, convenience, or improved operation.

The components of a minimal system include a wind-powered, electrical generator and an electrical load. This minimum-component system is shown schematically in Figure 1.

As only DC systems are being considered in this discourse, the assumption has been made that the electrical generator produces a DC output and the electrical load is capable of operating properly from a DC source. The DC output of the generator could be derived from a DC generator or by rectifying the output of an alternating current (AC) generator.

A minimum-component system could display unstable operation that would result in damage to the windmill, a situation which may occur when the load exhibits a high electrical resistance. Some resistive-type, electrical loads that might be considered for use as heating elements for space or water heating have too high a resistance, thus producing an instability in the rotor speed in the case of a high-speed, horizontal-axis windmill. The rotor may turn very slowly at low wind speeds but will rotate at a high speed with a small increase in wind speed. High rotational speeds produce stresses in the rotor that could lead to failure, particularly if any substantial wind speeds are

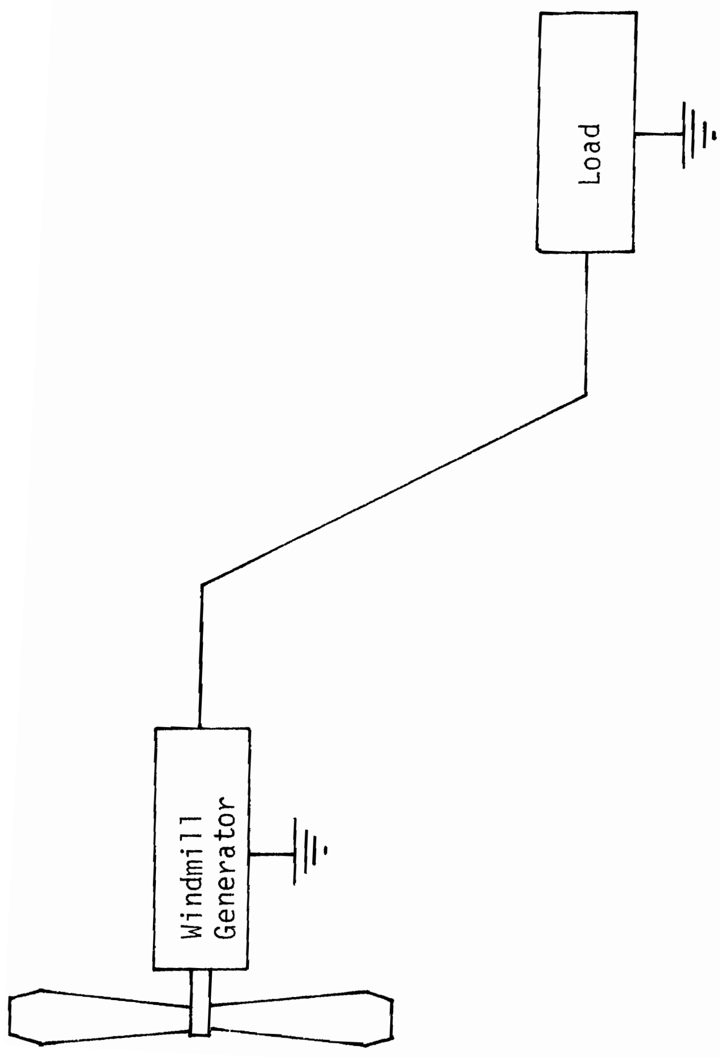


Figure 1. A Minimum-Component System

encountered. Rotor failure could also occur when the load is removed intentionally, inadvertently, or by electrical failure.

This minimum-component system has a serious disadvantage, i.e., the load can operate only when there is sufficient wind energy available. This situation is satisfactory in a few instances, e.g., pumping water (similar to the use of the American multibladed-type windmill). However, for reasons of convenience or necessity this method of operation would be inadequate for the majority of applications.

The problems of rotational speed stability can be greatly reduced by the addition of a battery in parallel with the load as shown in Figure 2. Electrical storage batteries for use in wind energy applications generally exhibit an inherently low internal resistance (typically 0.01Ω/V, or less). When the generator is capable of producing current, the effective resistance of the battery and a resistive load combination will decrease with increasing current produced by the generator. As the current increases, the effective load resistance will become less than that of the resistive load by itself. As illustrated in Figure 3 the addition of the battery provides, in effect, a variable resistive load as seen by the generator. In fact, the addition of a battery in parallel with a load having a substantial resistance causes the load curve to be nearly the same as for the battery alone. This can be seen in Figure 3 where the two load curves appear to be as one. As the windmill produces power the generator is capable of producing a greater electrical current with smaller increases in voltage.

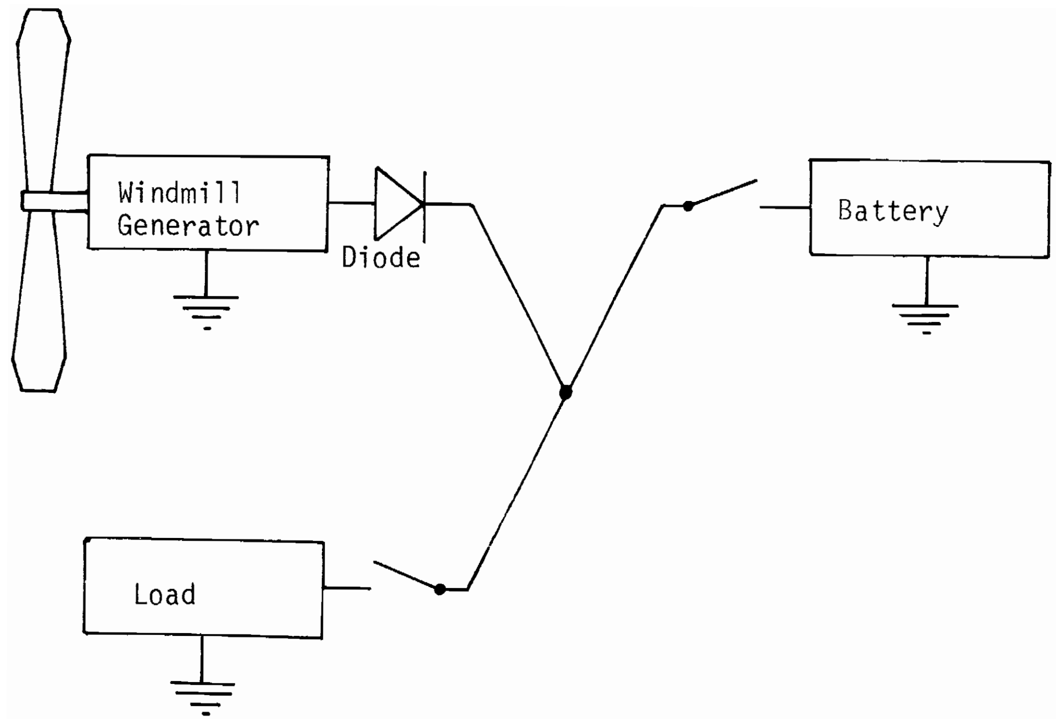


Figure 2. Basic System with a Storage Battery

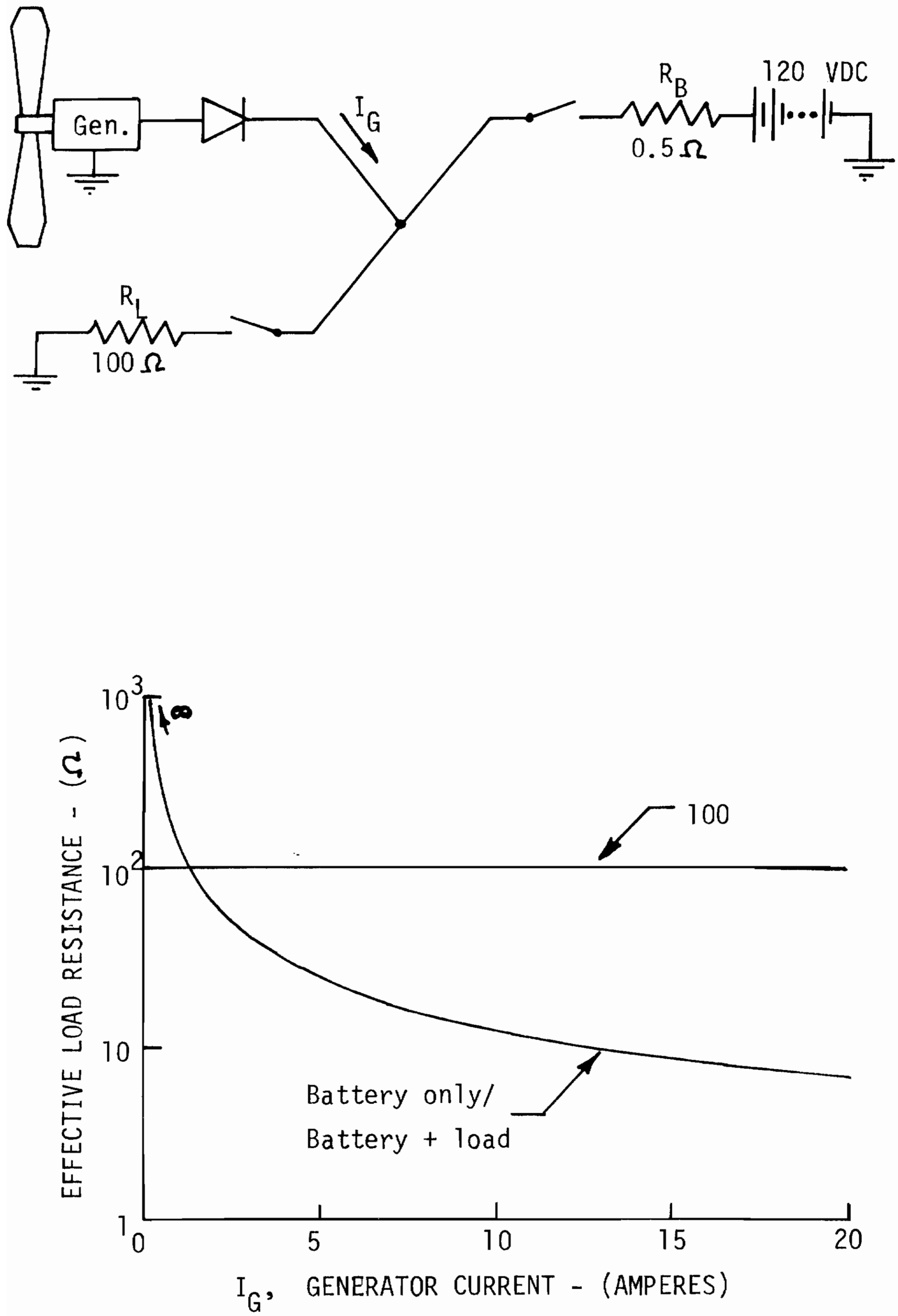


Figure 3. Comparison of Effective Load Resistance

Because the speed of the windmill's rotor is primarily governed by voltage, the speed of the rotor rapidly stabilizes with increasing current when the battery is included. With the resistive load alone this action does not occur, and the rotor continues to increase its speed.

With the addition of the battery to the system some means of preventing the flow of electricity from the battery to the windmill generator must be provided if the generator is of the direct current type. Otherwise, the battery will cause the generator to act as a motor whenever the voltage developed by the generator is lower than that of the battery. This requirement can be easily satisfied by the use of a diode as shown in Figure 2.

More important, possibly, is the ability, with the addition of a battery, to store energy for use at a later time. This feature is very advantageous to those applications where control of the load operation does not coincide with the availablity of wind energy. This benefit is offset, to a limited degree, by the significant loss of energy resulting from the inability of the battery to yield all of the energy delivered to it during its charging.

The system configuration shown in Figure 2 has a restriction placed on the operation of the load. The load can only be operated when there is sufficient wind energy available or when the battery is not fully-discharged. Otherwise, the load cannot be operated. For some applications this mode of operation may be satisfactory.

Many applications, however, require that the load be operated without regard for the battery's state-of-charge or weather conditions. This problem can be overcome by the use of an external source of power, if available. The auxiliary power could be provided by a motor-driven generator (diesel, gas, or propane-fired) or by connection to the local electric utility, if available. The auxiliary power must provide direct current to the system. When alternating current sources are employed, rectification is necessary.

The operation of the auxiliary power may be intermittent or continuous. It may also be used as a primary, supplementary, or backup power source. A schematic representation of such a system using both a battery and an auxiliary power supply is shown in Figure 4.

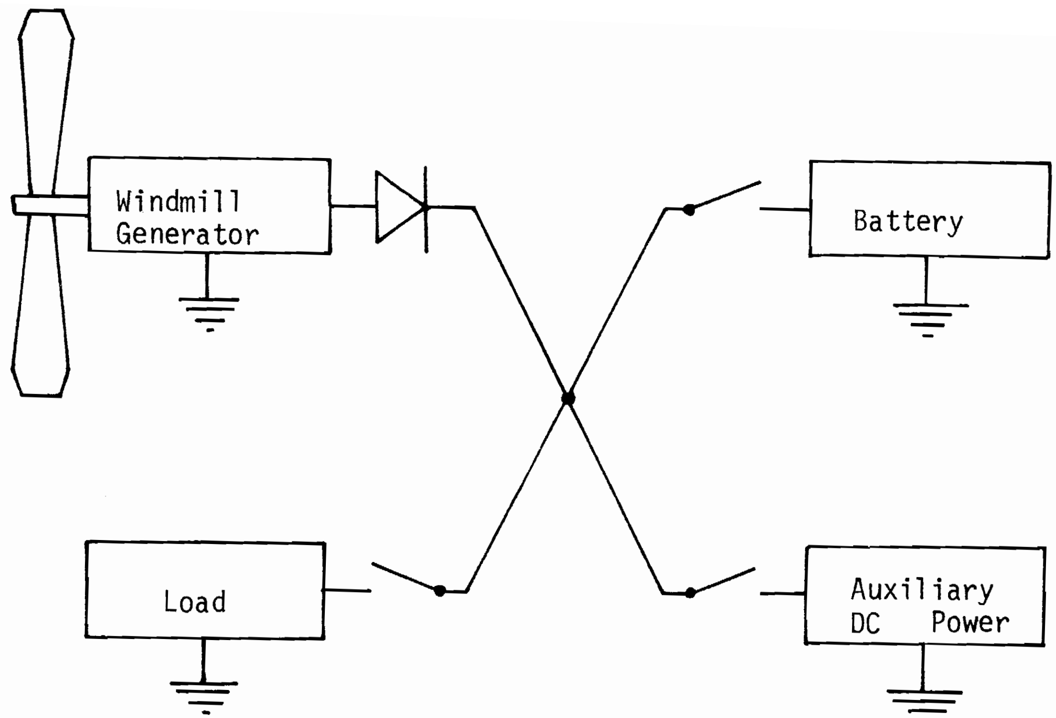


Figure 4. Basic System with a Storage Battery and Auxiliary Power

X. DESCRIPTION OF THE VPI&SU WIND-POWERED REFRIGERATION SYSTEM

General Description

A two-year research program was conducted at Virginia Polytechnic Institute and State University to demonstrate the application of wind energy for the refrigerated storage of apples. The program was funded by the Energy Research and Development Administration (ERDA) through the U.S. Department of Agriculture - Agricultural Research Service (USDA-ARS) and involved the joint efforts of the aerospace, agricultural, and mechanical engineering departments.

The majority of the research was conducted at the University's Horticulture Research Farm about five miles from the main campus. An existing structure was available for renovation at that location for use as an apple storage facility. Also, the site was considered topographically similar to locations where such applications might be considered. The relative locations of the storage building and windmill are shown in Figure 5.

Further detailed information relative to the VPI&SU research project can be found in Reference [9].

Storage Building and Ice Storage Tank

The existing structure available for use as an apple storage building was extensively modified for that purpose. Cost estimates, beyond the limits of budgeted funds, prohibited the construction of a new building designed specifically for apple storage.

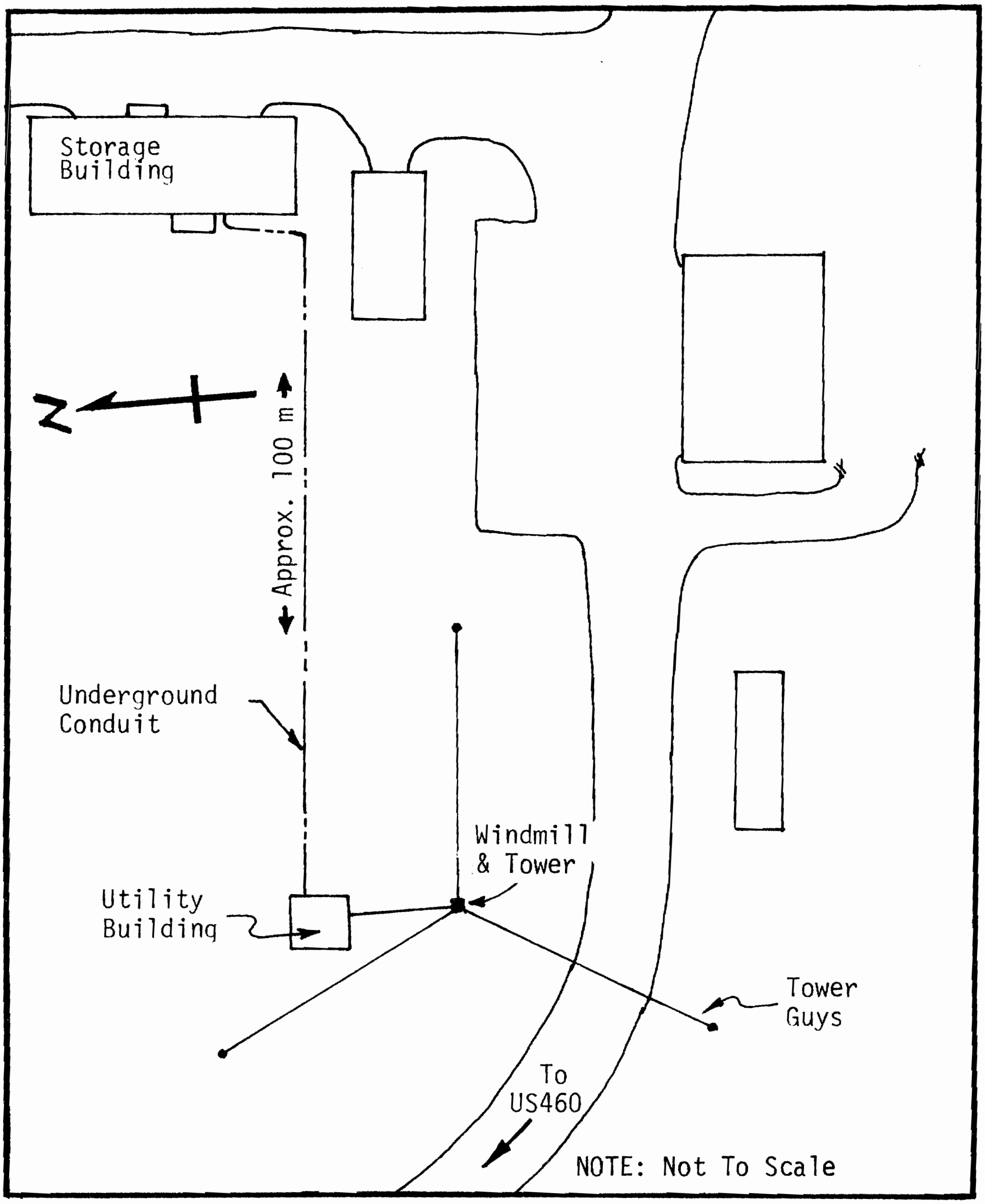
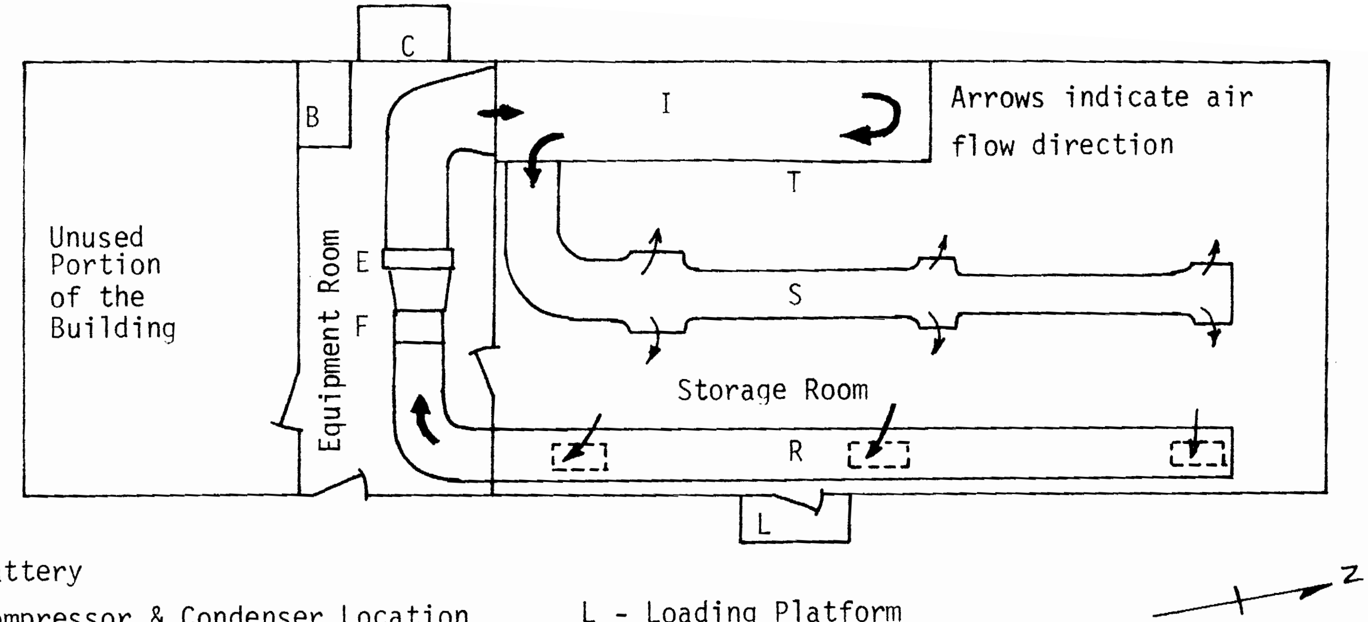


Figure 5. Relative Locations of the Windmill and Storage Building

A floor plan of the apple storage building after renovation is shown in Figure 6. The locations of the ice storage tank, ducts, compressor and condenser, refrigerant evaporator, and battery are indicated. Views of the front of the building and the interior of the equipment room are shown in Figures 7 and 8.

Insulation of that part of the building to be used as a cold storage room was required. The room was fully-lined with a plastic vapor barrier and six inches of block-type, polystyrene insulation. A new concrete floor was placed over the floor insulation, and the walls and ceiling were finished with exterior-grade plywood and painted. Both doors in the storage area were constructed in a similar manner and gasketed to reduce air infiltration. Standard refrigerated-room door hardware were installed on both doors.

An ice storage tank was located in the refrigerated area and was designed to contain ninety steel tubes filled with a dilute solution of ethylene glycol antifreeze and water. The purpose of the ice storage tank was to provide a means of storing refrigeration via the latent heat of fusion of the antifreeze mixture. This ice could be later melted to assist in refrigeration of the storage area. The dilute concentration provided a freezing point of the mixture of approximately -1^{o}C (30^{o}F). The quantity of antifreeze mixture was selected to accommodate the refrigeration requirements for the removal of field heat of the apples to be placed in storage. The storage area and the volume of the ice storage tank were designed to house 1008-bushels of apples.



B - Battery

C - Compressor & Condenser Location

E - Evaporator

F - Duct Blower

I - Ice Storage Tank

L - Loading Platform

R - Air Return Duct

S - Air Supply Duct

T - Thermostat Location

(Approximate Scale: 3/32 in. = 1 ft.)

Figure 6. Plan View of the Apple Storage Building

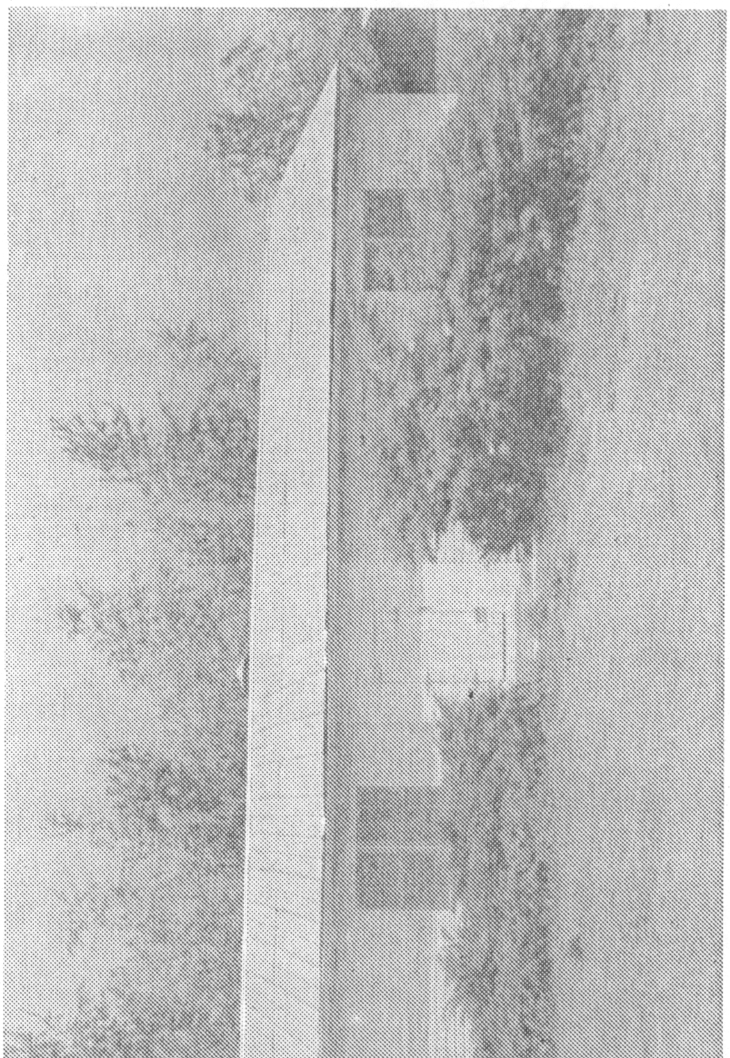


Figure 7. View of the Apple Storage Building

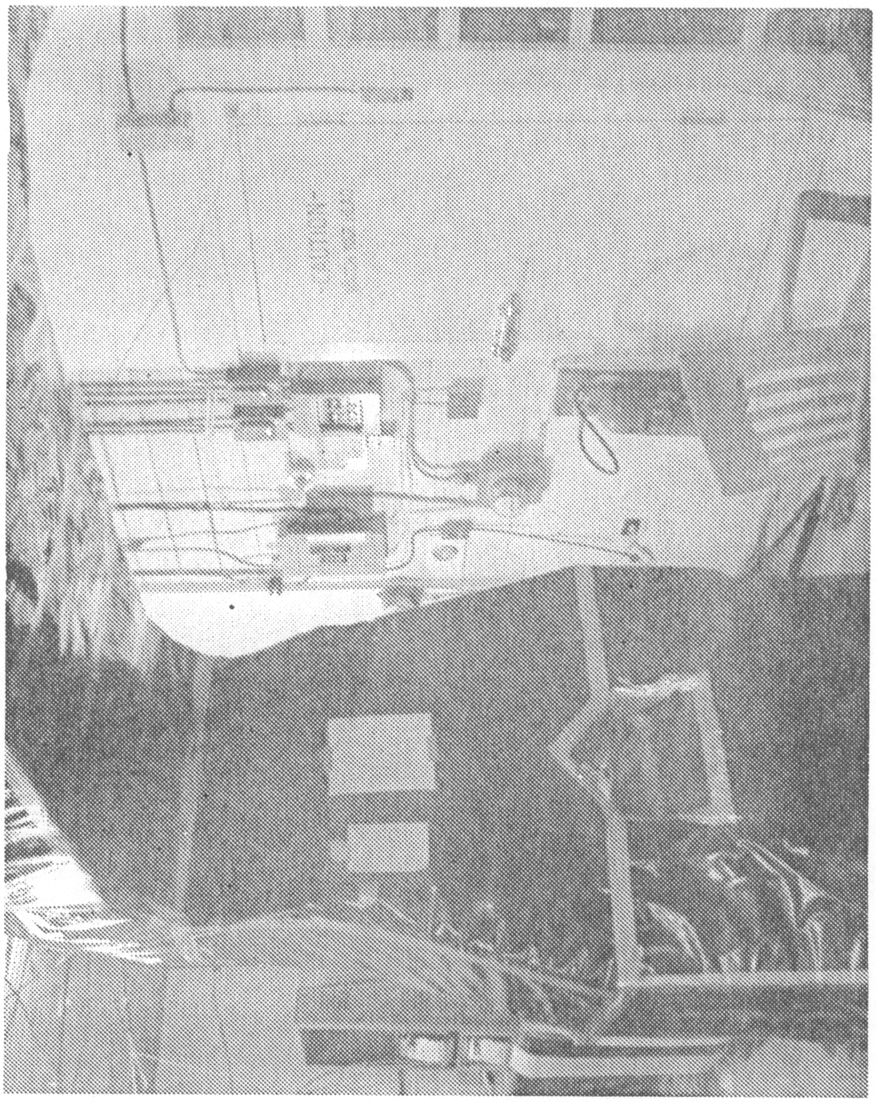


Figure 8. View of the Equipment Room Interior

The storage room was designed for air to be drawn from the area through the return air duct to the adjacent equipment room where it was cooled when passed over the coils of the evaporator unit. The air then passed through the ice storage tank before being distributed by the air supply duct into the storage area. The storage tank behaved like a large, constant-temperature thermal mass when the mixture in the tubes was at the freezing point, moderating the temperature of the air leaving the tank and entering the storage area.

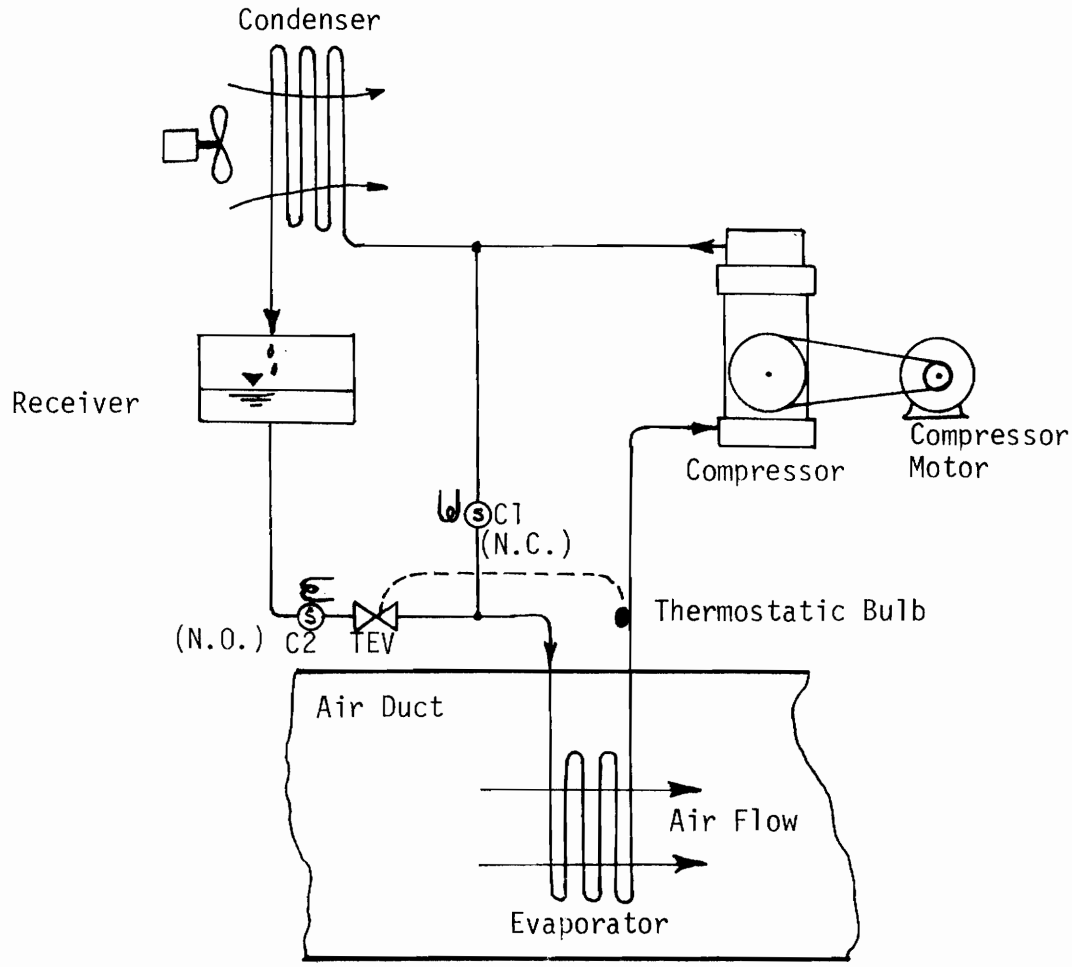
The electrical equipment, battery, duct fan, and system controls were located in the equipment room adjacent to the storage area.

Refrigeration Equipment

A vapor-compression refrigeration system was selected for use in this wind energy system. The direct refrigeration provided simplicity and convenience. A schematic representation of the refrigeration system is given in Figure 9.

The compressor, condenser, and receiver were placed outside the building on a concrete base. The equipment was housed in a small, well-ventilated structure for protection from the weather. A 2.3 kW (3 hp) DC electric motor was installed to drive the compressor and to operate the condenser's cooling fan. Specifications of the refrigeration system are given in Appendix A.

To remove ice from the evaporator coils, an active, hot-gas defrosting system was installed. It was operated by opening solenoid valve C1 shown in Figure 9 allowing hot gas from the high pressure side



N.O. = Normally Open

N.C. = Normally Closed

Figure 9. Schematic Representation of the Refrigeration System

of the compressor to be diverted to the evaporator. Solenoid valve C2 was closed when C1 was opened to ensure that refrigerant could not enter the evaporator through the expansion valve during defrosting. This occurrence, otherwise, greatly reduces the defrosting action.

The compressor motor, compressor, and condenser are shown in Figure 10.

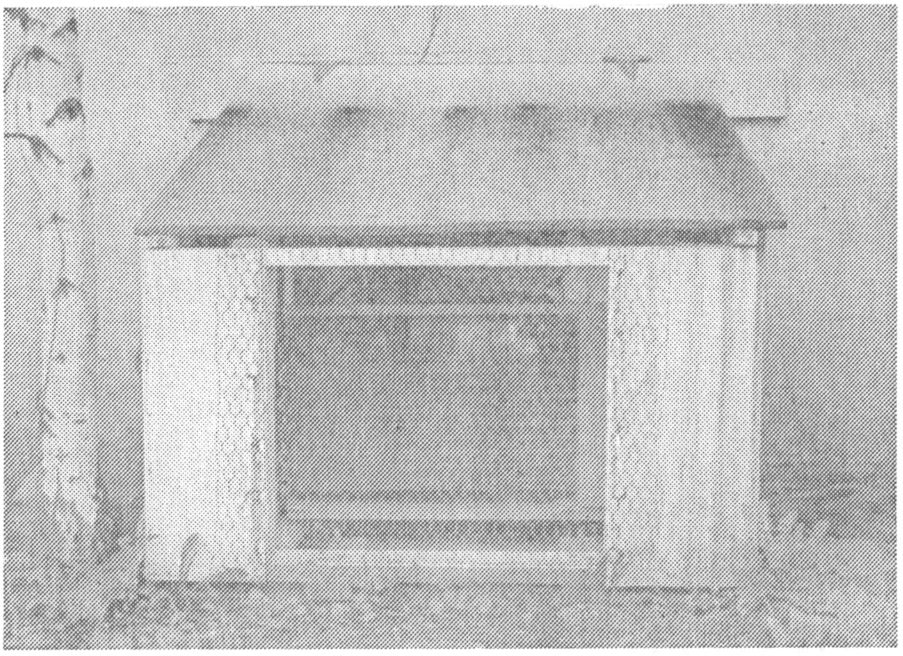
Windmill and Generator

A Swiss-manufactured Elektro 120 WVG windmill was purchased for use in this wind energy application. The windmill rotor was of the 3-blade type with a diameter of approximately 6.6 m (22 ft). The unit was rated by the manufacturer at 10 kW at a wind speed of 24 miles per hour.

The windmill and generator were mounted atop a 27 m (90 ft) tower (later reduced to 12 m (40 ft) for easier access). The guyed-tower was, actually, a radio tower with a reinforced upper section. The tower was placed approximately 90 m (300 ft) from the storage building.

Figure 11 shows the Elektro 120 WVG windmill mounted atop the 12 m tower at the VPI&SU Horticulture Research Farm.

A winch system at the tower base operated to take the windmill rotor out of the wind, i.e., to put the plane of the rotor parallel to the direction of the wind velocity, thus, preventing rotation of the rotor. The winch was driven by a small electric motor and was controlled from the equipment room in the storage building. The winch



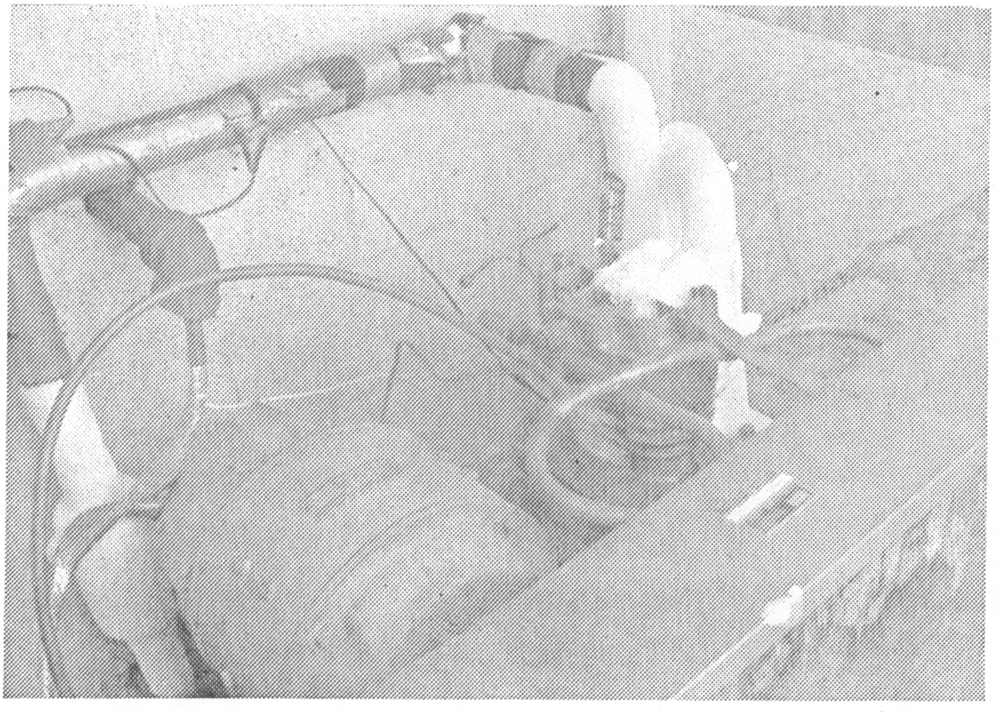


Figure 10. Views of the Compressor Shed and Condenser Installation

could also have been operated manually at the base of the tower with a hand crank.

A view of the control box at the base of the windmill tower housing the winch to turn the windmill out of the wind is also shown in Figure 11.

The generator produced 3-phase AC power which was rectified at windmill location. The resulting DC power was transmitted by a cable in an underground conduit to the storage building.

Specifications for the Elektro 120 WVG windmill are given in Appendix A. The variation of power with the rotor speed as specified by the manufacturer is shown in Figure 12.

Battery

A nickel cadmium battery with 91 cells, shown in Figure 13, was used for electrical energy storage and to provide stable windmill rotor speeds. Specifications for these cells are given in Appendix A. The battery was to provide a working voltage range of 91 - 135 VDC with a capacity of 13,200 W·h. The efficiency of these cells was initially expected to be 60 - 70 per cent.

Auxiliary Power Supply

Auxiliary power was provided by the local electric utility through the circuit shown in Figure 14. The circuit permitted the DC voltage to be varied, thus, varying the amount of power delivered to the system. Specifications for the components of the auxiliary power

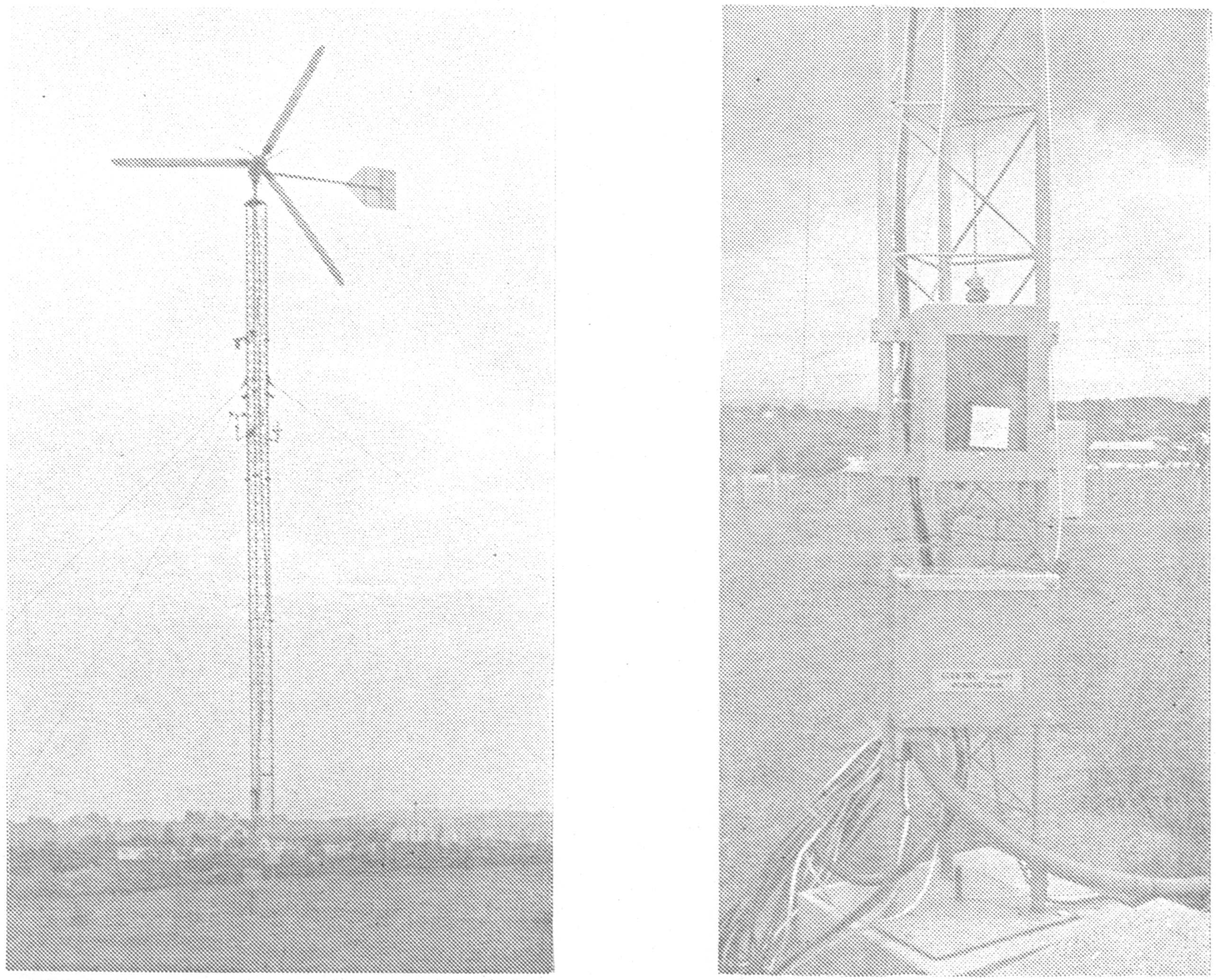


Figure 11. Views of the Elektro 120WVG and Control Box

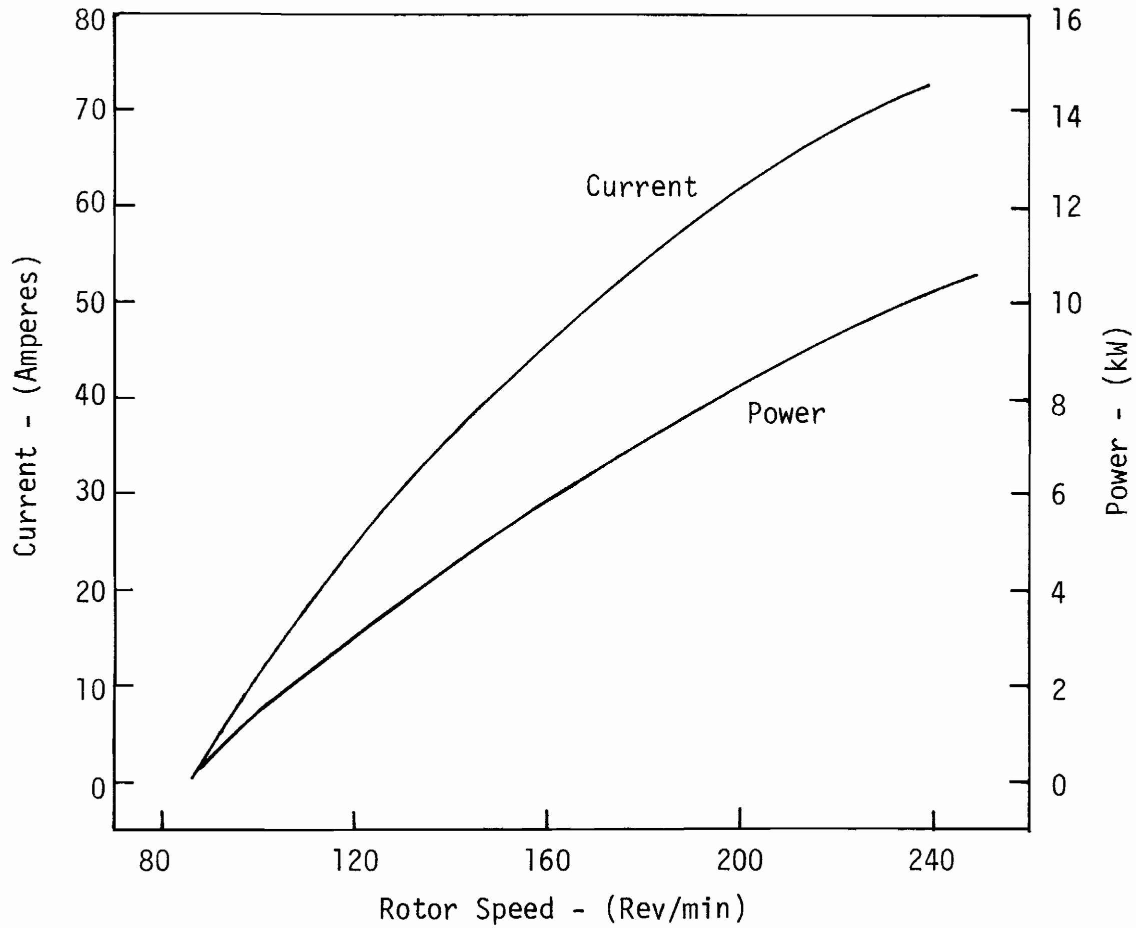


Figure 12. Manufacturer's Performance Data for Elektro 120WVG

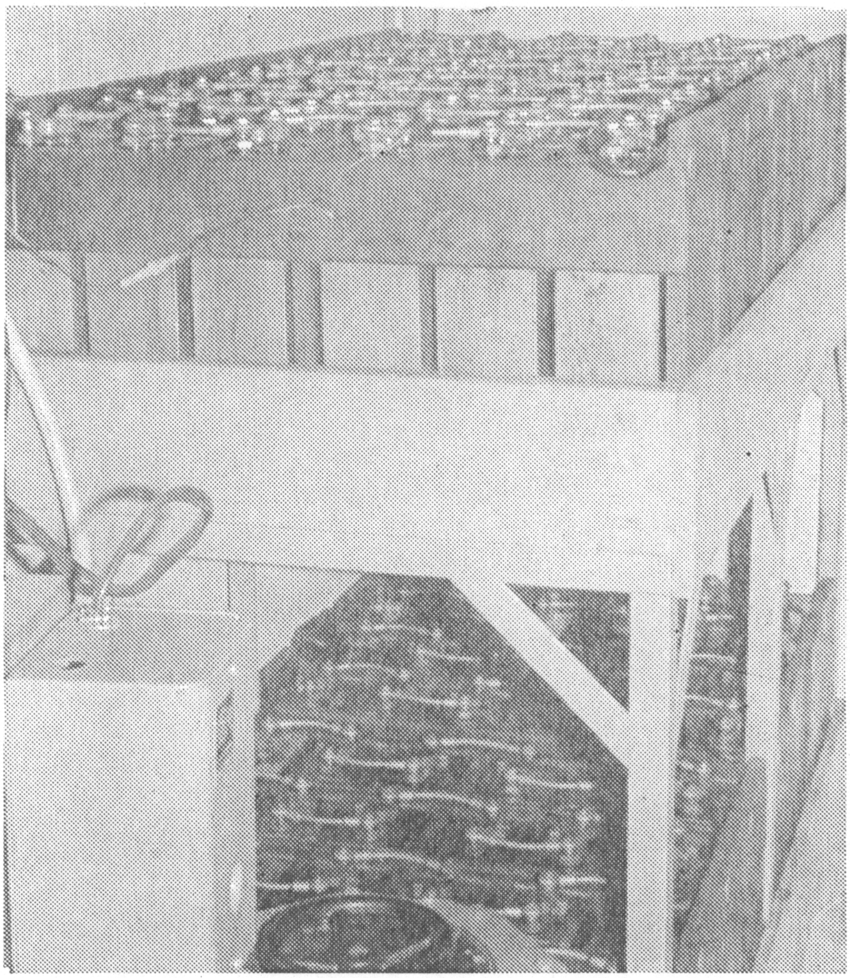


Figure 13. NiFe Nickel Cadmium Battery

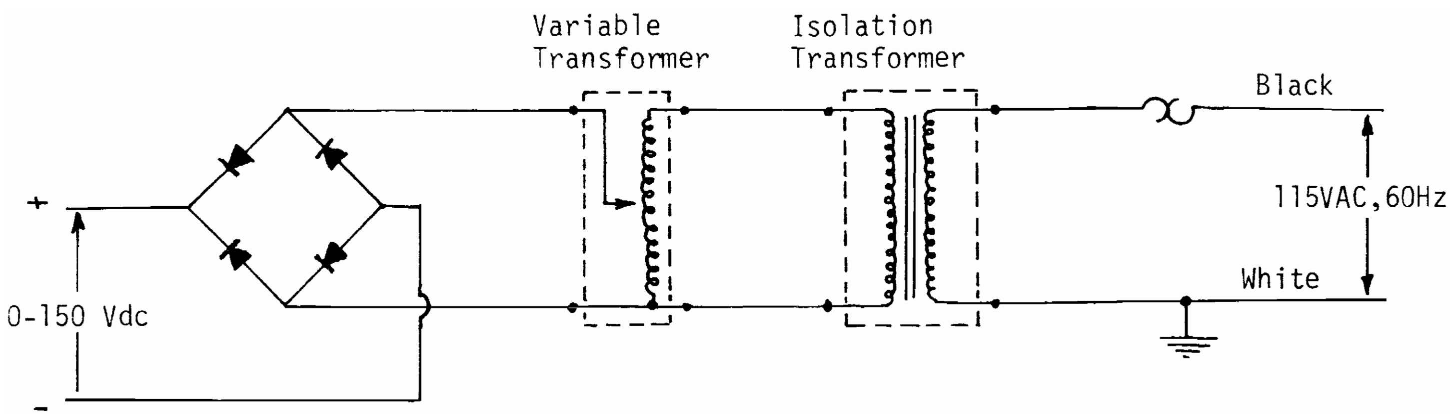


Figure 14. Circuit for Rectification and Control of the Auxiliary Power

supply are given in Appendix A.

The isolation transformer was employed to electrically isolate the system's electrical system from that of the utility. A variable transformer was used to vary the AC voltage applied to the full-wave, bridge rectifier which, in turn, provided the direct current for use by the electrical system. The bridge rectifier also prevented the windmill system from attempting to feed current back into the electric utility's service drop. The bridge rectifier with its heat sink and fan is shown in Figure 15.

A manually-actuated relay permitted the auxiliary power to be disconnected from the electrical system.

System Controls

The system controls can be divided into three groups: refrigeration system control, windmill control, and electrical system control. These groupings are not distinct, as some of the devices operate in more than one of these groups.

The refrigeration system control consisted of devices that determined when refrigeration was needed, when and how to defrost the the evaporator coils, and when precautionary measures were needed to protect the refrigeration equipment. A thermostat was located in the storage area and was used to determine if refrigeration was needed. If refrigeration were needed, the refrigeration system could be operated continuously in the refrigeration or defrost modes or cyclically with a period of one hour. When operated on an hourly cycle, the refrigera-

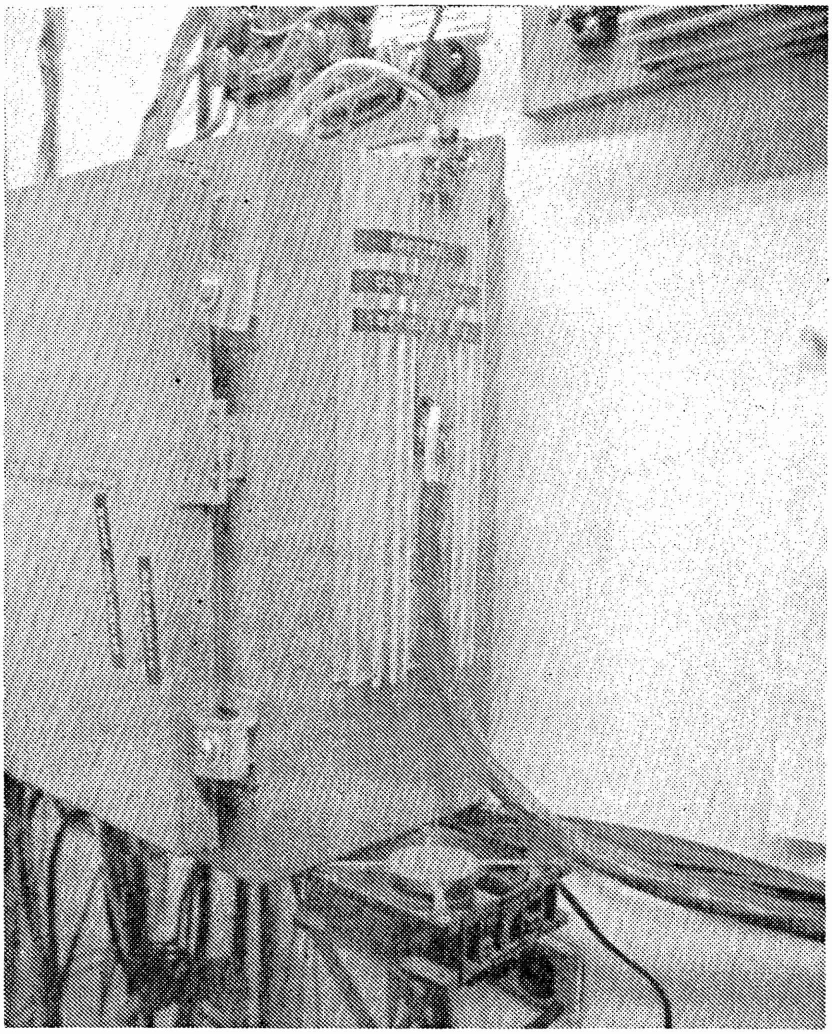


Figure 15. View of the Full-Wave Bridge Rectifier

tion system was operated with pre-set periods of hot-gas defrost or air defrost. The duty cycle of each option was manually adjustable. In either defrost mode the circulating fan could be operated continuously or cycled on and off with the compressor motor.

A 24-hour timer permitted the refrigeration system to operate in a particular mode (continuous refrigeration, continuous defrost, or off) for a selected time before continuing in either cyclic mode of operation. This operation was accomplished by disabling the drive motor of the one-hour timer with the timer mechanism set at the desired position.

In the event of colder weather a thermostat with its sensor located outside the building was used to determine when the outside (ambient) temperature dropped below some pre-set value (4-5^{o}C). When this occurred electric heaters (115/230 VAC) were turned on to heat the accumulator and the oil sump of the compressor. The sump heater was needed to prevent condensation of the refrigerant in the cylinder head which could damage the compressor when started.

The windmill control was designed to prevent damage to the unit and to return it to operation automatically. These controls were provided by the windmill manufacturer and were adjustable to a limited degree.

To prevent damage to the rotor when high wind speeds were encountered, a wind pressure switch was located on the windmill's generator housing. In the event of wind speeds in excess of 13 m/s (30 mph), the switch was activated, and the windmill was automatically turned out of the wind. After six hours (as determined by a timer) the windmill control would attempt to put the rotor back into the wind.

Controls were also available to sense an overvoltage (>150VDC) or overcurrent (> 55 Amperes) condition. The triggering values were adjustable to approximately ± 10 per cent. These conditions would automatically turn the windmill out of the wind for a period of six hours after which the system would attempt to put the rotor back into the wind. The overvoltage and overcurrent detection were needed to prevent damage to the generator and the electrical system to which it delivered power.

The electrical system control was designed to prevent damage to the refrigeration and electrical systems and to alter the operation of the electrical system.

A voltage-range, limit switch was used to ensure that the system (battery) voltage was within certain limits to ensure safe operation of the compressor motor. If the voltage dropped below the lower limit, the compressor motor was disabled for a 30-minute period to prevent damage to the motor. If the voltage increased above the upper limit the windmill was automatically turned out of the wind.

When it had been determined by the refrigeration system control that the compressor motor should be started, an electrical circuit initiated the motor's field current and ensured that it was sufficient for safe motor operation. This control also prevented overspeeding of the compressor motor during starting. If there were an insufficient field current, starting of the motor would be prevented.

The compressor was started (after a sufficient field current had been established) by connecting the armature of the motor to the system voltage through a motor starter. The motor starter had an electrically-locking coil and overload protection. The latter caused the circuit to be interrupted if excessive current ($>$ 40 Amperes) was drawn by the motor. When tripped, the motor starter had to be manually reset by the system operator.

A drop-out relay was used to prevent damage to the system in the event of an electrical failure in the local AC power because part of the system was operated from this source. In the event of such a failure, the system operator had to manually reset (energize) this relay.

The auxiliary power supply was connected to the electrical system through a motor starter operated, also, from the local utility. This relay also had to be reset by the system operator in the event of a local utility power failure. The transformers were protected by a 50-Ampere circuit breaker.

The auxiliary power could be varied manually by the adjustment of the variable transformer.

Instrumentation

The instrumentation employed at the VPI&SU wind energy research facility included those instruments necessary for monitoring the environmental conditions relative to the refrigeration performance and those for monitoring the condition and performance of the total electrical system.

A 16-channel temperature recorder recorded the temperatures at various points of interest through the use of iron-constantan thermocouples. An ice-bath was also used to compensate the recorded data for a zero offset in the recorder's signal processing circuitry. Thermocouples were located in the storage area, in the air ducts at several locations, and outside the storage building.

The relative humidity within the storage area was monitored with a wall-mounted hygrometer and a portable recording hygrometer.

Electrical system instrumentation was provided to monitor instantaneous system conditions as well as energy usage and production. The system voltage, motor current, and battery current were monitored with meters. The instantaneous power developed by the windmill generator and consumed by the compressor motor were displayed by a pair of Watt-hour meters shown in Figure 16. These units (WH-7 Watt-Hour Meter, Series 917U, Ohio Semitronics, Inc.) also included the circuitry for integrating instantaneous power and present the result via a mechanical counter displaying accumulated Watt-hours of electrical energy.

Wind speeds were determined with the use of an M.C. Stewart anemometer with a mechanical counter to total the accumulated wind distance measured in sixtieths of a mile. Thus, the average wind speed during a given time interval could be determined by dividing the total by the length of the time interval measured in minutes.

The accumulated electrical energy taken from the local electric

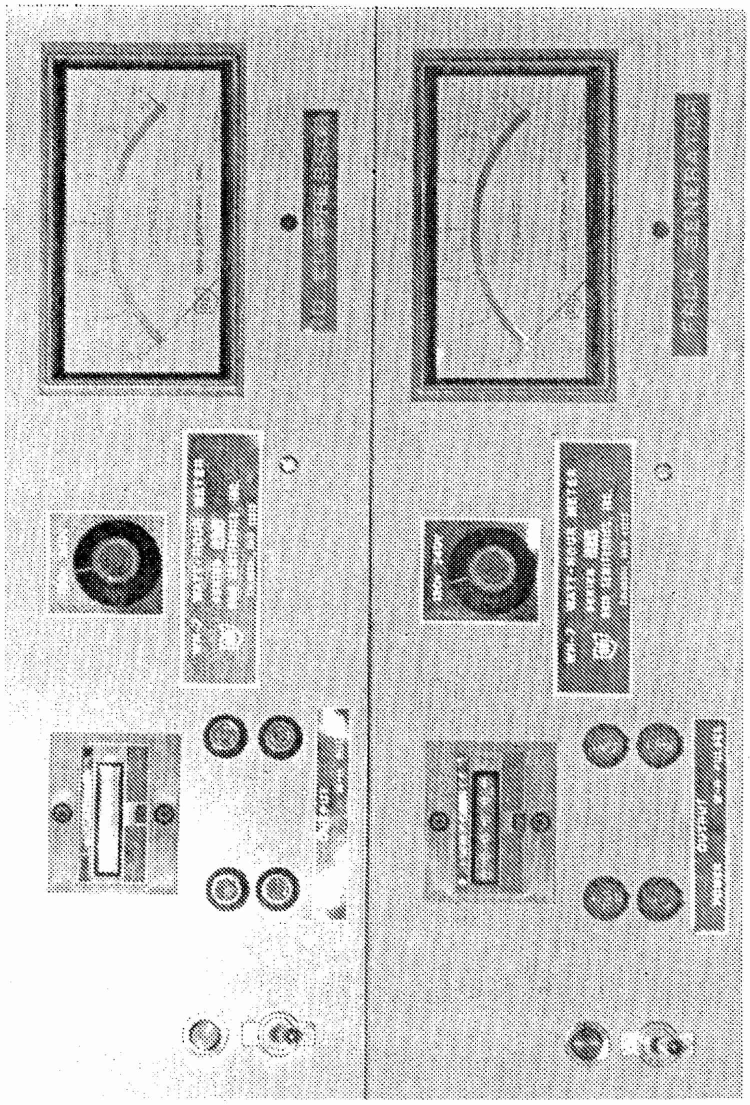


Figure 16. WH-7 Watt-Hour Meters

utility was determined with an electrical circuit and digital display used in conjunction with a standard 120 VAC electric kilowatt-hour meter. The circuit was based on the fact that each revolution of the disk in the electric meter used represented two Watt-hours of electrical energy. A schematic representation of the detector and pulse generating circuit is shown in Figure 17. The presence of two holes in the disk resulted in the need to count the passage of these holes; the passage of each hole representing the consumption of one Watt-hour of electrical energy. This counting was done with the use of the infra-red emitting diode and matching phototransistor detector. These devices together with a single PNP switching-transistor provided a TTL-compatible, negative pulse at the passage of each hole in the meter disk. These pulses were counted and displayed with standard TTL circuitry and a three digit LED (light-emitting diode) display. The accumulated Watt-hour counts in excess of 1000 W·h could be accommodated by synchronization of the LED display with the indicating dials on the face of the electric meter. Appropriate filtering was required to prevent false triggering of the digital counter circuitry.

An additional meter was employed to measure the Watt-hours of electrical energy taken from the local electric company to operate the duct fan.

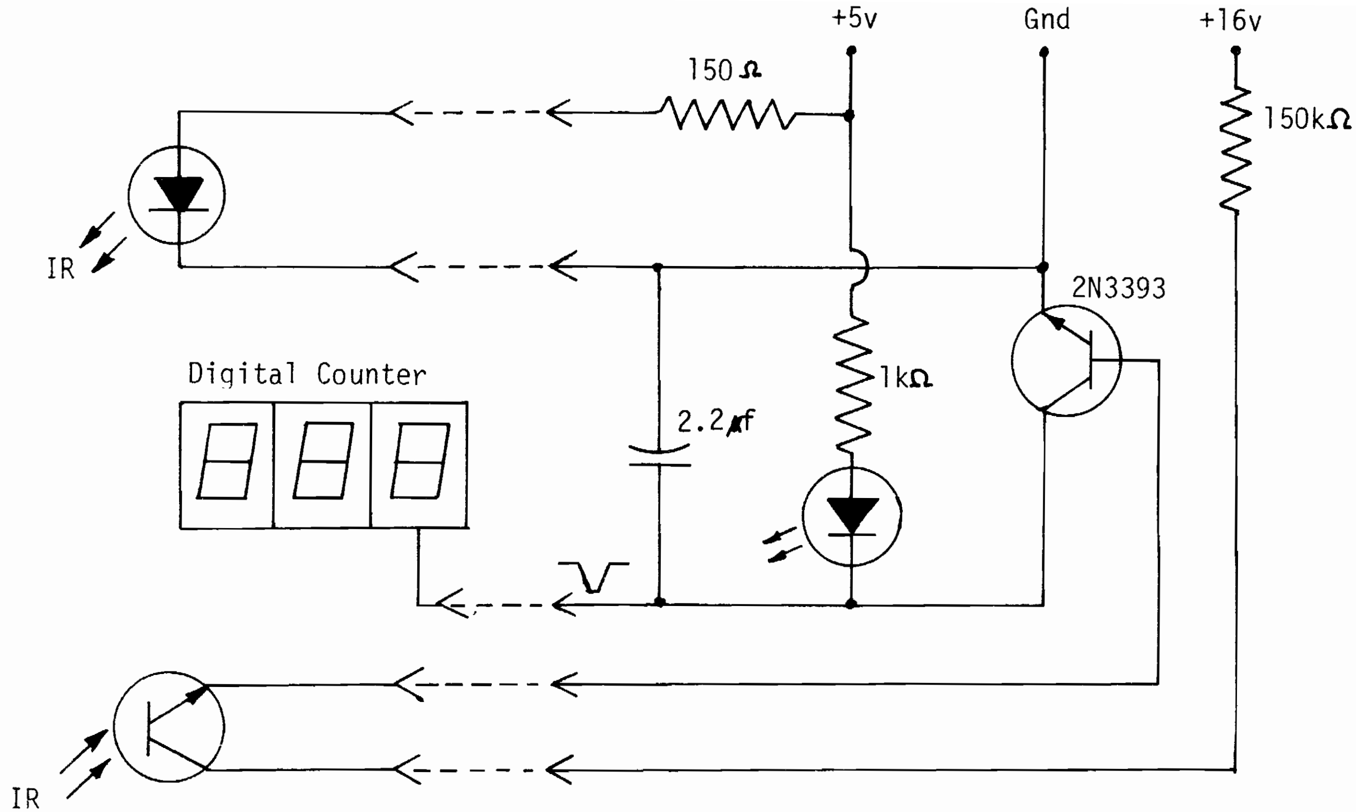


Figure 17. AC Watt-Hour Detection and Pulse Generator Circuit

XI. PERFORMANCE STUDIES OF THE VPI&SU WIND-POWERED REFRIGERATION SYSTEM

To develop an improved control strategy for the VPI&SU wind-powered refrigeration system, it was necessary to study the performance of each component or sub-system. The pertinent data relative to the energy usage, transmission, or production of each were collected through tests with specific intent and from data collected during a five-day test period in March, 1979.

Compressor Motor

The DC motor used to drive the compressor constituted the major electrical load of the system, and data were obtained relating to its performance under various operating conditions. The motor, the specifications of which have already been presented, was shunt-wound, i.e., field windings in parallel with the armature windings. The performance of the motor was expected to be similar to that of shunt-wound motors in general. In October, 1977 the motor was tested by Inland Motor Co., Radford, Virginia to determine the motor characteristics at its rated voltage of 115 VDC [10]. The load torque was varied so that the power developed varied from 0.4 to 4.5 kW (0.5 to 6.0 hp). The armature current, speed, and efficiency were also determined. The results of the test are shown graphically in Figure 18.

That the armature current varies linearly with torque is apparent, as expected for a shunt-wound motor, because the field current remained constant throughout the test. Good speed regulation, characteristic of

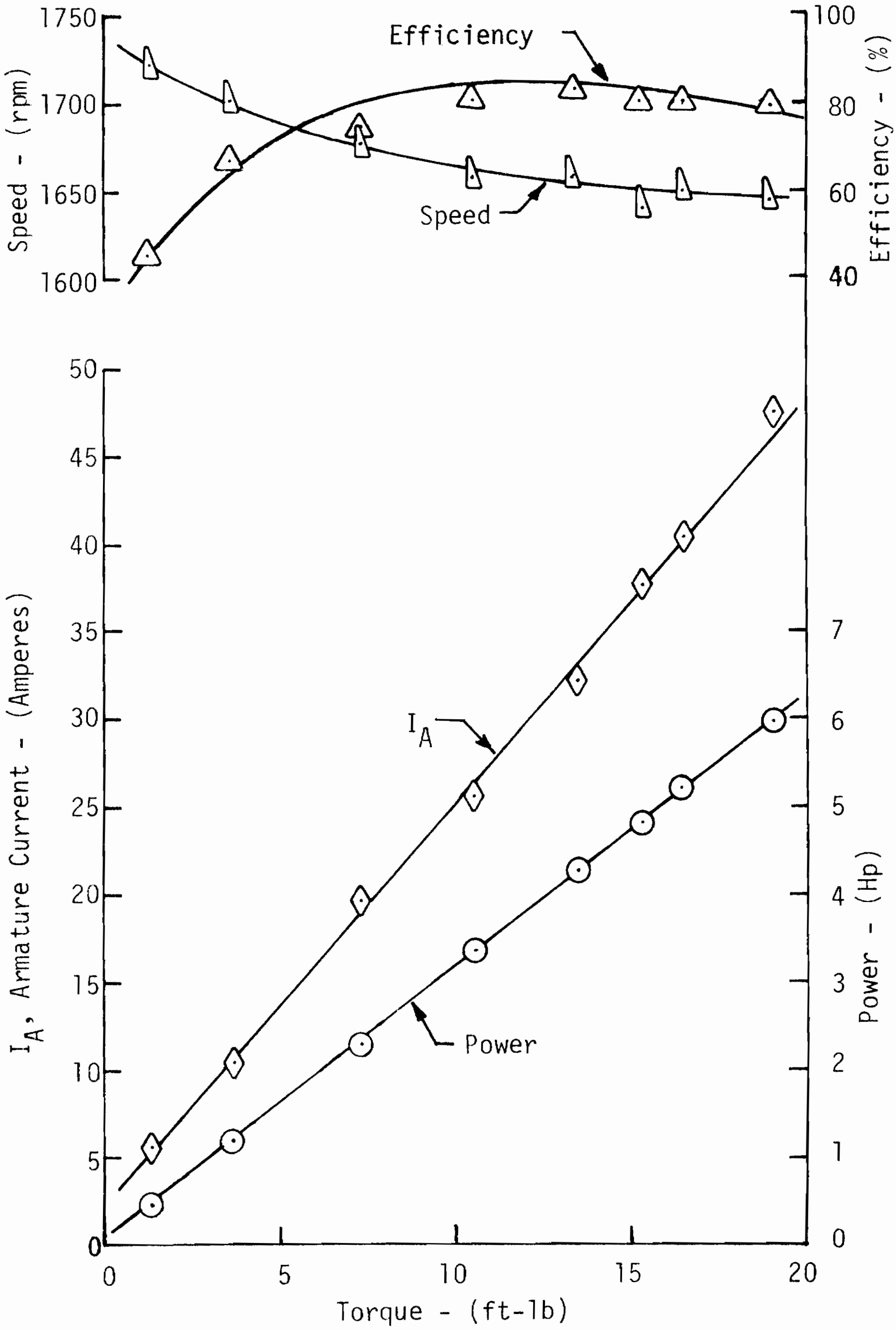


Figure 18. Compressor Motor Performance at 115 Vdc [10]

these type motors, was also evident in this test. The motor had a maximum efficiency of 82 per cent and dropped rapidly for developed power below 2.6 kW (3.5 hp). The test investigators noted that the "motor would become unstable at higher torque with this field and at lower torque values for lower fields" [10].

Because the system voltage could vary significantly, the voltage impressed on the armature and field windings differed greatly from the motor's rated voltage. This variation should have also caused the field current and the field strength to vary. Therefore,the armature current should have varied inversly with the impressed voltage [11].

A series of tests were conducted to determine this effect. Because of the good speed regulation of shunt-wound motors, operation of the compressor at a given condenser pressure was expected to produce a nearly constant torque demand on the motor. The compressor motor was operated in both the refrigeration and defrost modes for small time intervals. During the tests the system voltage was varied while the variation of the power consumed by the motor and the system voltage were recorded. The average compressor power at each voltage was determined by measuring the time required for a given number of Watt-hours to be accumulated as recorded by the WH-7 Watt-Hour Meter. The time period was measured with a hand-held stop watch. Voltages were measured with a Keithley digital multimeter.

From the obtained data, the corresponding total motor current I_m (field current + armature current) was determined from

$$I_m = P_C/V \tag{1}$$

where P_C and V are the power drawn by the compressor motor and impressed voltage, respectively.

The results of these tests together with grouped data from a 5-day test are presented in Tables 1-3. In both the defrost and refrigeration modes of operation the motor current had little apparent variation. The data in Group 6 were taken when the ventilation of air through the condensing unit was restricted by surrounding the compressor covering with heavy carpeting. Restricted air flow caused elevation of the condensing pressure which might be useful in periods of cold weather. Two additionally important observations can be made from the test data, i.e., the power required increased with condensing pressure and at a given pressure the required power increased with voltage. The latter observation appears to contradict the known behavior of shunt-wound motors. However, if the field windings were in a saturated condition, there would be little, if any, effect of voltage on field strength. Thus, little variation of armature current would be expected [12].

A summary of the test data has been compiled in Table 4. The range of the voltage, the average condensing pressure, the number of observations, the average total motor current, and the sample standard deviation for motor current are given for each group.

The average motor current was plotted as a function of condensing pressure as shown in Figure 19. The resulting plot suggests that the required motor current increases in direct proportion with the conden-

Table 1

Motor Voltage Variation Test (Groups 1-4)

Group	p_c - (psig)	Mode*	P_C - (Watts)	V - (Vdc)	I_m - (Amperes)
1	60	D	1823	126.3	14.43
			1875	130.3	14.39
			1748	121.8	14.35
			1702	118.8	14.33
			1698	118.0	14.39
			2017	139.5	14.46
			2010	141.0	14.26
2	80	D	1910	119.0	16.05
			1967	125.2	15.71
3	70	D	1674	112.0	14.95
4	115-120	R	2970	134.2	22.13
			2857	129.8	22.01
			2727	125.3	21.76
			2637	119.8	22.01
			2590	117.4	22.06
			2526	114.3	22.10
			2520	110.6	22.78

* Note: D = Defrost; R = Refrigeration

Table 2

Motor Voltage Variation Test (Groups 5 & 6)

Group	p_c - (psig)	Mode*	P_C - (Watts)	V - (Vdc)	I_m - (Amperes)
5**	121	R	2650	121	21.9
	117.5		2600	122.5	21.2
	118		2550	123	20.7
	118		2500	120	20.8
	125		2520	117	21.5
	120		2550	121	21.1
	122		2600	121	21.5
	120		2360	111	21.3
	120		2400	109	22.0
	122		2380	109	21.8
6**	160	R	2750	110.5	24.9
	163		2800	111.5	25.1
	165		2850	120	23.8
	163		3300	139.5	23.7

* Note: D = Defrost; R = Refrigeration

** 5-day test data

Table 3

Motor Voltage Variation Test (Groups 7 & 8)

Group	p_c - (psig)	Mode*	P_C - (Watts)	V - (Vdc)	I_m - (Amperes)
7**	98	R	2510	122	20.6
	99		2530	122	20.7
	103		2530	120	21.1
	100		2500	121	20.7
	98		2400	121	19.8
	100		2500	124.5	20.1
	95		2400	125	19.2
	100		2175	106	20.5
	101		2200	107	20.6
	100		2190	107	20.5
	102		2260	111	20.4
	100		2250	112	20.1
	96		2210	110	20.1
	100		2275	113	20.1
8**	78	R	2300	121	19.0
	80		2350	125	18.8
	80		2300	122	18.9

* Note: D = Defrost; R = Refrigeration

** 5-day test data

Table 4

Motor Voltage Variation Test Summary

Group	p_c - (psig)	No. of Observations	Voltage Range (Vdc)	Avg. Motor Current $\overline{I}_m$ (Amperes)	$s_{\overline{I}}$ (Amperes)
1	60	7	118 - 141	14.37	0.0665
2	80	2	119.0 - 125.2	15.88	0.2404
3	70	1	112	14.95	------
4	118	7	110.6 - 134.2	22.12	0.3145
5	120.35	10	109 - 123	21.38	0.4442
6	162.8	4	110.5 - 139.5	24.38	0.7274
7	99.4	14	106 - 125	20.32	0.4677
8	79.3	3	121 - 125	18.90	0.1000

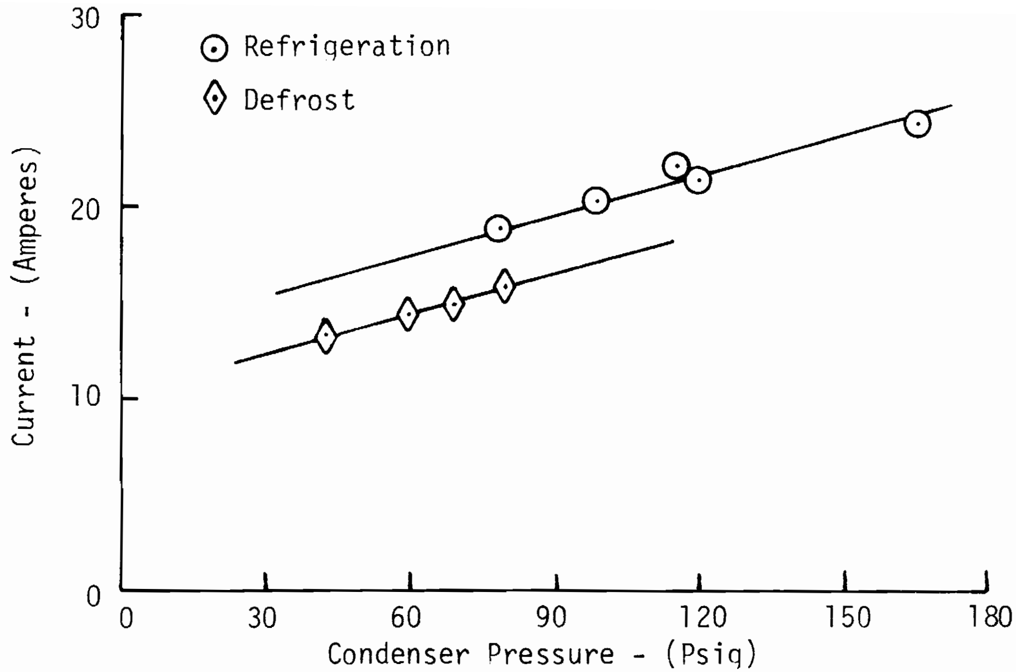


Figure 19. Variation of Motor Current with Condenser Pressure

sing pressure in a given mode of operation. The rate of increase is nearly identical in both the refrigeration and defrost modes, with the refrigeration mode requiring a constant amount of current above that required in the defrost mode at the same condensing pressure.

The condensing pressure varied with ambient temperature as shown in Figure 20 when the compressor was operated in the refrigeration mode. The data for restricted flow were obtained when the circulation of ambient air through the condenser was reduced by placing carpet material around the compressor shed. This technique would be useful for colder weather to prevent evaporator pressures from becoming too low and causing excessive production of ice on the coils.

The power required by the compressor motor decreased with the impressed voltage. The efficiency is not improved, however. Tests conducted at a later time indicated a corresponding reduction in the compressor motor speed. The speed reduction, in turn, led to a proportional decrease in the refrigeration effect produced. Thus, a reduction in the system voltage does not improve the system efficiency directly. Because of the efficiency of the auxiliary power supply, however, there is a resulting reduction in the need for auxiliary power when it is used.

Battery

A test was conducted to compare the performance of the C3600 nickel cadmium battery with data provided by the manufacturer. The primary objective was to determine the capacity of the battery and to

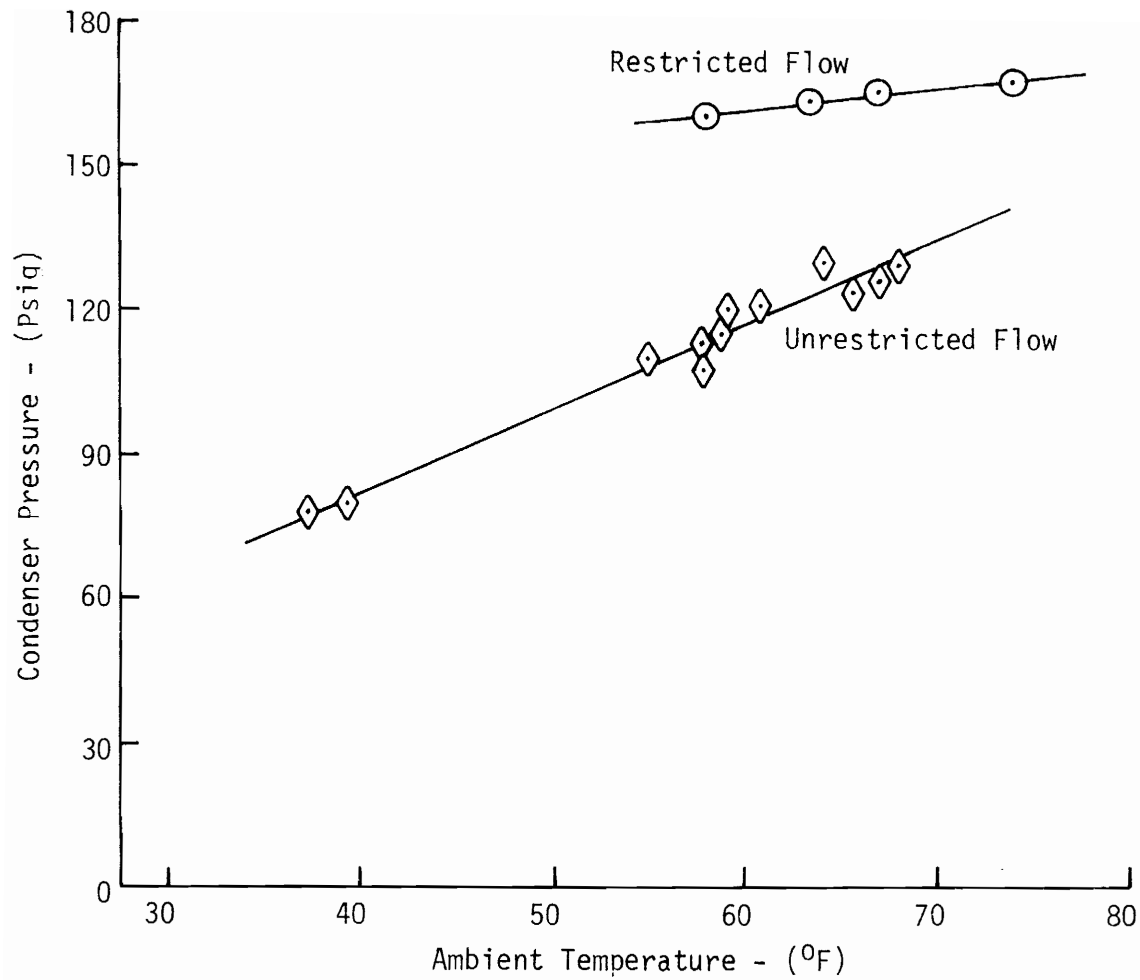


Figure 20. Variation of Condenser Pressure with Ambient Temperature develop an estimate of the battery's internal resistance. The history of this battery's prior usage was unknown.

In preparation for the test the battery was discharged to a working voltage of 94 VDC by operation of the compressor motor. The battery was then charged from power delivered by the auxiliary power supply. Charging of the battery continued until the impressed voltage of 144 VDC was attained. The auxiliary power supply was then disconnected and the compressor motor operated in the hot-gas defrost mode to discharge the battery. The windmill was turned out of the wind for the entirety of the test to prevent extraneous power from entering the system.

A history of the battery terminal voltage during the test is shown in Figure 21. The change in battery voltage at the beginning of the charging and discharging periods combined with the associated battery currents provided an estimate of the battery's internal resistance at full-charge of 0.35 Ohms and 0.50 Ohms at discharge. Integration of the voltage and current product indicated that the capacity of the battery was only 15 per cent of the rated capacity for new batteries. This reduction in capacity indicated that the useful life of the battery had expired. Although the discharge and charge characteristics differ little from that of a new battery, a nearly expired nickel cadmium battery will typically demonstrate little more than a reduction in capacity. In most battery applications where nickel cadmium batteries are employed, the battery is considered to have expired when the capacity has been reduced to 80 per cent of the original [13].

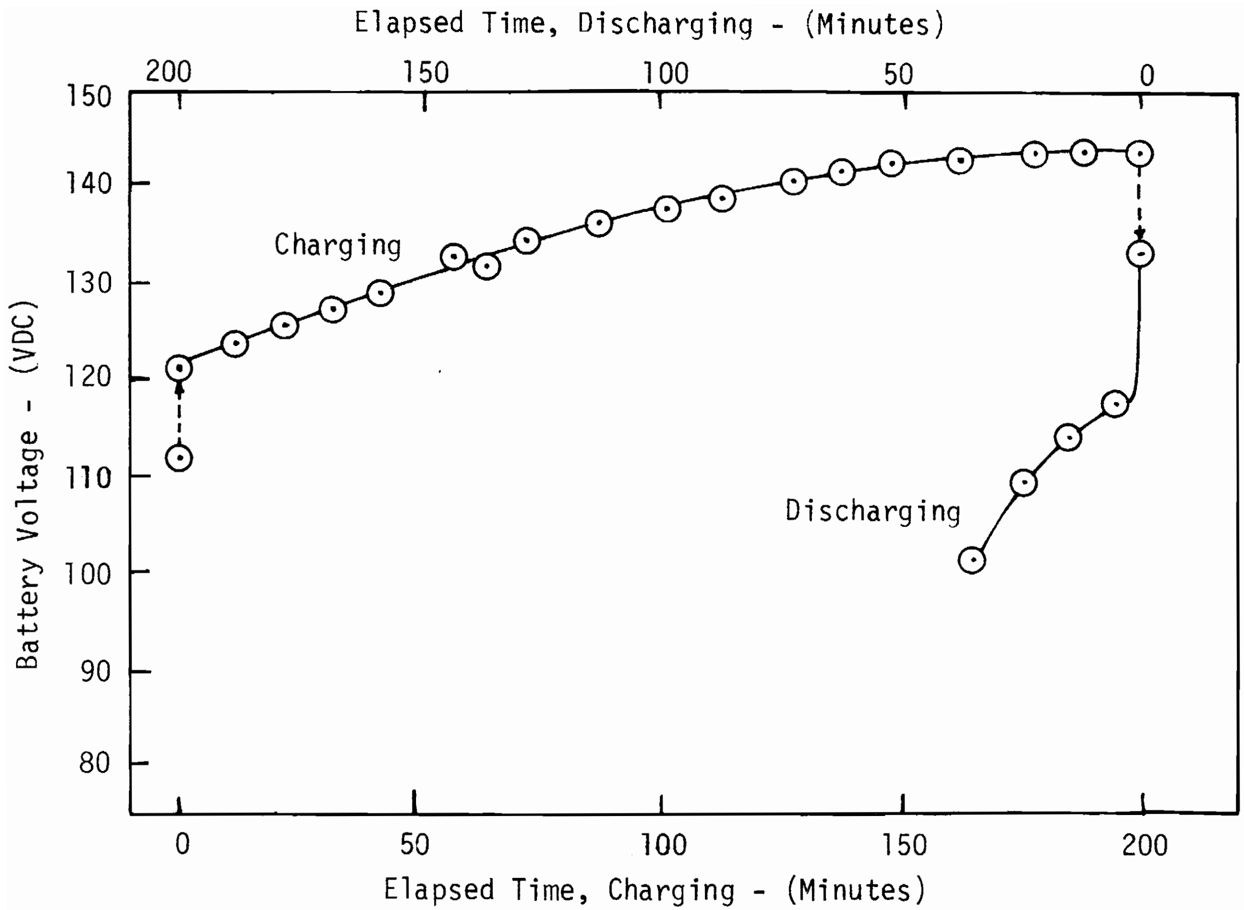


Figure 21. Voltage Variation During the Battery Test

During the charging period of the test, 3337 W•h of electrical energy were delivered to the battery, of which only 1950 W•h were recovered during the discharging period. This compares with the rated capacity of 13,200 W•h as given by the manufacturer's data for new, fully-charged batteries. The above data also indicate that the efficiency is approximately 58 per cent. Some inaccuracy was inherent in this efficiency estimate because of the difficulty in determining when the battery was fully charged and when, after discharging, the battery had returned to the same state-of-charge that existed prior to charging.

Auxiliary Power and Rectification

The performance of the auxiliary power system is of considerable importance in developing an improved operational strategy for a wind energy system, especially with a system which needs to be operated most of the time because of the requirements of the application. The VPI&SU wind energy system is an example of this need.

The need to extract as great an amount of available wind energy becomes apparent when the realization is made that the use of electrical power from a local utility is inefficient. Without any wind energy being developed, a direct current electrical system will require more total electrical energy than an equivalent alternating current electrical system, due to the greater inefficiency resulting from the rectification of the alternating current.

In deleloping an improved operational strategy, _in situ_ windmill system performance tests were conducted. No means of directly measuring the net energy transfer to or from the battery were available. However, this transfer could be determined indirectly if the efficiency of the auxiliary power system were known.

A series of tests were conducted to determine the variation of the auxiliary power supply efficiency with load, battery voltage, and auto-transformer settings. The efficiency was found to be nearly independent of all the factors mentioned above (Table 5).

The AC and DC power were determined by operating the compressor solely from the rectified output of the auxiliary power system. Under these conditions the battery current was held at zero. This condition was equivalent to removing the battery from the system. The efficiency was then determined by measuring the Watt-hours consumed by the compressor motor and the corresponding number of Watt-hours consumed from the local utility. The system voltage, which was altered by adjustment to the variable transformer was also recorded. The battery was then charged or discharged to the equilibrium point where the battery current was reduced to zero. The voltage output of the variable transformer with and without a load were also recorded.

Windmill

To develop optimal operational strategies, determination of the effect of various loads on the generator was necessary. While data can be provided by the manufacturer of a windmill, inherent deviations are present due to differences in permanent magnets, bearing tolerances,

Table 5

Power Supply Efficiency Test

V_U-(Vac)*	Battery Voltage (Vdc)	Mode **	Power, In (Watts)	Power, Out (Watts)	Efficiency (%)
95	106.5	D	1920	1594	83
95	106.5	D	1821	1566	86
95	107	D	1855	1595	86
95	101	R	2418	2031	84
95	101	R	2405	2020	84
100	114.5	D	1998	1678	84
100	114	D	2044	1696	83
100	108	R	2643	2194	83
100	108.5	R	2588	2174	84
105	122.5	D	2095	1718	82
105	122	D	2138	1689	79
105	122.5	D	2076	1744	84
105	121	R	2183	1899	87
105	116	R	2719	2338	86
113	117	R	3468	2879	83
113	117	R	3568	2854	80
110	119.5	R	2868	2409	84
---	103	R	2510	2109	84
---	102.5	R	2473	2077	84
---	107	D	1915	1609	84
---	108	D	1846	1588	86
98	112.5	D	2014	1760	87.4
98	112	D	2023	1740	86
98	106	R	2560	2150	84
98	106	R	2529	2150	85

Table 5 (Cont.)

Power Supply Efficiency Test

V_U-(Vac)*	Battery Voltage (Vdc)	Mode **	Power, In (Watts)	Power, Out (Watts)	Efficiency (%)
95	100	R	2610	2140	82
95	101	R	2512	2110	84
95	105	D	2083	1750	84
110	118	R	3185	2580	81
110	117.5	R	3159	2590	82
104	119.5	D	2110	1850	87.7
114	120	R	3352	2812	83.9
112.5	118	R	3186	2717	85.3
107.5	118.3	D	2261	1978	87.5
113.7	123.5	R	3019	2570	85.1
---	130	R	3243	2951	91.0
---	130	D	2456	2156	87.8
Average Efficiency = 84.42 %					
Standard Deviation = 2.32 %					

* No-load, Secondary Voltage of Variable Transformer
** D = Defrost; R = Refrigeration

etc. Variations can also occur as a result of improper maintenance, weather conditions and temperature, and malfunctions.

Generator Lab Test

The performance of the windmill's generator was studied by Hinerman [14]. The generator was connected to a dynamometer and the applied torque, speed, and electrical load were varied and recorded. The resulting voltage and current developed were also recorded. The data have not been tabulated here, but are presented graphically for several nominal speeds in Figures 22 and 23. In Figure 22 lines of constant developed power have also been included.

As seen in Figure 22, when the generator is unloaded, i.e., zero current output, the output voltage of the generator varies linearly with speed. However, to maintain a given voltage as the load on the generator is increased the speed of the generator must also increase. Also, the current that can be derived from the generator at a given speed is limited, as evidenced by the downward-turning behavior of the lines of constant speed.

The empirical equation

$$V = 1.6794N - 15 - 2.1I_G - \frac{0.0016N^2}{(0.2857N - I_G)} \qquad (2)$$

was developed to relate the voltage, speed, and output current of the generator.

The generator efficiency was evaluated for several rotor speeds

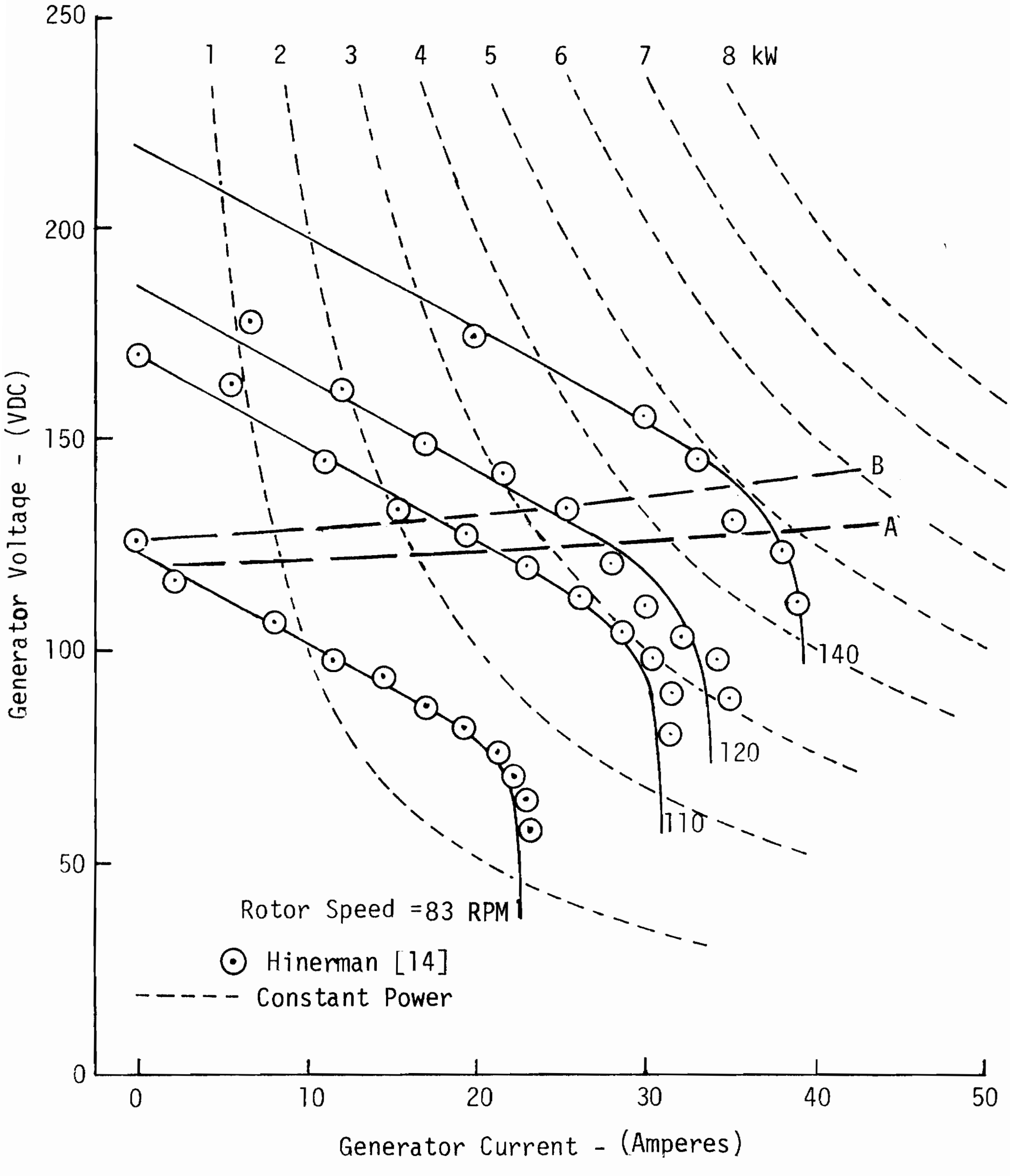


Figure 22. Elektro 120WVG Performance Test (Voltage vs. Current, RPM)

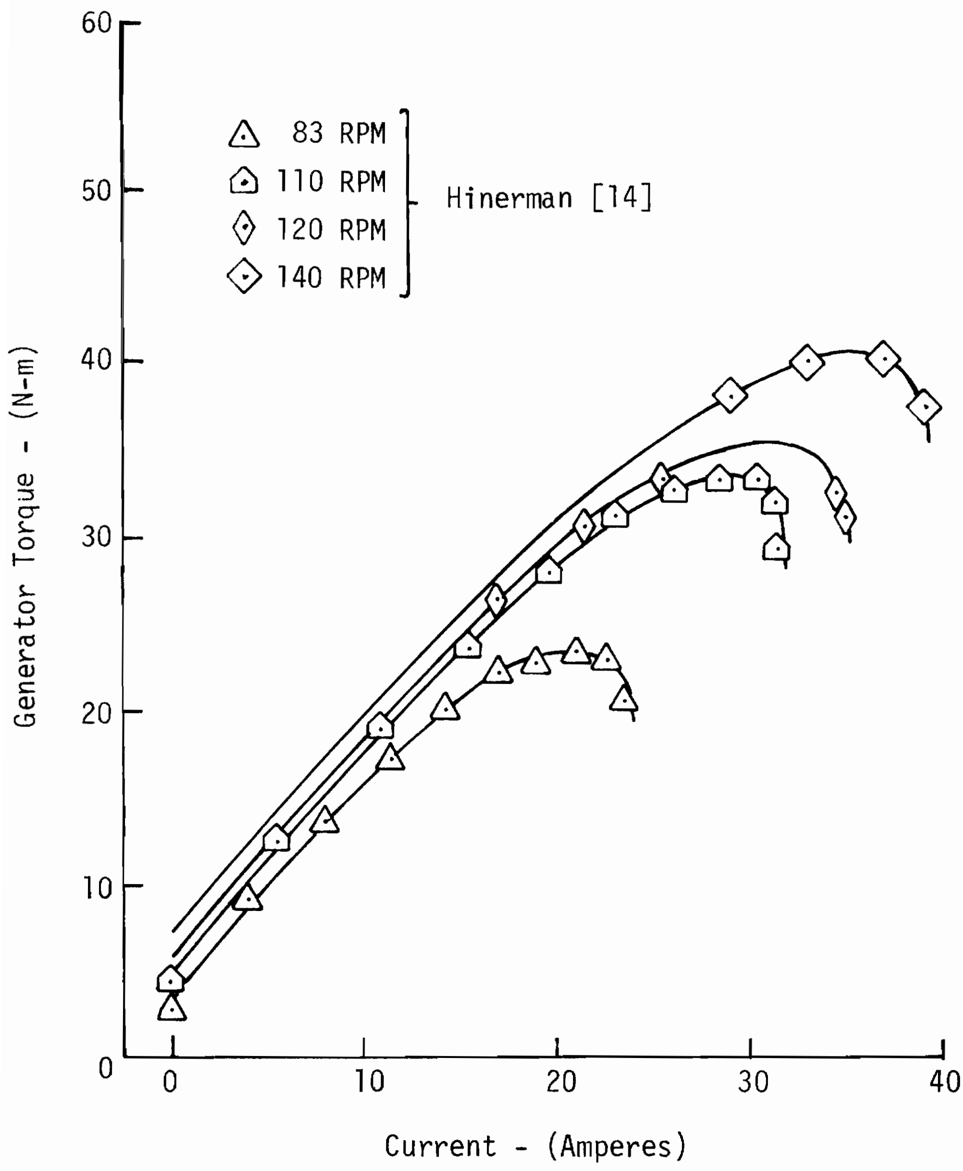


Figure 23. Elektro 120WVG Performance Test (Torque vs. Current, RPM)

and its behavior is depicted graphically in Figure 24.

Rotor Characteristics

Since the windmill's rotor has its own performance characteristics relating torque, rotor speed, and wind speed, the performance data presented in Figures 22 and 23 do not indicate the operating point of the generator at a given wind speed. For a given type of electrical load, i.e., variation of current with voltage, a single operating point exists at each possible wind speed where the torque and speed of both the rotor and generator coincide. This behavior produces some difficulties for a windmill manufacturer in specifying the power output of a given wind-powered generator because the power developed at a given wind speed depends upon the electrical load characteristics. Obviously a set of operating points exists for each wind speed and one of these points produces the greatest amount of electrical power from the available power of the wind. The collective set of these optimum operating points then constitutes the maximum power output of the windmill as a function of wind speed. This result could be expected to be the manufacturer's rated power curve.

Referring back to the Elektro 120 WVG power versus rotor speed shown in Figure 12, the optimum load curve, i.e., voltage versus current, can be determined by taking the power, P_G, and current, I_G, at each rotor speed, N, and determining the corresponding voltage, V_G, from

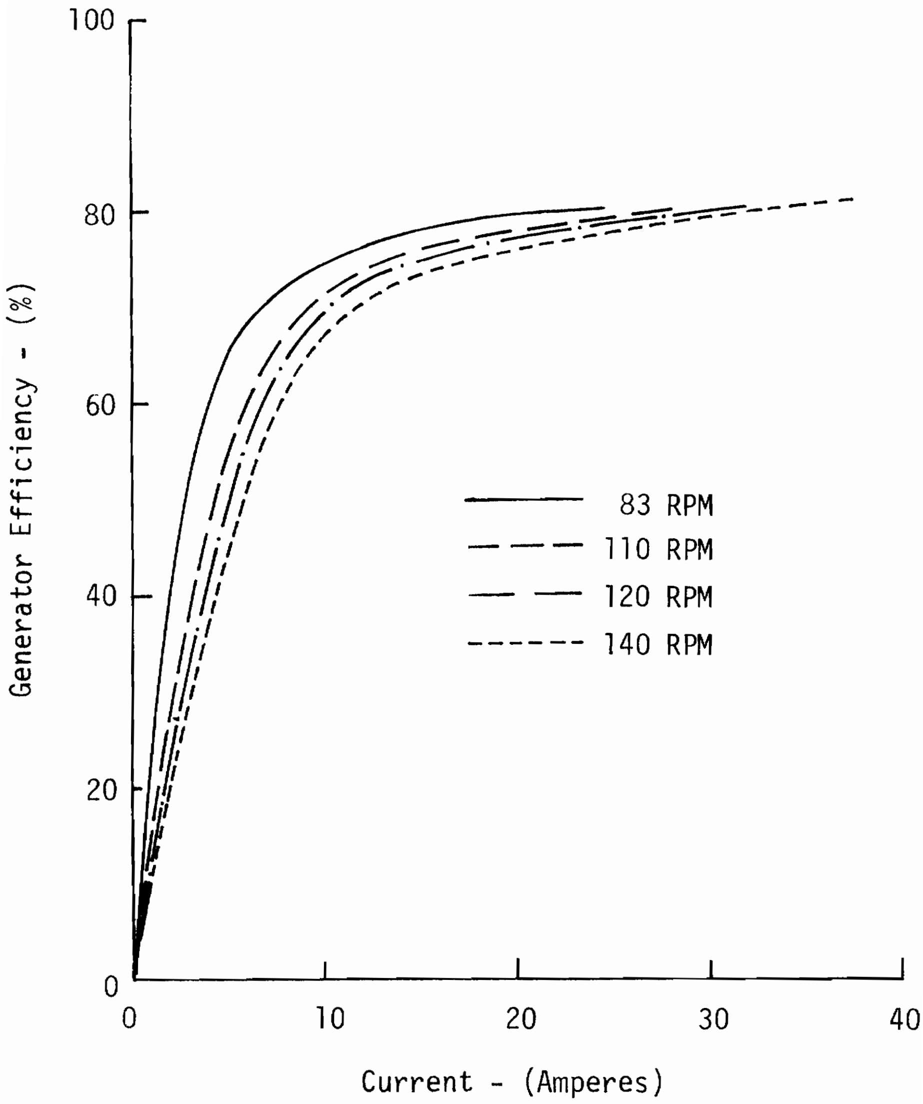


Figure 24. Elektro 120WVG Generator Efficiency

$$V_G(N) = \frac{P_G(N)}{I_G(N)} \tag{3}$$

The voltage computed above should then be the same as would be computed by Equation (2). These two values are not the same, however, indicating that there are either significant manufacturing differences or that there have been significant modifications, perhaps field winding changes, made to the unit purchased for the VPI&SU research project. These differences could drastically alter the efficiency of the windmill.

An error could possibly have been made in the development of one of the manufacturer's curves. Two different load curves were developed from the manufacturer's curves of Figure 12 and are shown in Figure 22. Curve A was developed by computing values of $V_G(N)$ in Equation 3 with values of P_G and I_G taken from Figure 12 for several selected values of rotor speed N. Curve B was determined from the manufacturer's current versus rotor speed curves with the use of the empirical relationship (Equation 3). Curves A and B have nearly equal slopes with the difference primarily being a voltage displacement.

Generator Load Curves

The efficiency at which a wind-driven generator converts wind energy into electrical energy is controlled, in part, by the nature of the electrical load imposed on the generator and its deviation from the ideal. The ideal load curve, however, is governed by the characteristics of the rotor and generator designs.

A generator load curve is a continuous set of points for which every point represents a unique combination of generator voltage and current. These curves are generally plotted as voltage versus current. The simplest load curve is that for a fixed-value resistive load. In this case the load curve is a straight line passing through the origin; the slope of the line is equal to the load resistance.

The electrical configuration employed in the VPI&SU windmill system has been simply modeled for illustrative purposes as shown in Figure 25. The internal resistance of the battery was assumed to have a constant value of 0.4 Ohms. The open-circuit battery voltage was assumed to be 120 VDC and that neither the internal resistance nor the open-circuit battery voltage are affected by the battery's state-of-charge or by the direction or magnitude of the battery current. The auxiliary power supply was modeled as a constant DC voltage source with an internal resistance. The resistance was assumed to be a function of the current I_{AUX} as is typical for full-wave bridge rectifiers. From data employed in the power supply efficiency test the resistance was estimated as

$$R(I_{AUX}) = 2.4 - 0.035I_{AUX} \tag{4}$$

where the resistance is in Ohms and I_{AUX} is given in Amperes.

From this circuit with the parameters shown three typical, generator load curves were developed (Figure 26). Load curve A is for operation of the battery and the windmill generator alone. Since no cur-

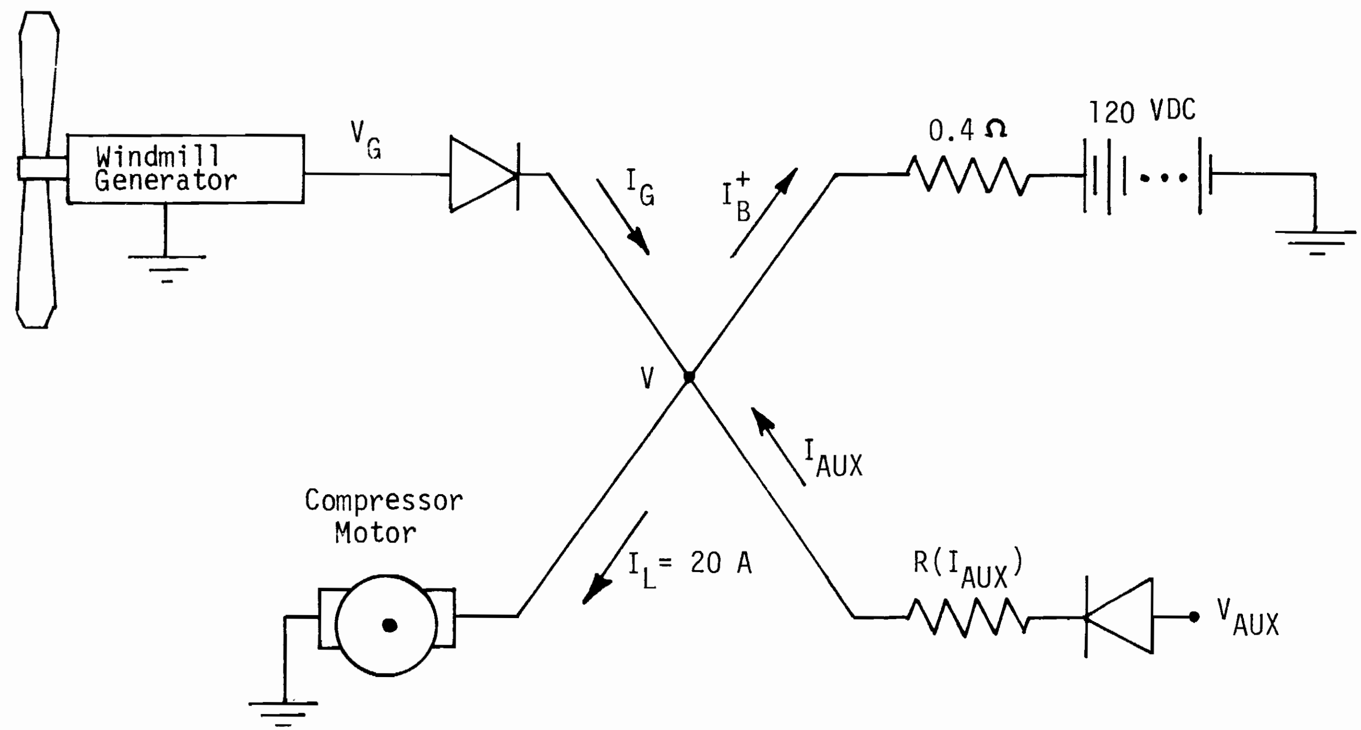


Figure 25. Generator Load Curve Model

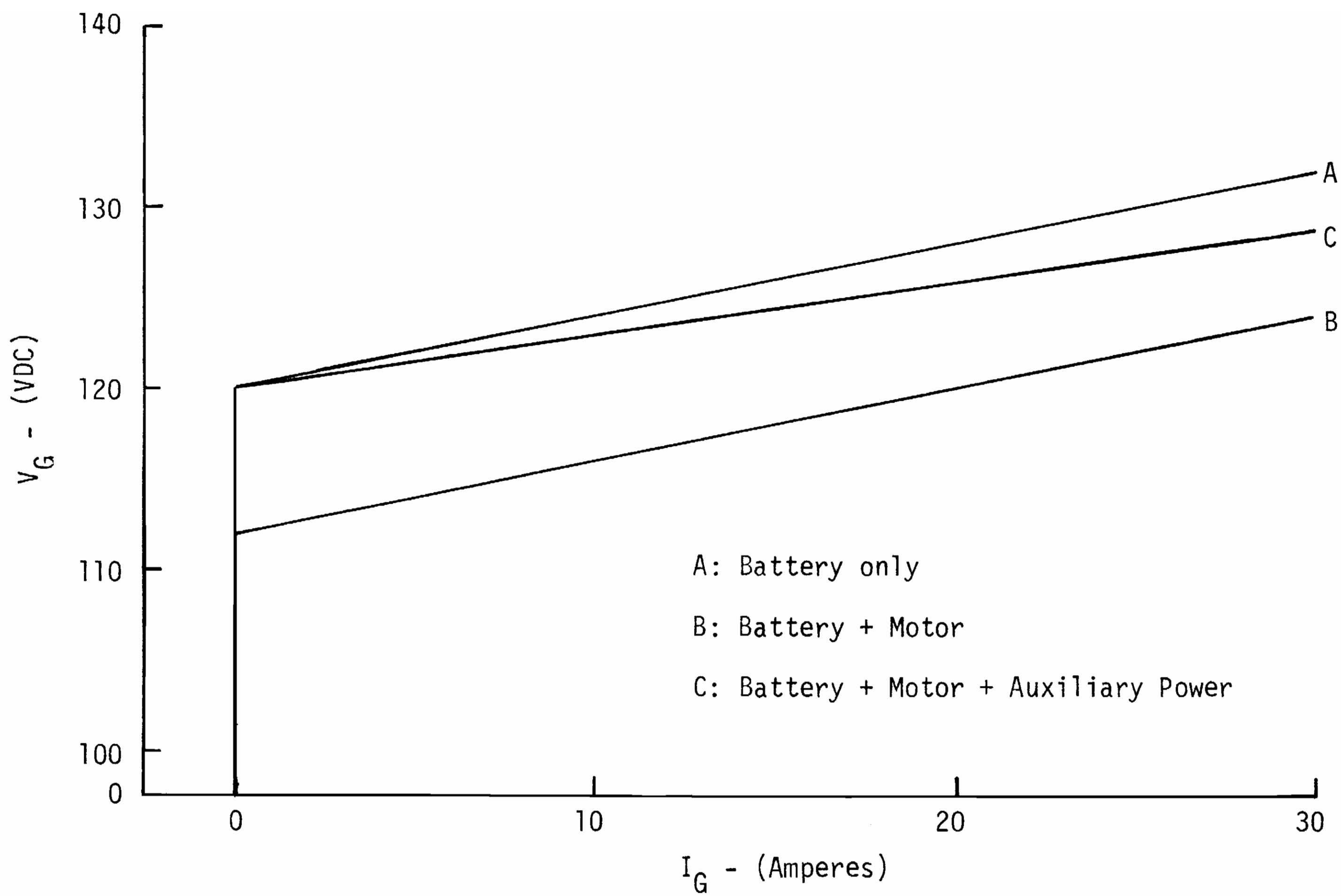


Figure 26. Typical Generator Load Curves

rent can flow out of the battery, the generator cannot provide current until the voltage reaches the open-circuit voltage of the battery. Once this potential (120 VDC) has been reached, large currents can be delivered with little increase in generator voltage. The slope of curve A is the internal resistance of the battery, 0.4 Ohms.

Operation of the compressor motor with the battery results in load curve B. It is similar to load curve A except for a downward displacement of 8 VDC which corresponds to the voltage drop across the battery's internal resistance when the motor is operated solely from the battery. As the generator current increases the current demanded by the battery decreases. This decrease continues until the generator delivers 20 A and the motor is operated solely by the windmill generator. Further increases in current are diverted for charging the battery.

When the auxiliary power supply is connected to the system and adjusted to a "balanced" state with the system voltage equal to the battery's open-circuit voltage and the generator is delivering no current, load curve C is obtained. At this balanced state the compressor motor is operated solely from the auxiliary power supply, i.e.,

$$I_L = I_{AUX} = 20 \text{ A} \tag{5}$$

From the resistance relationship given in Equation (4) the constant DC voltage, V_{AUX}, of the auxiliary power supply must be 154 VDC. The slope of load curve C is less than that of load curve A because the internal resistances are in parallel. For load curve C this voltage of 154 VDC is assumed to be maintained at all times. One might expect

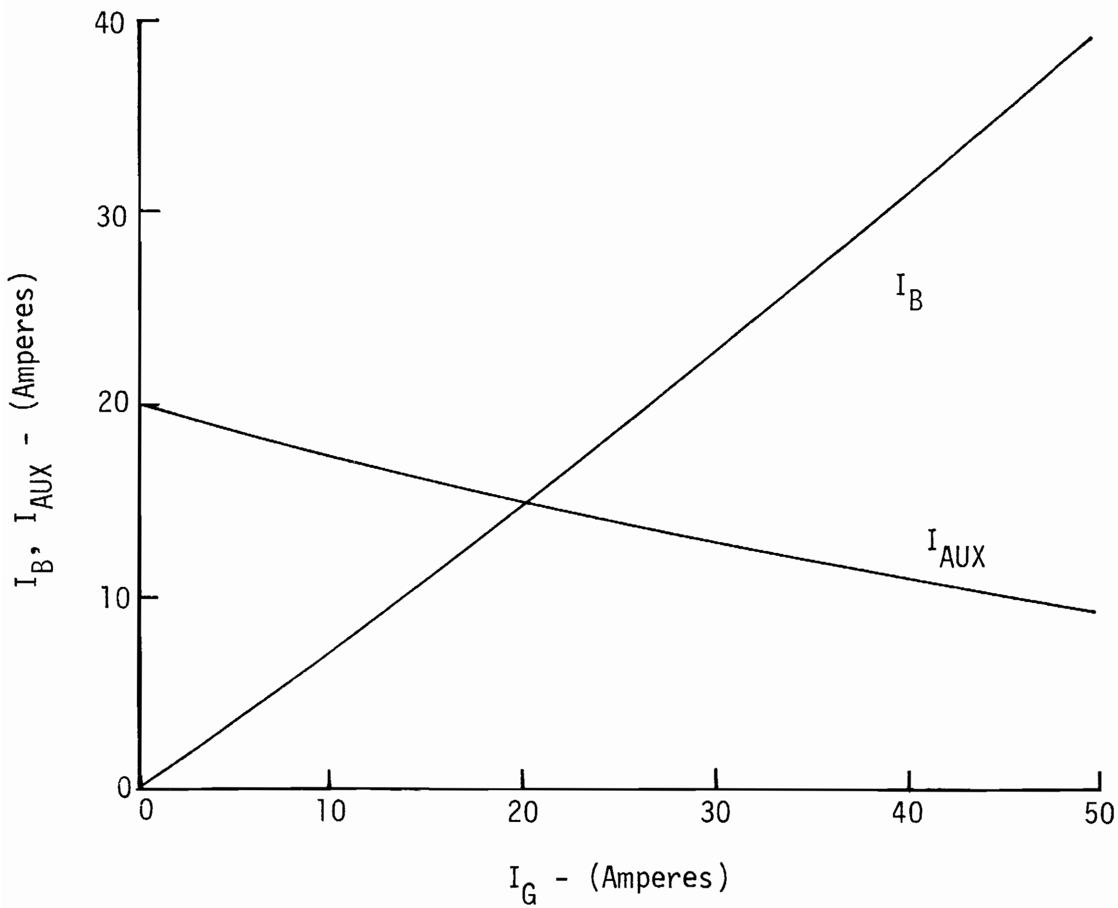


Figure 27. Typical Auxiliary Power Reduction with Developed Windmill Power

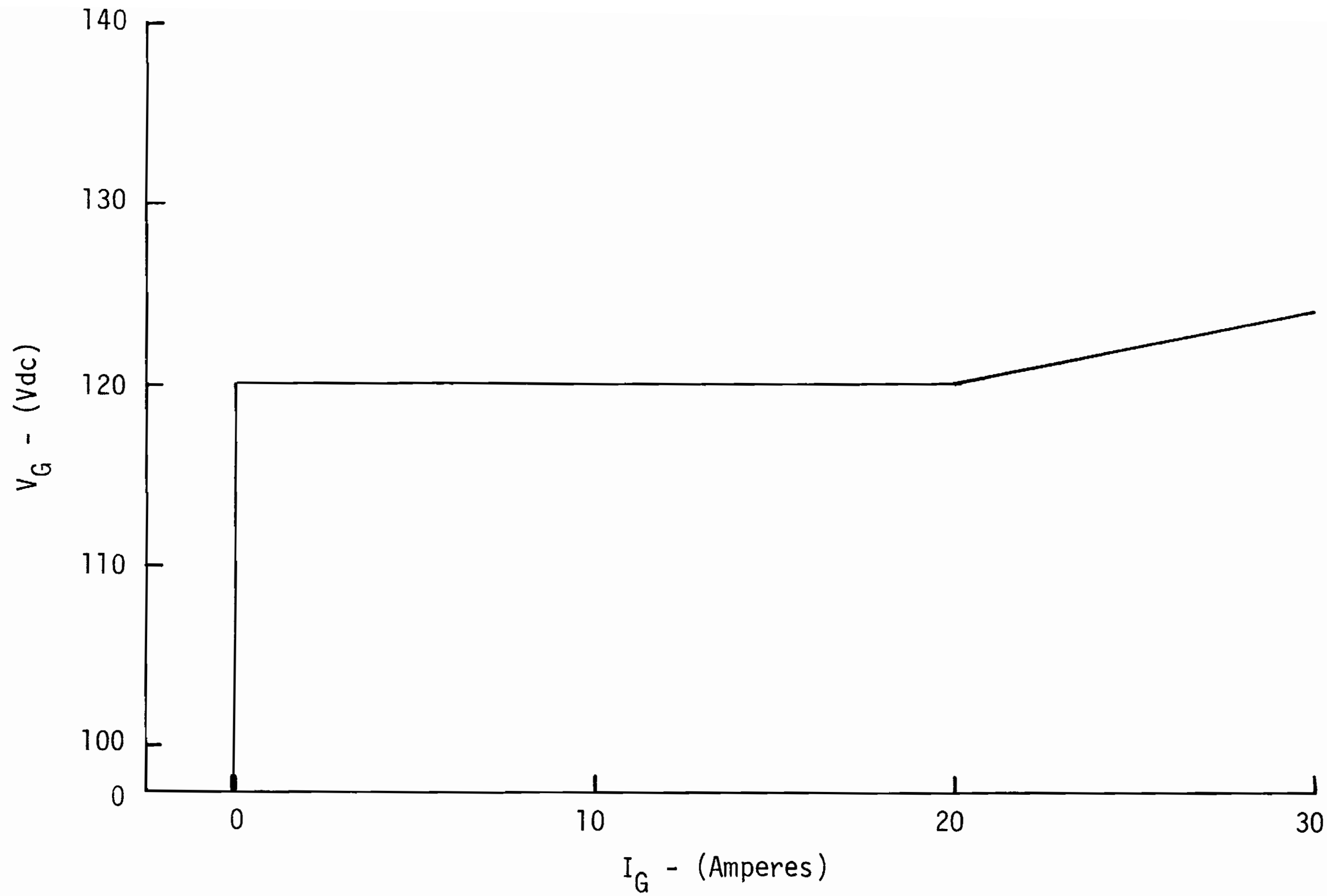


Figure 28. Generator Load Curve for Variable Auxiliary Power

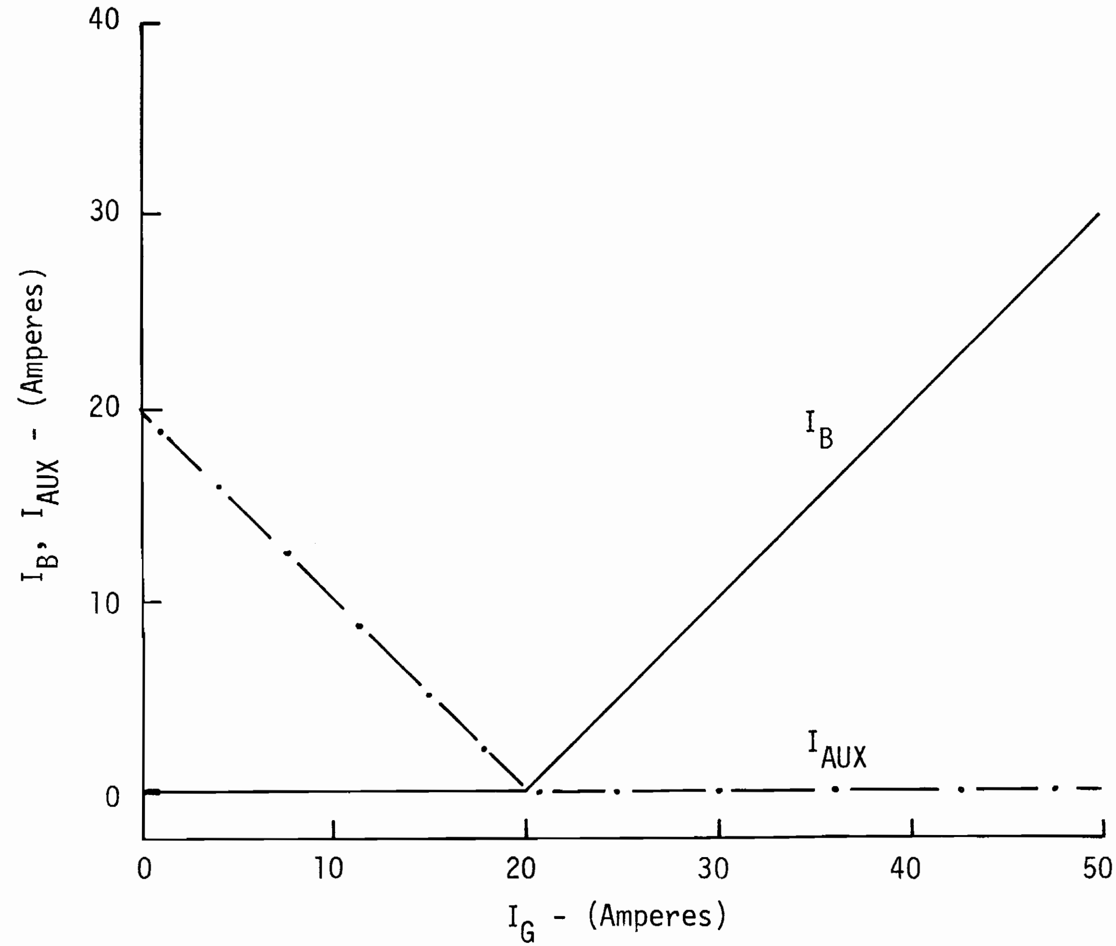


Figure 29. Auxiliary Power Reduction for Variable Auxiliary Power

that the auxiliary power supply current would drop an amount equal to an increase in the generator current developed, i.e.,

$$\Delta I_G = -\Delta I_{AUX} \qquad (6)$$

However, this behavior is not the case as seen in Figure 27. The generator current in excess of the reduction in the auxiliary power supply current is diverted to charging the battery. This condition leads to significant losses of energy delivered by the windmill because of the inability to recover all of the energy transferred to the battery during the charging process. Losses result and the system still continues to use auxiliary power.

A more efficient system would ensure that the condition given by Equation (6) is satisfied. A variable power supply with continuous adjustment to attempt to provide a "balanced" state at all values of generator current can satisfy this condition. The load curve for such a system is shown in Figure 28. When the generator delivers no current the auxiliary power supply voltage would be adjusted to 154 VDC as before. As generator current increases this voltage is continuously decreased to maintain a "balanced" state with a system voltage of 120 VDC. Thus, increases in generator current would be matched by decreases in the auxiliary power supply current as shown in Figure 29. When the voltage has been reduced from 154 VDC to 120 VDC the entire current demand of the compressor motor is satisfied by the generator. Further increases in generator current are then diverted to charging the battery with no current required from the auxiliary power supply. This latter technique provides optimal utilization of available wind energy when auxiliary power must be provided.

Little difference exists between load curves A and C. Load curve C is noted for its lower voltages and the load curve for the variable auxiliary power scheme is essentially flat and lies between load curves A and B. Thus, little difference in windmill efficiency should be observed between the charging of the battery with the wind and operating the compressor motor with the auxiliary power supply adjusted to a fixed setting so that a balanced state is achieved when there is no power developed by the windmill generator. Appropriate control of the generator field, however, should be able to provide equal efficiency for all loads.

XII. *IN SITU* WINDMILL PERFORMANCE STUDIES

The performance of the Elektro 120 WVG windmill was studied *in situ* for several operational modes. These tests were conducted to determine if significant differences resulted from different electrical load characteristics. The results of these tests were used to develop an improved control strategy for the operation of the total system.

Test and Data Reduction Procedures

These tests were conducted to determine the effect on developed windmill power when operating with each of four different electrical loads:

(i) Battery only

(ii) Battery with compressor motor operating without auxiliary power

(iii) Battery + auxiliary power (fixed voltage) with compressor motor operating

(iv) Battery + auxiliary power (variable voltage) with compressor motor operating

To evaluate these differences it was necessary to evaluate the developed windmill power and windspeed by computing their average values over a given interval of time (held constant during all tests). This procedure helped to reduce the effects of rotor and generator response to changes in wind speed and direction and provided a means for evaluation of the auxiliary power consumed with the available instrumentation.

The average windmill power and auxiliary power for each time interval were determined from Watt-hour counter readings and

$$\overline{P}\text{ (Watts)} = \frac{E}{\Delta t} \times 60 \tag{7}$$

where E represents the number of Watt-hours developed or consumed in a given time Δt measured in minutes. A time interval of 2 minutes was used to provide an error range of $\pm$ 30 Watts.

During each test a photographic record was made of the instruments every 2 minutes. The data obtained from each photographic record included:

(i) Time (hr:min:sec)

(ii) Instantaneous power required by the compressor motor (W)

(iii) Accumulated energy required by the compressor motor (W•h)

(iv) Instantaneous power developed by the windmill generator (W)

(v) Accumulated energy developed by the windmill generator (W•h)

(vi) Accumulated energy taken from the electric utility through the auxiliary power supply (W•h)

(vii) Accumulated wind travel distance (miles/60)

The system voltage and current into or out of the battery were also recorded simultaneously with each photographic record.

For each 2-minute time interval in a given test the following data were obtained from the recorded data:

(i) Average windmill power, $\overline{P}_W$, (W)

(ii) Average power required by the compressor motor, $\overline{P}_C$, (W)

(iii) Average power taken from the electric utility through the auxiliary power supply, $\hat{P}_{AUX}$, (W)

(iv) Average wind speed, $\overline{W}$, (mph)

(v) Average system voltage, $\overline{V}$

From the data obtained during each test it was possible to determine the total electrical energy developed by the windmill, E_W, required by the compressor motor, E_C, and taken from the electric utility through the auxiliary power supply, $\hat{E}_{AUX}$. From the performance tests conducted on the auxiliary power supply, the amount of electrical energy delivered by the auxiliary power supply, E_{AUX}, was estimated from

$$E_{AUX} = 0.8442\ \hat{E}_{AUX} \tag{8}$$

The net electrical energy delivered to (+) the battery, E_B, could then be estimated from

$$E_B \approx E_W + E_{AUX} - E_C \tag{9}$$

Test Results

Test Identification

The *in situ* windmill performance tests that were conducted are given in Appendix B. The tests have been identified with a test number and the test conditions have been indicated. The tests have been divided into four groups according to the mode of operation employed.

The battery remained connected to the system in all of the tests.

Tests 1 through 8 were conducted with the battery as the only electrical load, i.e., the compressor motor and the auxiliary power supply were disconnected. Thus, the battery could only be charged by the windmill generator when sufficient wind energy was available.

Tests 9 through 14 were conducted with the compressor motor operating and the auxiliary power supply disconnected from the system. The compressor was operated in either the refrigeration or defrost modes as indicated. Tests were stopped when the system voltage had fallen to the lower end of the operating voltage range of the battery.

Tests 15 through 26 were also conducted with the compressor motor operating in either the refrigeration or defrost modes as indicated. The auxiliary power supply was connected to the system, however, with the setting of the variable transformer remaining fixed throughout each test. In most of the tests the variable transformer was adjusted to give a zero battery current when the windmill was not developing power.

A variable auxiliary power supply was simulated in Tests 27 and 28. The compressor motor was operated while the variable transformer was manually adjusted to maintain a zero battery current as power developed by the windmill generator varied with wind speed. This test was called a "Driver Test" because the manner in which the variable transformer was controlled was similar to steering a car. Maintaining a zero battery current electrically eliminated the battery from the system.

Data Tabulation

Reduced data from each of the twenty-eight tests are found in Appendix B. These data include 2-minute averages only and may, therefore, not be sequentially continuous. The data include 2-minute wind speed, windmill power, and voltage averages and, where applicable, 2-minute compressor power and auxiliary input power averages.

Data summaries for each of the four groups of tests (based on test conditions) are presented in Tables 7 through 10. The data include the duration of each test, the average wind speed and windmill power, and the initial and final system voltages for each of the tests. For those tests in which the compressor motor was operated, the ratio of the energy provided by the windmill to the energy required to operate the compressor motor have also been presented. For those tests (15-28) in which the auxiliary power supply was employed, the electrical energy required from the local electrical utility by the auxiliary power supply and an estimate of the electrical energy delivered by the auxiliary power supply have also been presented. Also, an estimate of the net electrical energy delivered to (+) the battery in each of these tests has been presented.

Data Comparison for Effects

The data taken during the *in situ* windmill performance tests were analyzed to determine what options, if any, existed to permit an improvement in the system's usage of available wind energy. The char-

Table 7

Performance Test Data Summary (Tests 1-8)

Auxiliary Power: OFF Compressor Motor: OFF								
Test No.	1	2	3	4	5	6	7	8
Duration (minutes)	26	60	98	142	10	12	34	34
Avg. Wind Speed, m/s	6.3	6.1	4.0	4.1	6.5	6.1	3.3	3.7
(mph)	(14.1)	(13.6)	(8.9)	(9.1)	(14.5)	(13.7)	(7.4)	(8.2)
Avg. Windmill Power (Watts)	755	651	152	189	768	860	84	196
Voltage:								
Initial	124	111	113	124	126	142	131	137
Final	134	125	117	124	143	147	131	138

Table 8

Performance Test Data Summary (Tests 9-14)

Auxiliary Power: OFF Compressor Motor: ON						
Test No.	9	10	11	12	13	14
Compressor Mode	REF	DEF	REF	REF	DEF	REF
Duration (min.)	52	36	32	28	18	16
Avg. Wind Speed, m/s	7.2	6.3	4.2	5.3	7.1	6.3
(mph)	(16.0)	(14.1)	(9.3)	(11.8)	(15.8)	(14.0)
Avg. Power (Watts):						
Windmill	687	523	210	366	793	788
Comp. Motor	1692	1522	2612	2522	1550*	2648
Windmill/ Comp.Motor	0.406	0.344	0.080	0.145	0.512*	0.298
Voltage:						
Initial	*121	117	110	119	122	121
Final	97	95	96	104	118	114

*Estimated Values

Table 9

Performance Test Data Summary (Tests 15-26)

Auxiliary Power: ON (fixed) Compressor Motor: ON						
Test No.	15	16	17	18	19	20
Compressor Mode	REF	DEF	REF	DEF	DEF	REF
Duration (min.)	32	20	104	10	18	10
Avg. Wind Speed, m/s	3.6	7.8	5.9	6.5	5.3	5.5
(mph)	(8.1)	(17.5)	(13.2)	(14.5)	(11.8)	(12.3)
Avg. Power (Watts):						
Windmill	148	750	522	642	510	432
Comp. Motor	2623	1500	2614	1752	1777	2751
Aux. Power Input	2957	----	2091	1206	1467	4104
Voltage:						
Initial	103	103	119	119	119	127
Final	104	103	120.5	119	118	127.5
Total Watt-Hours:						
Windmill	79	250	905	107	153	72
Comp. Motor	1399	500	4530	292	533	459
Aux. Power Input	1577	----	3624	201	440	684
Est. Aux. Output	1331	----	3059	170	372	605
Est. Battery (+=in)	+11	----	-566	-15	-8	+218
Wind/Comp. Motor	0.057	0.500	0.200	0.366	0.287	0.158

Table 9 (Cont.)

Performance Test Data Summary (Tests 15-26)

Auxiliary Power: ON (fixed) Compressor Motor: ON						
Test No.	21	22	23	24	25	26
Compressor Mode	REF	REF	REF	REF	REF	REF
Duration (min.)	64	12	10	16	34	10
Avg. Wind Speed, m/s	5.4	6.0	6.4	5.6	4.1	5.8
(mph)	(12.0)	(13.5)	(14.3)	(12.6)	(9.2)	(13.0)
Avg. Power (Watts):						
Windmill	396	535	612	439	184	654
Comp. Motor	2719	2645	2592	2543	2772	1932
Aux. Power Input	2986	1905	1260	2183	2068	1884
Voltage:						
Initial	122.5	122	119.5	116	115	130
Final	124.5	120.5	118.5	115	113.5	129
Total Watt-Hours:						
Windmill	422	107	102	117	104	109
Comp. Motor	2900	529	432	678	1571	322
Aux. Power Input	3185	381	210	582	1141	314
Est. Aux. Output	2689	322	177	491	963	265
Est. Battery (+=in)	+211	-100	-153	-70	-504	+52
Wind/Comp. Motor	0.146	0.202	0.236	0.173	0.066	0.339

Table 10

Performance Test Data Summary (Tests 27&28)

Auxiliary Power: ON (variable - 'Driver' Test) Compressor Motor: ON		
Test No.	27	28
Compressor Mode	REF	REF
Duration (min.)	14	72
Avg. Wind Speed, m/s	6.0	4.9
(mph)	(13.4)	(10.9)
Avg. Power (Watts):		
Windmill	720	330
Comp. Motor	1877	2724
Aux. Power Input	1346	2796
Voltage:		
Initial	127.5	122
Final	126	122
Total Watt-Hours:		
Windmill	168	396
Comp. Motor	438	3269
Aux. Power Input	314	3355
Est. Aux. Output	265	2832
Est. Battery (+=in)	-5	-41
Wind/ Comp. Motor	0.384	0.121

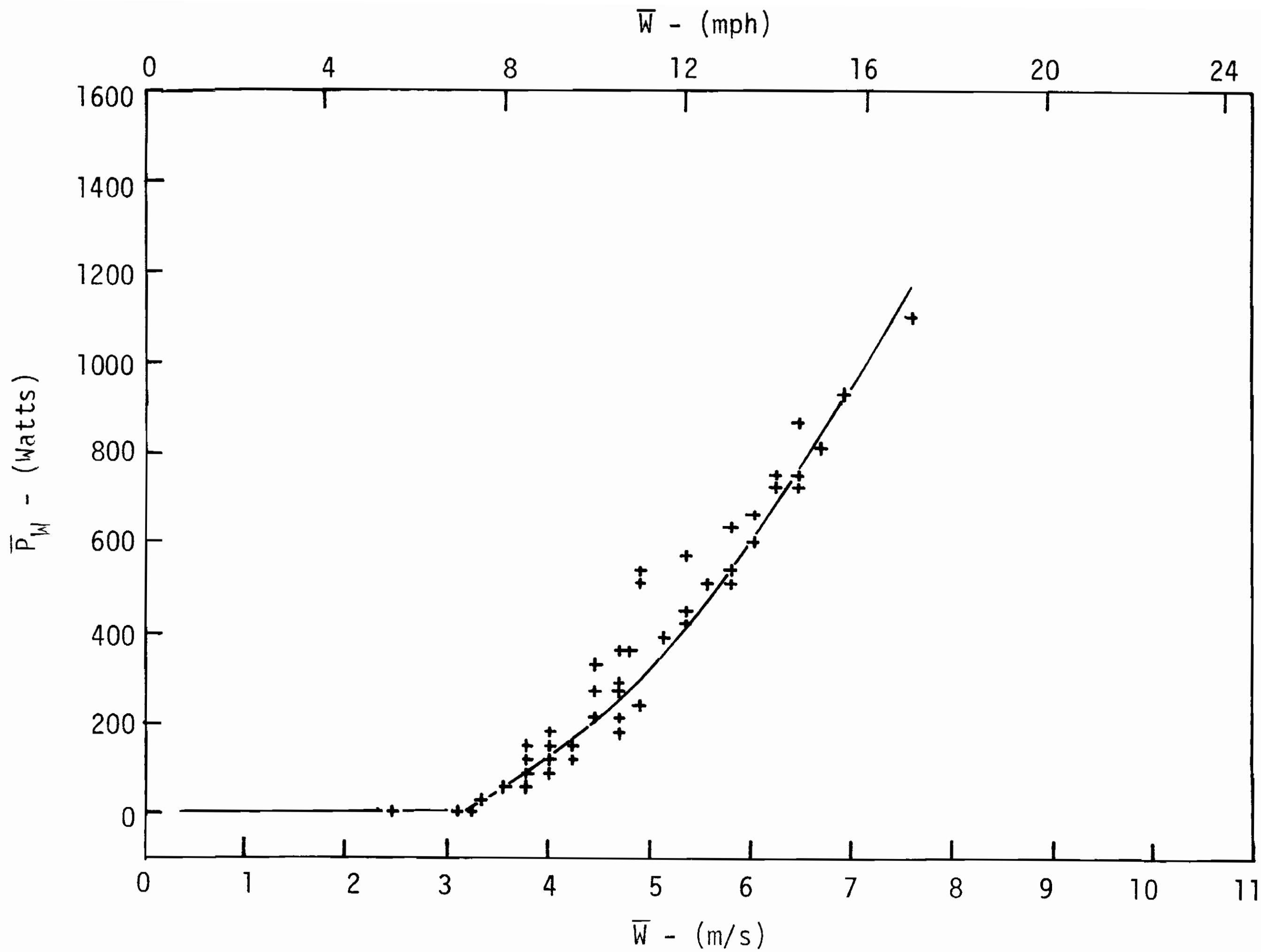


Figure 30. In Situ Windmill Performance (Tests 1-8: V<125 Vdc)

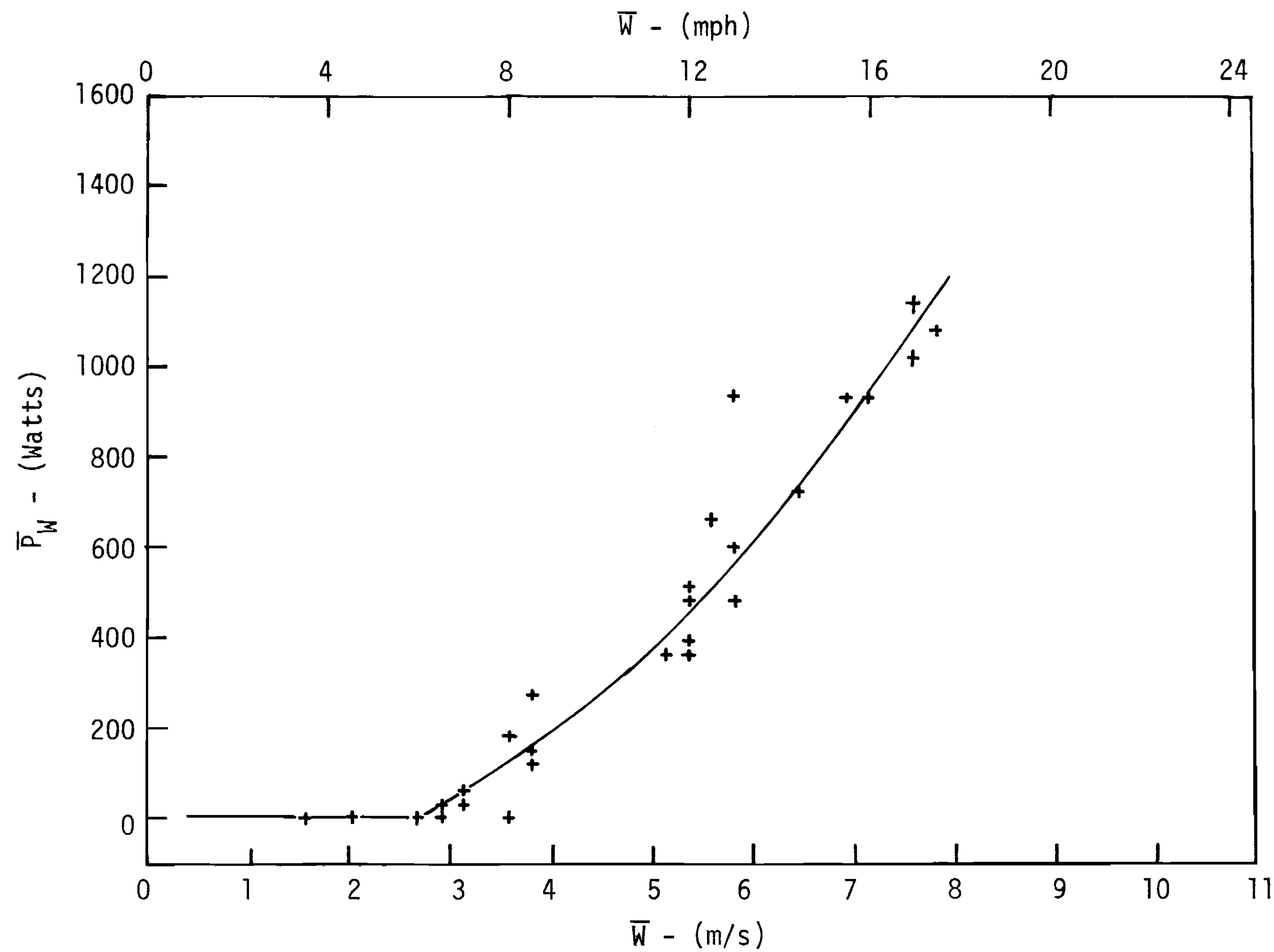


Figure 31. *In Situ* Windmill Performance (Tests 1-8: 125 $\leq$ V $\leq$ 135 Vdc)

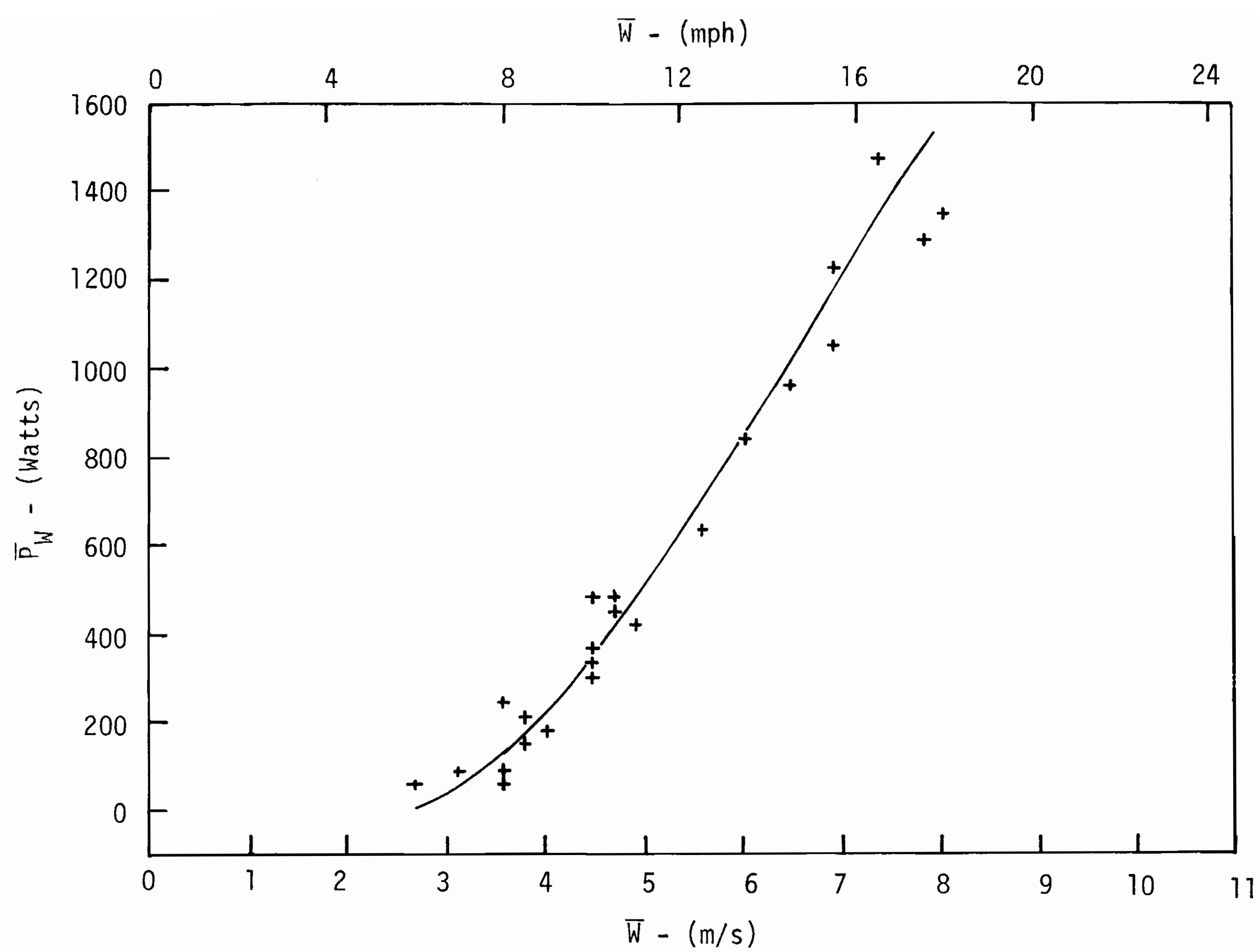


Figure 32. <u>In Situ</u> Windmill Performance (Tests 1-8: V > 135 Vdc)

acteristic generator load curves for the modes of operation during these tests were found to share a limited, qualitative similarity. All of these curves exhibited low slopes. These slopes tended to the one indicated by the windmill manufacturer for optimum performance. The basic difference appeared to be one of voltage. Thus, a greater influence on the windmill efficiency was expected to result from the system voltage rather than a combination of voltage and generator current.

To ascertain the effect of voltage on the efficiency of the windmill system as a function of wind speed, the data of Tests 1-8 were taken collectively and divided into three groups according to voltage: less than 125 VDC; between 125 and 135 VDC, inclusively: and greater than 135 VDC. These groups of 2-minute averaged windmill power and wind speed are shown in Figures 30 through 32 in order of increasing voltage range.

For purposes of comparison and discussion only, a line was drawn through the data of each group to give an indication of each group's central tendency. This line was developed by visual inspection because there is a lack of information with which to apply standard regression analyses. This limitation results from the unquantified behavior of the variance of the data population as a function of windspeed (the independent variable). No accurate regression can be made without this knowledge. Also, the functional behavior of the regression is unknown. Some form of regression could be assumed, but the results are likely to be no more, and probably less, significant than one achieved by visual inspection. Gross differences, however, between groups of data should be apparent by this method.

To aid in the comparison of these groupings of data the lines of central tendency have been shown together in Figure 33. A comparison of these lines indicates a significant difference between the higher voltage ($>$135 VDC) data and the other two groups. A comparison between the other two groups indicates little apparent difference. Therefore, charging the battery with the windmill is more efficient at voltages greater than 135 VDC. This improvement results from operation at more favorable tip speed ratios, i.e., the ratio of the linear speed at the tip of the rotor to that of the speed of the wind [15]. It is likely that the efficiency of the windmill increases with voltage and the generator's field strength should be greater to give higher efficiencies at lower voltages at which the system normally operates when the compressor motor is operated. Furthermore, some form of automatic field control should lead to optimum windmill operation at any given voltage.

While it becomes apparent that system voltage has some effect on the efficiency of the windmill, an effect due to current can be neither demonstrated nor refuted - at least with the limited data available. For this reason the data for other modes of operation have been analyzed accordingly.

Averaged windmill power and wind speed data for Tests 9-14 are presented in Figure 34. In these tests the compressor motor was operated from the battery and windmill with no use of auxiliary power.

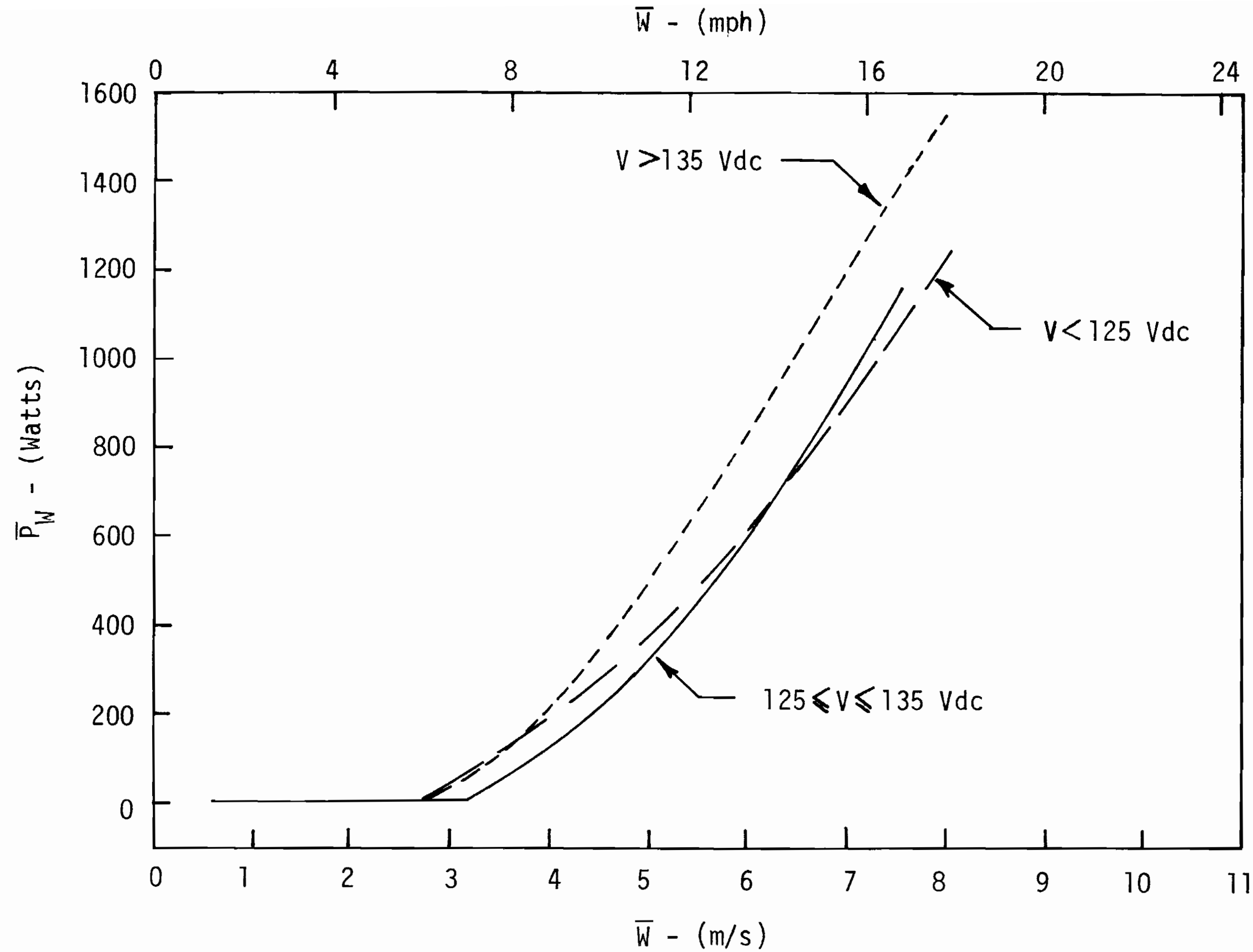


Figure 33. Voltage Range Comparisons (*In Situ* Windmill Performance Tests 1-8)

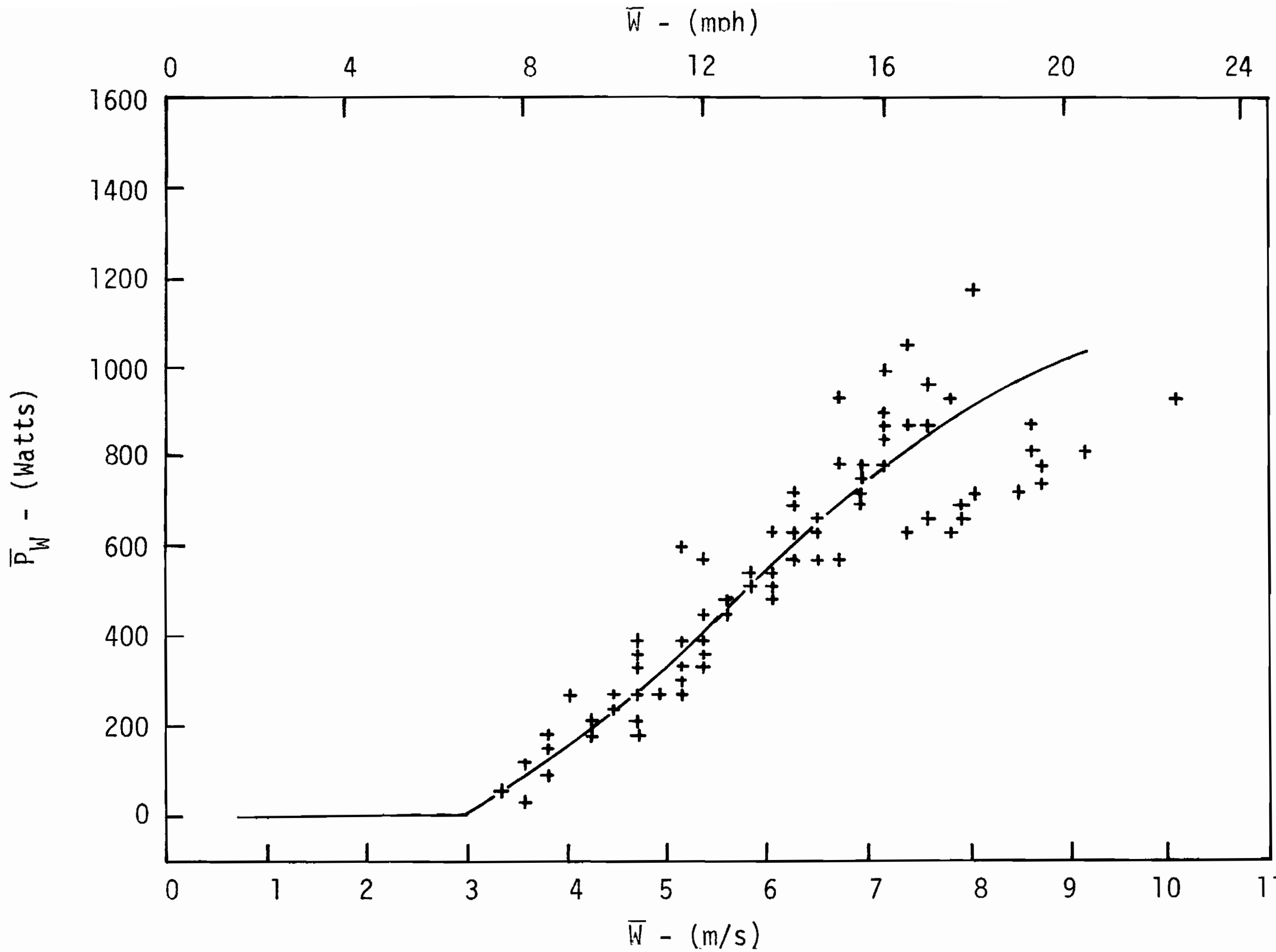


Figure 34. In Situ Windmill Performance (Tests 9 - 14)

Because of the voltage drop of the battery, the limited capacity of the battery, and developed windmill power (far less than that drawn by the compressor motor) the system voltages are significantly lower for the most part than those encountered while charging the battery. Thus, it would be expected that the VPI&SU windmill would not operate as efficiently in Tests 9-14 as it did in Tests 1-8. A line of central tendency was developed and has been shown in Figure 34 for comparison with those previously shown. This comparison is shown in Figure 35. At averaged wind speeds below 5.3 m/s (12 mph), little difference exists in the efficiency of the windmill when compared with the lower voltage data during charging of the batteries. This observation is in agreement with the reduced voltages observed in Tests 9-14. At higher wind speeds the developed power approaches a constant level resulting in significantly reduced efficiency. This limitation may result from rotor feathering action induced at higher rotor speeds due to the voltage and current characteristics of the electrical load in this mode of operation. It may also be the result of the rotor's tip speed ratio under these operation conditions. Thus, if the refrigeration requirements could be deferred during periods of high wind speeds, i.e., greater than 8.8 m/s (20 mph), more of the available wind energy could be utilized by halting operation of the compressor motor, charging the battery, and operating the compressor motor from the battery at a later time. However, a significant improvement (approximately 70 per cent) in windmill efficiency during the charging of the battery must be derived for this strategy to be effective. The losses incurred in the

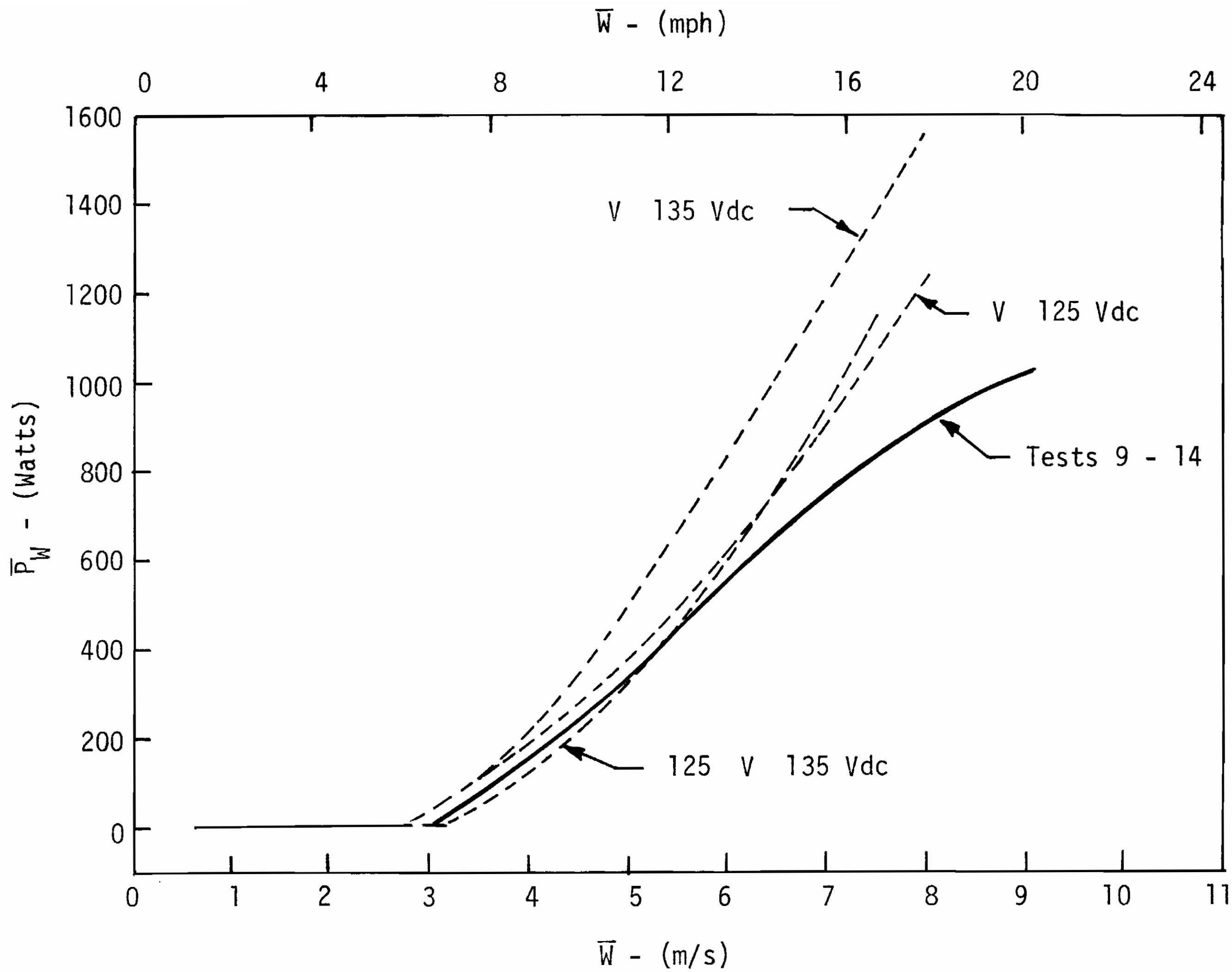


Figure 35. Central Tendency Comparison (Tests 1-8 & Tests 9-14)

charging and discharging of a battery give a false impression when evaluating the utilization of available wind energy. The switching of operational modes would be effective during sustained periods of high winds, but the duration of these periods are insufficient to justify this operational technique. Moreover, automatic regulation of the generator's field control should optimize the efficiency of the windmill for any electrical load.

In Tests 15-26 auxiliary power was used. In the majority of these tests the auxiliary power supply's variable transformer was adjusted to eliminate the flow of electrical current into or out of the battery when the windmill generator was not capable of providing current to the system. Accurate adjustment was not always possible because of sustained wind speeds, variation in the battery's state-of-charge, and minor variations in the current demand of the compressor motor with changes in the ambient temperature. The average developed windmill power and wind speed data for these tests have been combined and are shown in Figure 36 with the line of central tendency. The line of central tendency for this data bore a striking resemblance to the one developed for Tests 9-14. A comparison was made and is shown in Figure 37. There appears to be no significant difference in these lines and, therefore, little significant difference in the use or lack or auxiliary power. During these tests with a fixed setting of the auxiliary power supply it was noted that the behavior of the electrical system was, indeed, as described earlier, i.e., that only a minor fraction of the power developed by the windmill was used directly by the compressor

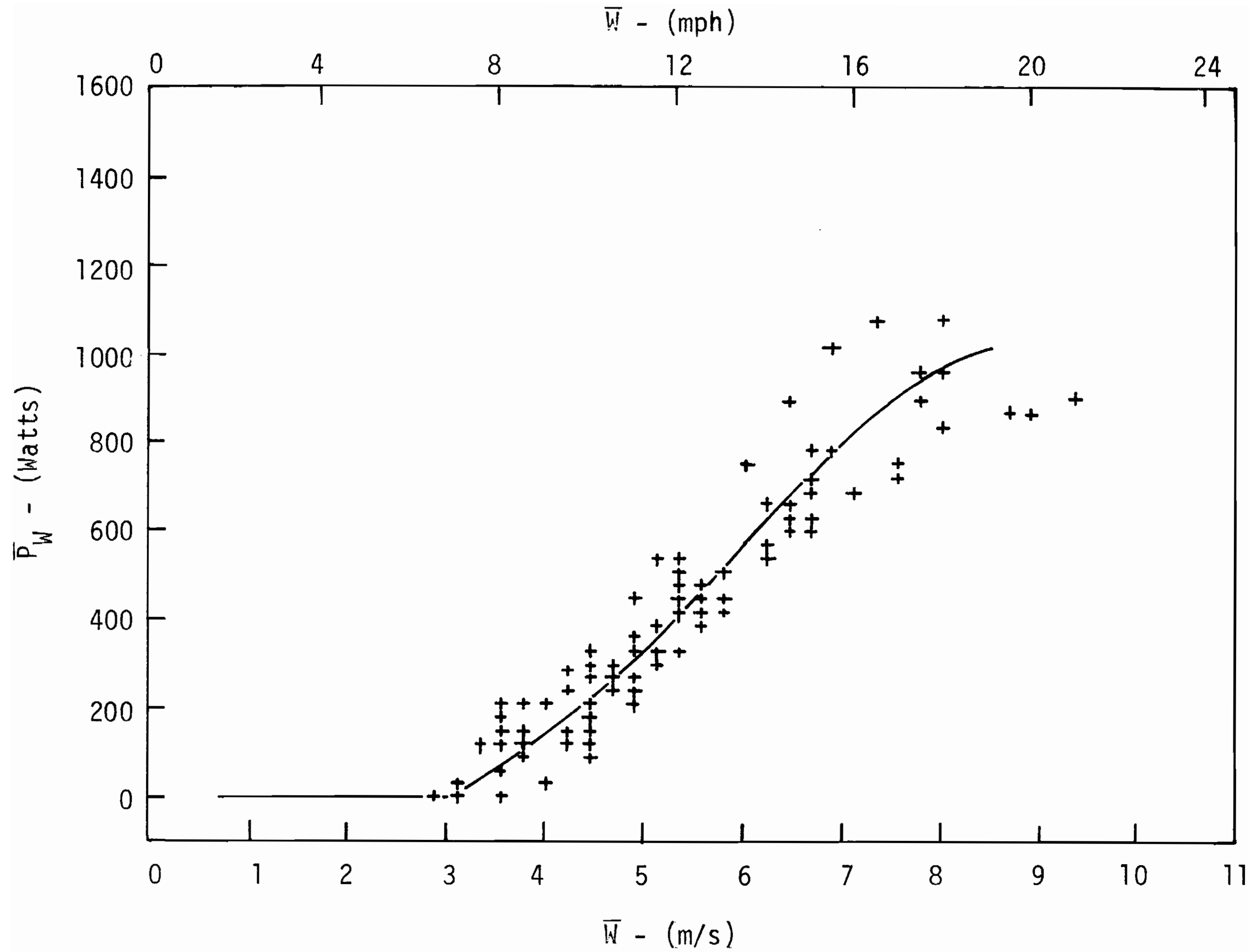


Figure 36. *In Situ* Windmill Performance (Tests 15 - 26)

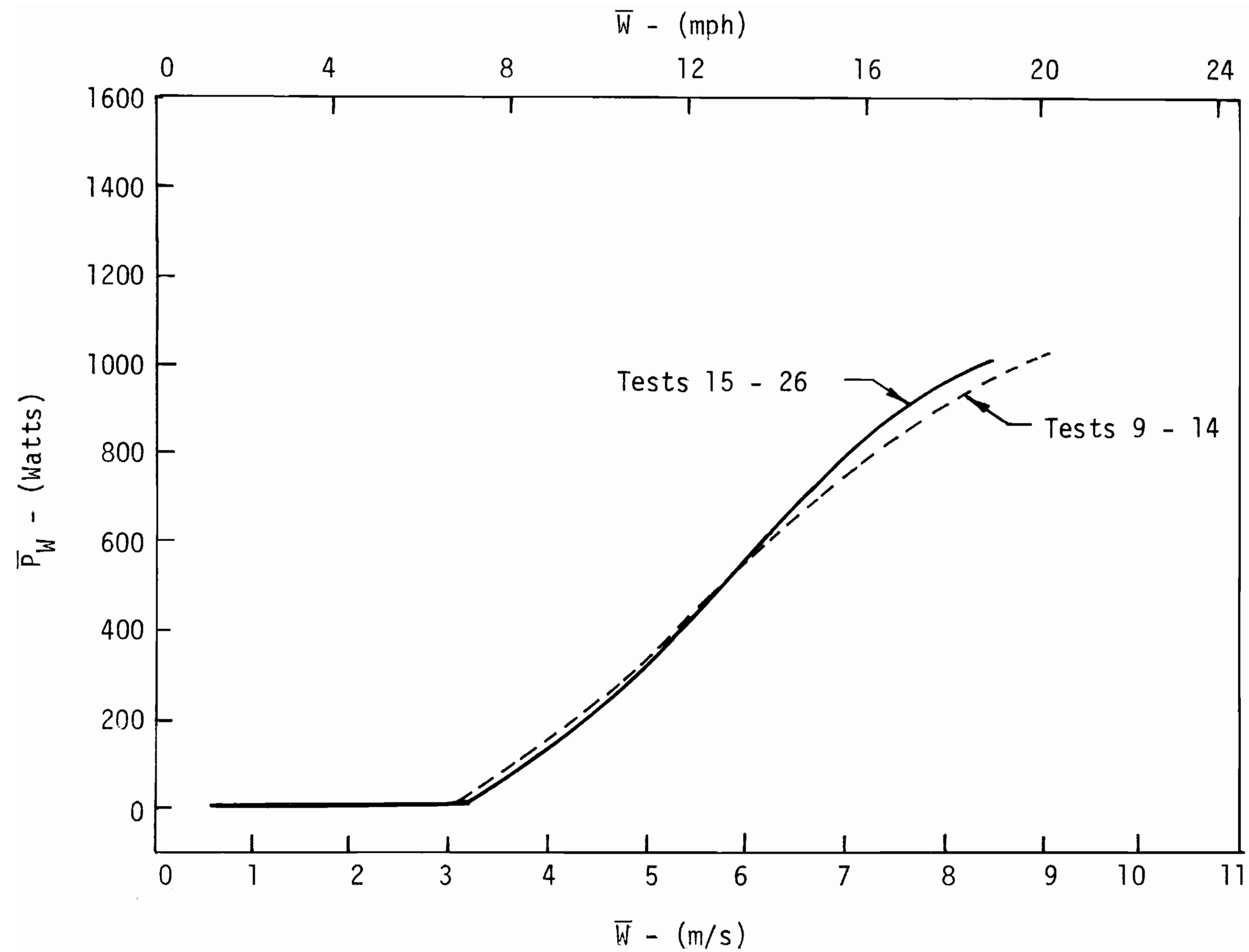


Figure 37. Central Tendency Comparison (Tests 9-14 & Tests 15-26)

motor with an equal reduction in auxiliary power consumed. The balance of the windmill power was diverted to the battery, increased the battery's state-of-charge, and produced slight increases in the system voltage. Reduction of the wind speed then caused the battery to provide a greater fraction of the required compressor power. This charging and discharging of the battery resulted in lower utilization of available wind energy. Frequent charging and discharging may have also contributed to unnecessary deterioration of the battery and may have led to an early failure of the battery's capacity. An automatic auxiliary power supply to eliminate the battery (in an electrical sense) may aid in extending the life of the battery and provide total utilization of available wind energy.

For the purpose of comparison, typical histories for two of the *in situ* tests have been presented in Figure 38 (Test 9) and Figure 39 (Test 25). These data histories compare the performance of the system without and with the use of auxiliary power, respectively.

In Test 9 discharging of the battery during the test resulted in a continuous reduction of the system voltage and the power required by the compressor motor. The effect of this reduction in the system voltage is apparent in the performance of the windmill. While the average wind speed tended to increase during the test period, the power developed by the windmill tended to decrease.

The system voltage changed relatively little during Test 25 as evidenced by the near-constant power required by the compressor motor. The auxiliary power taken from the local electric company did vary sig-

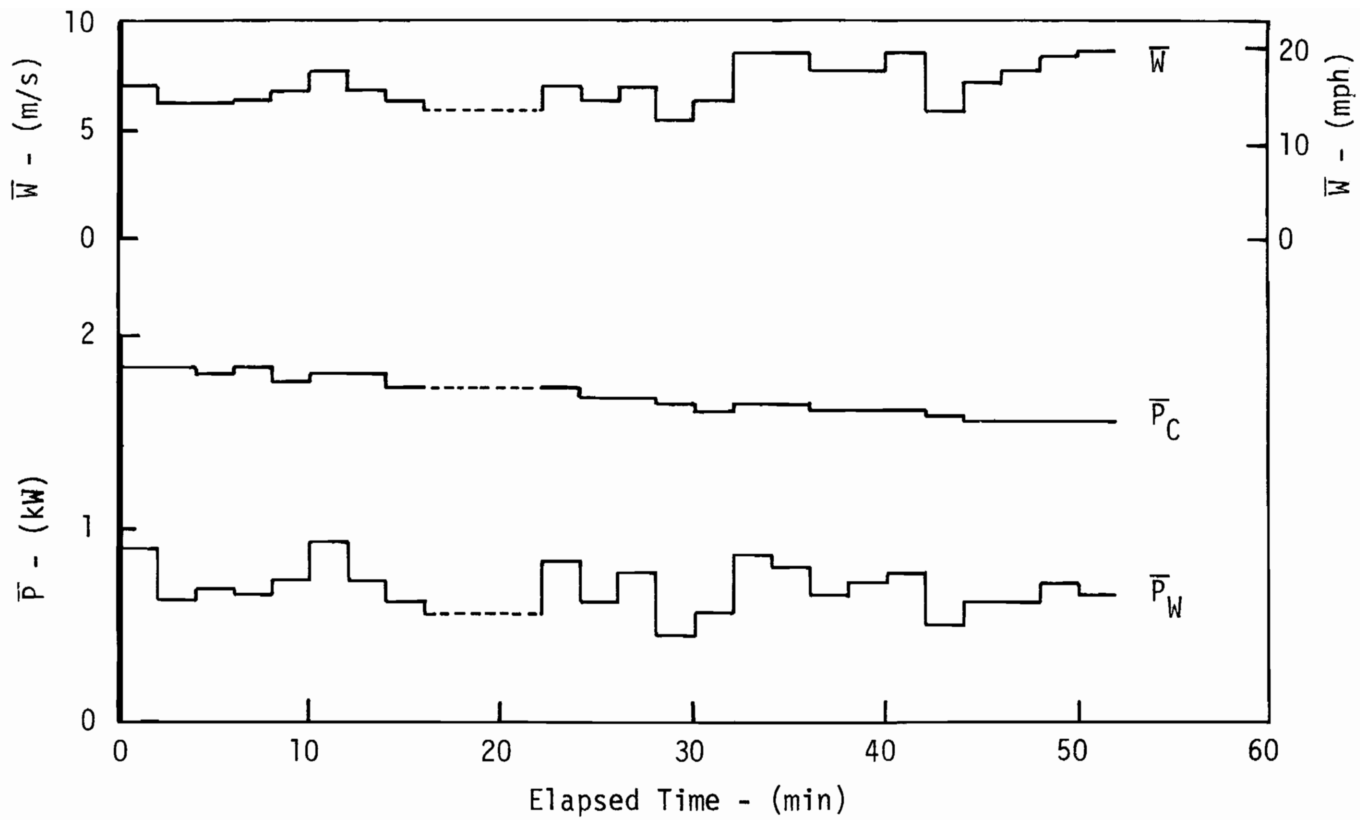


Figure 38. In Situ Windmill Performance History (Test 9)

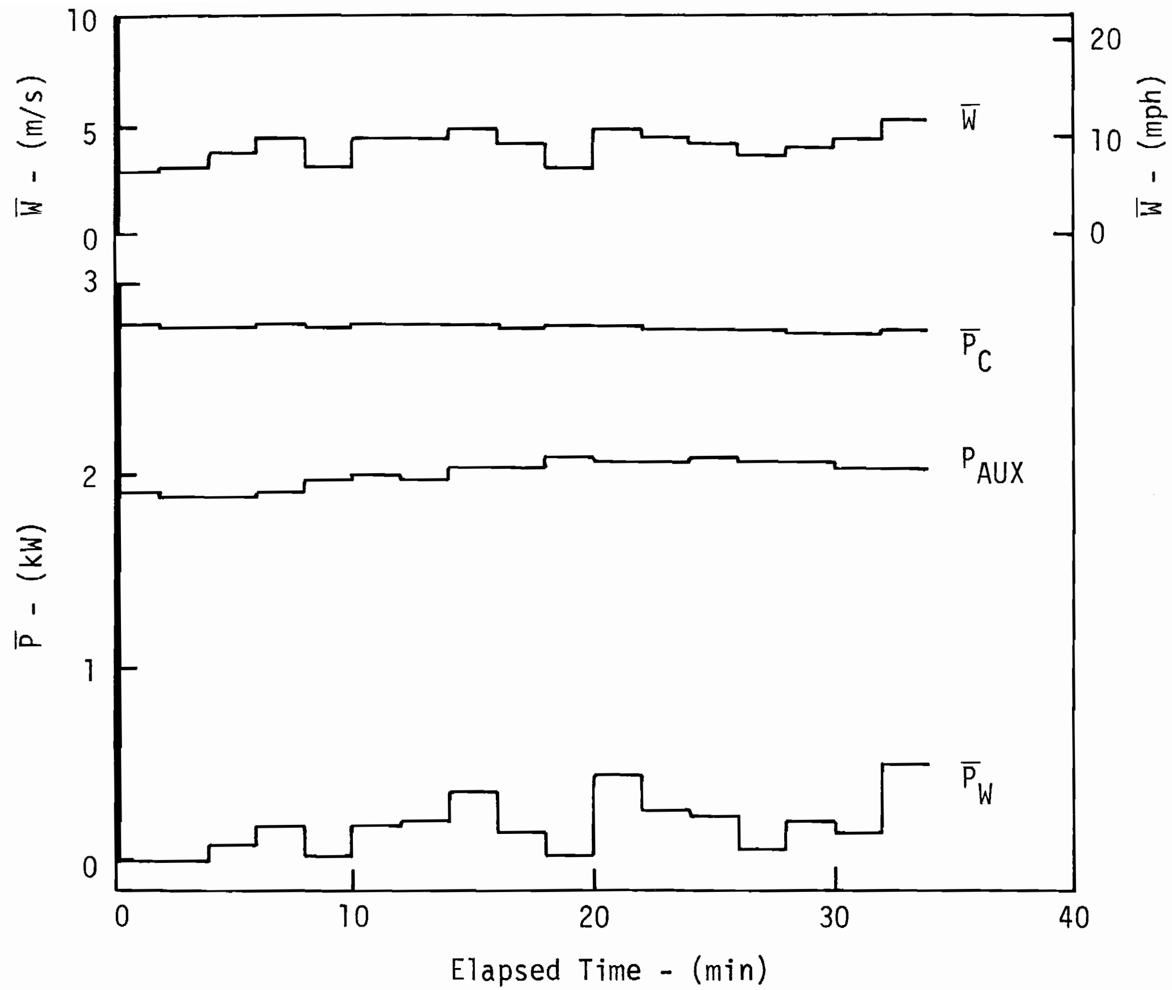


Figure 39. <u>In Situ</u> Windmill Performance History (Test 25)

nificantly, however. This variation resulted from the fact that the battery initially delivered a substantial amount of the power required by the compressor motor when little power was developed by the windmill. As the test proceeded the power delivered by the battery was reduced and the auxiliary power supply was required to supply the increasing balance.

Tests 27 and 28 were conducted with manual variation of the auxiliary power supply to maintain a zero battery current. This technique resulted in full utilization of the power developed by the windmill. The average developed windmill power and wind speed data were combined and are shown in Figure 40 together with the line of central tendency. The significance of the line of central tendency is quite small because of the lack of a sufficient number of data points. For this reason no comparison has been made with the previously developed lines of central tendency.

It had been previously assumed that a straightforward averaging of wind speed data was not adequate and an averaging of the cube of the wind speed would provide less error in considering the energy available during a given period. For n time intervals for which the average wind speed of each interval is known the following formulation was suggested [9].

$$\overline{W}_{CRMC} = \left[\frac{1}{n} \sum_{i=1}^{n} (\overline{W}_i)^3 \right]^{1/3} \qquad (10)$$

This formula for the cube root-mean cubed value of wind speed was

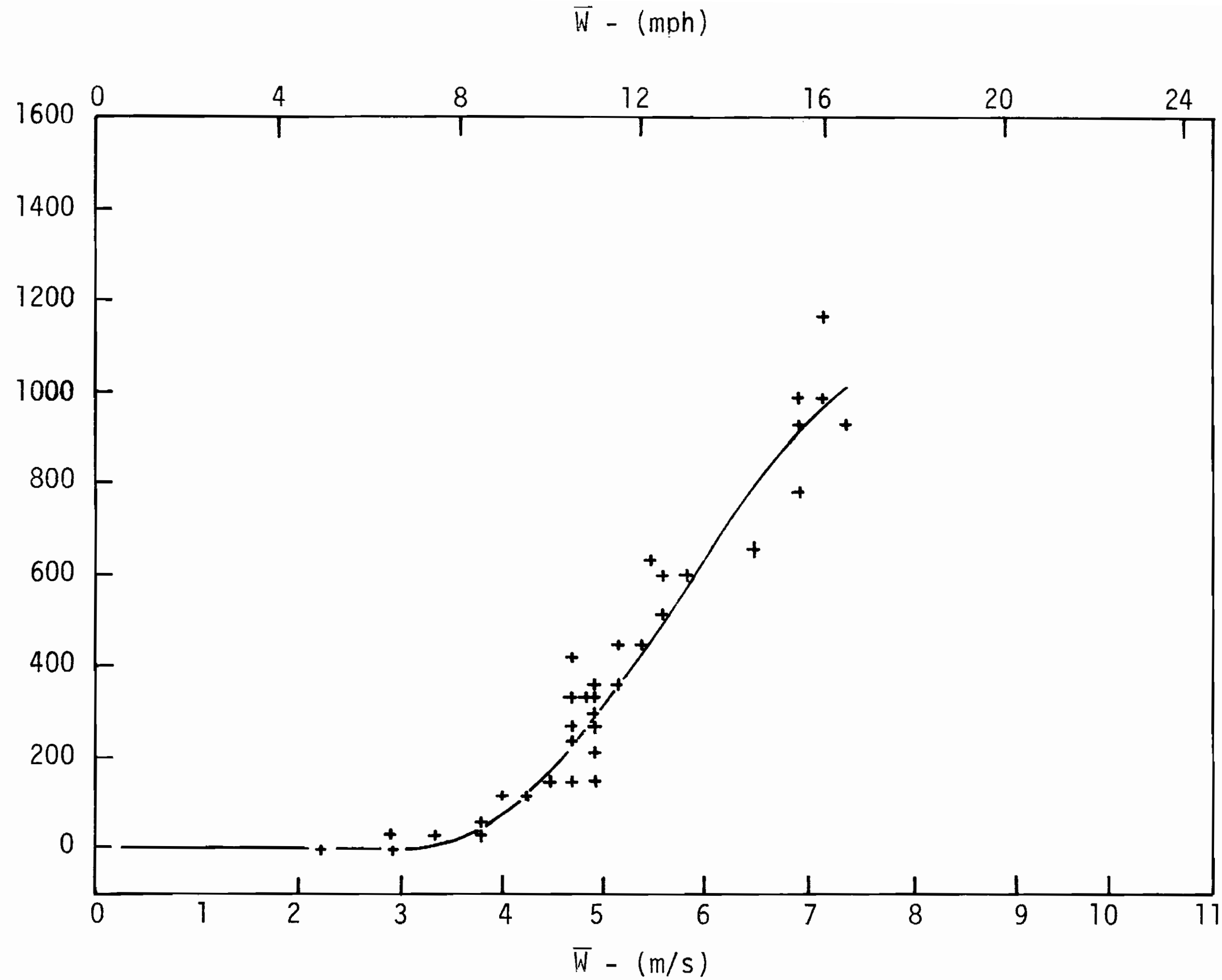


Figure 40. <u>In Situ</u> Windmill Performance (Tests 27 & 28)

determined for the windspeed data of the in situ windmill tests. A comparison was made between the values of $\overline{W}_{CRMC}$ and the average wind speed value

$$\overline{W}_{AVG} = \frac{1}{n} \sum_{i=1}^{n} (\overline{W}_i) \qquad (11)$$

for each of the twenty-eight tests. The results of this comparison, given in Figure 41, show little difference in the values computed by either method, the $\overline{W}_{CRMC}$ values being slightly greater than the corresponding $\overline{W}_{AVG}$ values.

In summary, it was found that there is a significant effect of the system voltage on the efficiency of the windmill, the efficiency being greater for higher voltages ($>$135 VDC). The average power developed continuously increased with increasing average wind speed when the battery was the only electrical load. The operation of the compressor motor or the use of auxiliary power was associated with a diminishing increase in developed power as the wind speed increased. This effect may have been the result of blade feathering or the aerodynamic characteristics of the windmill's blades (tip speed ratio). The effect of the various operating modes was not sufficiently significant at the lower wind speeds to provide improved operation by altering the operating mode, and the fifference at higher wind speeds was significant but these occurrences were too infrequent to provide any disadvantage. The use of automatic field control of the windmill generator could possibly lead to optimal operation for all loads.

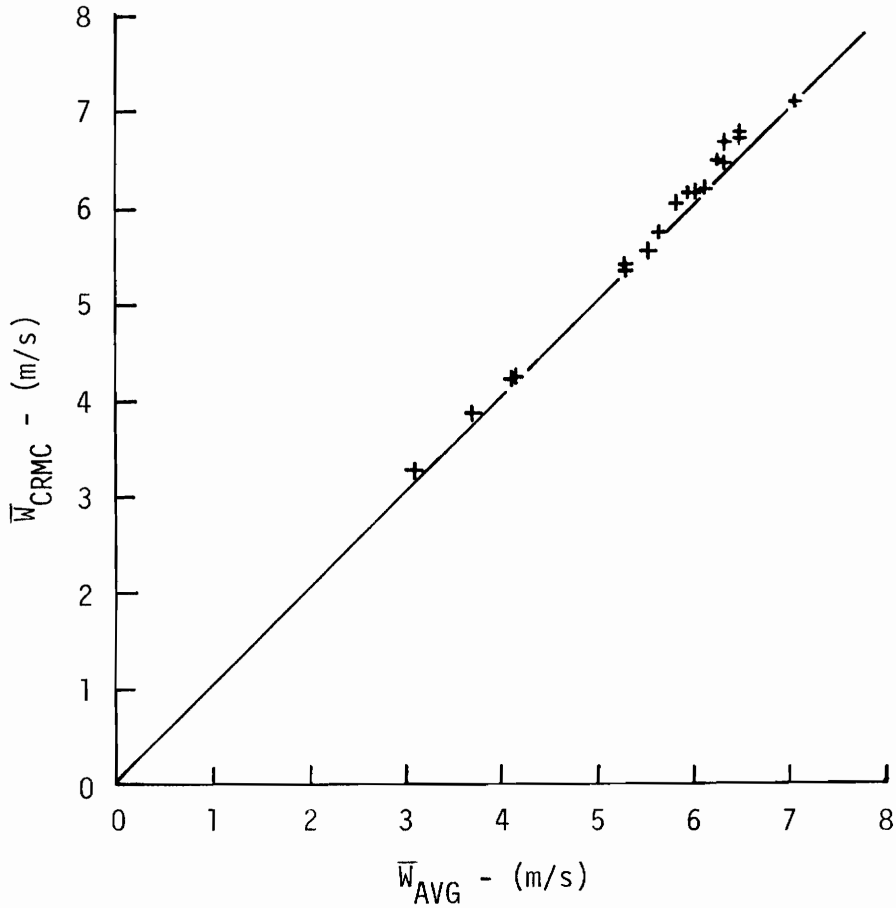


Figure 41. Comparison of $\overline{W}_{AVG}$ and $\overline{W}_{CRMC}$ Values

XIII. DEVELOPMENT OF AN IMPROVED CONTROL STRATEGY

Experience gained from the operation of the VPI&SU windmill system indicated that its control system required a great deal of supervision and that the best use of available wind energy was not realized. The control system, however, did operate properly.

To improve the operation of the system a series of component and in situ windmill performance tests were conducted to provide the necessary information from which an improved control strategy could be developed. These tests, detailed in previous sections, indicated the energy requirements of the system and the efficiencies of the major components. Tests were also conducted which involved the defrosting operational modes, namely, air and hot-gas defrosting.

One of the following conditions resulted in the necessity of operating the refrigeration system continuously with the exception of periodic defrosting of the evaporator coils:

(i) a refrigeration load greater than anticipated,

(ii) less available wind energy than expected, or

(iii) poor windmill performance due to blade design, field control, or rotor-generator mismatch.

It became necessary, therefore, to operate the auxiliary power supply on a full-time basis. This dependency on auxiliary power could have been reduced by eliminating its cause. However, an improved control strategy would still have been needed to further reduce the need for auxiliary power, to improve the utilization of available wind energy, and to reduce the need for extensive supervision of the equipment.

One of the problems encountered in the operation of the VPI&SU system involved the control of the evaporator coil defrosting. The defrosting action, either by air or hot-gas, was controlled by an hourly timer having an adjustable duty cycle. The defrosting mode was initiated hourly for a fixed amount of time. The defrosting action was used, therefore, at times when it was not needed. At other times the length of the defrosting period was inadequate to fully clear the coils of frost or ice. This arrangement led to a lack of refrigeration effect at times and a gradual building of ice on the coils at other times. In the latter case the coils of the evaporator became so covered with ice that flow of air through the evaporator would become greatly reduced and any refrigeration effect (also greatly reduced) would result in the production of more ice.

Theses defrosting problems indicated the need for defrosting on demand, i.e., defrosting action should be initiated only when a significant amount of ice is present on the evaporator coils. This determination could be done by monitoring the air flow through the evaporator with the use of a vane-type anemometer or other device. Defrosting could then be initiated when the flow of air had dropped below a pre-set value, say, 80 per cent of the unblocked (maximum) flow. Defrosting would then be continued until the air flow had returned to a greater value, say, 95 per cent of the unblocked flow. With this arrangement either hot-gas or air defrosting of the coils could be employed. During air defrosting the compressor operation would be stopped while air form the storage area would be permitted to continue circulating over the evaporator coils to melt the ice or to cause the ice to sublimate into the air stream. In hot-gas defrosting the compressor operation would continue, but hot refrigerant gas from the discharge of the compressor would be circulated through the evaporator coils, causing the ice to melt or to sublimate. Circulation of air over the evaporator coils was generally maintained in both defrosting modes.

The need for full-time operation of the refrigeration equipment required that the auxiliary power supply also be operated on a full-time basis. With no means of automatically adjusting the auxiliary power supply, frequent manual adjustment was necessary. This adjustment was needed to maintain the system voltage within the allowable operating voltage range of the battery as the system voltage varied with the electrical load, the state-of-charge of the battery, and power developed by the windmill.

With the auxiliary power supply's variable transformer adjusted so that its rectified secondary voltage equalled the open-circuit battery voltage, the battery would neither charge nor discharge. This has been identified as a "balanced" state, i.e., the power required by the compressor motor was balanced by the auxiliary power supplied so that the state-of-charge of the battery would remain unchanged.

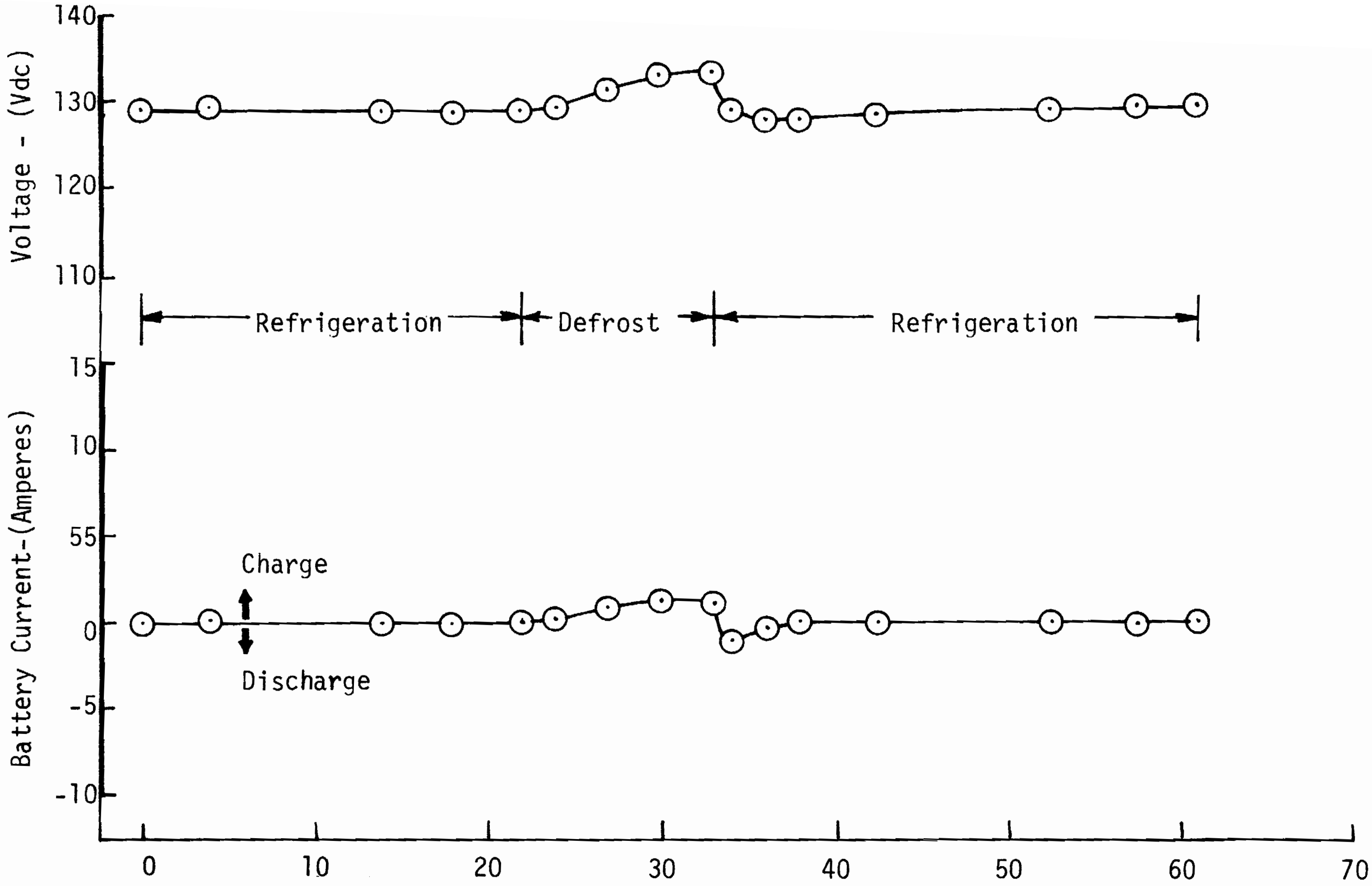
If the system were in a balanced state and the power required by the compressor were changed, then the balance would have been upset and the battery would have been charged or discharged accordingly in an attempt to re-establish a new balanced state at a new system voltage. A reduction (an increase) in the electrical load caused the battery to charge (to be discharged) and the system voltage rose (fell). With a significant change in the electrical load the system voltage may have been made to go out of the desired voltage range, assuming that no adjustment of the variable transformer setting had been made.

From the component performance tests it was found that when the compressor motor was operated, the power required increased with increased ambient temperature. The electrical load, therefore, varied throughout the day with the load being greatest, typically, in the mid-afternoon period. The system voltage consequently varied throughout the day. The state-of-charge of the battery also varied with the battery charging and discharging at low rates. The battery tended to discharge during the day and charge at night based on typical diurnal variation of the ambient temperature. The variation of the of the system voltage would not have been very significant if the compressor motor operated continuously with the compressor in the same mode of operation. Some excess auxiliary power would have been used as a result of the battery efficiency which prevented the usage of all of the electrical energy put into the battery while being charged.

Periodic defrosting operation increased this excess use of auxiliary power through the discharging and charging of the battery on a more frequent basis, e.g., hourly. This effect was greater when air defrosting was employed.

A typical variation of the system volatge and battery current during one cycle (one hour) of operation employing the hot-gas defrosting mode is shown in Figure 42. With no wind power available the system was in a balanced state during most of the cycle when the compressor was operating in the refrigeration mode. When defrosting was initiated, the power required by the compressor motor was reduced. The auxiliary power supplied was not fully reduced to compensate for the reduction in the load and auxiliary power was used to charge the battery. The battery voltage rose during the defrosting operation as did the current into the battery. Part of the voltage rise was due to a reduced voltage drop in the auxiliary power supply as the delivered power was reduced. If the defrost period had been greatly extended, the system would have approached a new balanced state with no further increase in system voltage and the battery current would have returned to zero, provided that the load on the compressor would have remained constant. When refrigeration was re-initiated, the voltage quickly returned to the pre-defrost value with an associated, diminishing discharge of the battery to the prior balanced state. In doing so, a significant fraction of the energy supplied to the battery by the auxiliary power supply during the defrost period, estimated at 42 per cent, was not recovered when refrigeration was re-initiated. The actual excess of energy consumed by the charging of the battery was probably 18 per cent greater owing to the inefficiency of the auxiliary power supply.

Figure 43 presents a typical variation of system voltage and battery current during one cycle of operation with air defrosting. No



Fiaure 42. System Behavior During Hot-gas Defrosting

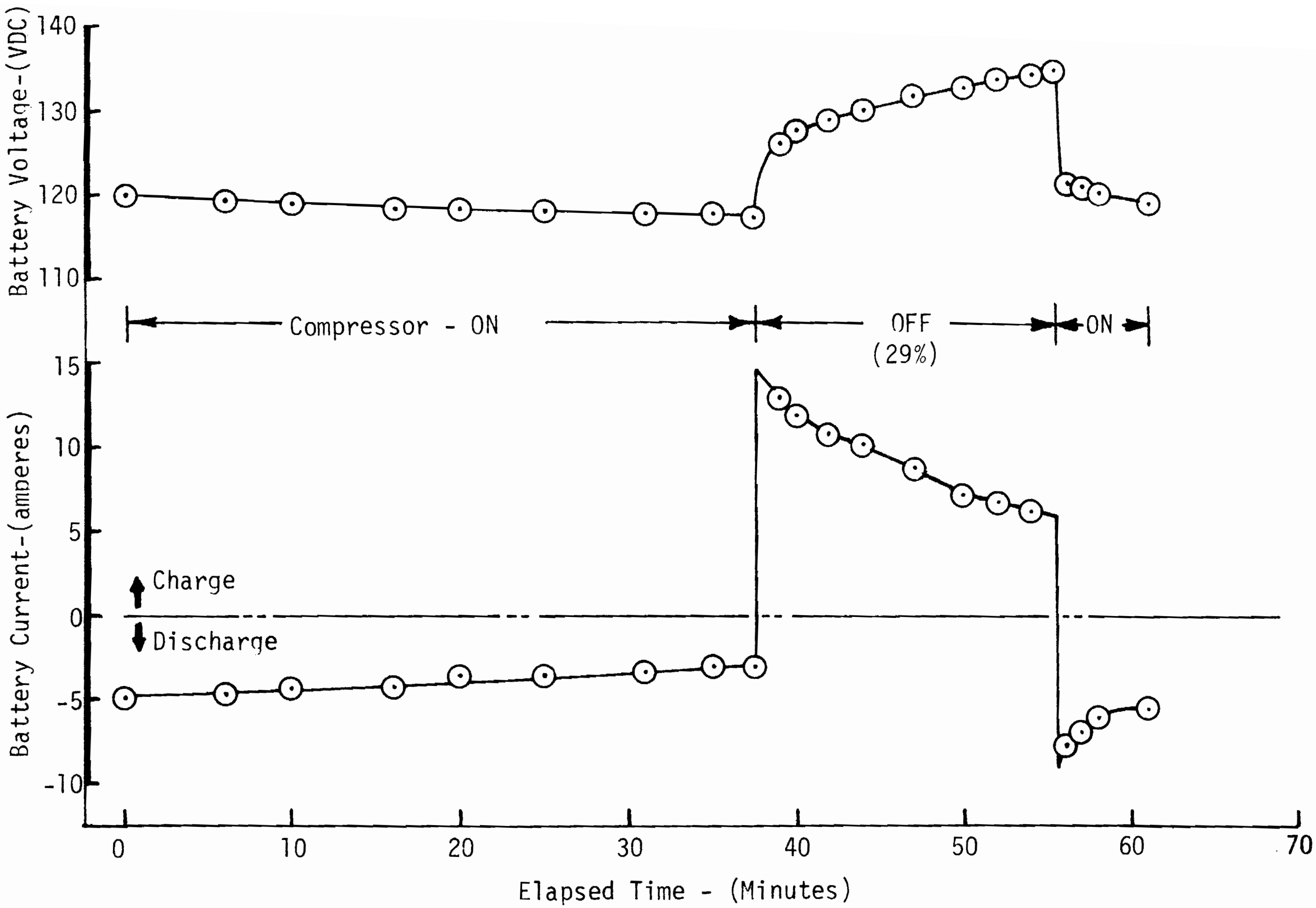


Figure 43. **System Behavior During Air Defrosting**

electrical power was supplied by the windmill during this cycle. With the auxiliary power operated continuously, the compressor motor was turned off during the defrost period to permit the air blowing over the evaporator coils to melt and sublimate accumulated ice. Because the auxiliary power supply was operated continuously as a result of having no means of disconnecting it from the system, the battery was charged by auxiliary power during the defrost period. To maintain an average voltage within the operating voltage range of the battery, it was necessary to adjust the variable transformer to charge the battery during the defrost operation with the battery discharging during operation of the compressor in the refrigeration mode.

Charging of the battery during air defrosting used significant amounts of energy from a continuously operated auxiliary power supply because this energy had to enter the battery prior to its use by the compressor motor. Moreover, air defrosting required a greater percentage of the operation cycle than hot-gas defrosting to provide a similar effect. A greater percentage of time required for defrosting, however, reduced the percentage of time available for providing refrigeration. This reduction became especially important when the need for refrigeration was critical.

Air defrosting could have been made more efficient by the addition of some means of disconnecting the auxiliary power supply during the defrost period. This ability would have increased the similarity in the auxiliary power usage between the hot-gas and air defrosting modes with the exception of the additional energy required for operating the compressor motor during hot-gas defrosting.

When the compressor motor was being operated with auxiliary power so that the system was nearly balanced when no power was delivered by the windmill generator, the ability of the windmill to supply power to the system reduced the need for auxiliary power. However, not all of the developed windmill power was used by the compressor motor with an equal reduction in the auxiliary power required. A portion of the windmill power was diverted, instead, to charging the battery. As the developed windmill power subsided, the recoverable fraction of that energy was discharged to operate the compressor motor. Thus, the balanced state operation resulted in a decrease in overall efficiency of available wind energy via battery inefficiency. If, however, the battery were discharging to operate the compressor motor, all of the power not in excess of that required by the compressor motor, would have been fully utilized.

To prevent charging the battery so as to fully utilize developed windmill power when operation of the auxiliary power supply was necessary, automatic control of the auxiliary power supply would have been required. This control could have been more easily accomplished with the use of a solid-state auxiliary power supply instead of one employing a mechanically adjustable variable transformer, i.e., an SCR (Silicon Controlled Rectifier) circuit. By monitoring the battery current when the auxiliary power supply was operated, continuous adjustment of the SCR would have produced a continuous balanced state, i.e., the battery current would be maintained at zero irrespective of load changes and variation of developed windmill power with the exception of those times when the developed windmill power was greater than the power required by the compressor motor. The system voltage, therefore, varied with the state-of-charge of the battery and was not affected by the voltage drop resulting from the battery's internal resistance.

When the evaporator coils developed a sufficiently thick coating of ice, defrosting becomes necessary and a choice of defrosting methods had to be made. In this study two choices, hot-gas defrosting and air defrosting, were evident. Other defrosting techniques might be developed, but it would be hoped that improvements in refrigeration system design and component selection would reduce evaporator icing and the need for defrosting. The two defrosting methods that have been described are similar with the exception that hot-gas defrosting provided extra heating action from within the ice-covered coils. Thus, the use of hot-gas defrosting reduced the time required to clear the coils of ice at the cost of requiring additional energy to operate the compressor. Air defrosting, on the other hand, reduced the average refrigeration effect by reducing the time in which the compressor operates in the refrigeration mode.

The use of air defrosting is recommended for those times when refrigeration is not needed, especially when the wind is blowing as the windmill operates more efficiently at the higher voltage. If, however, the wind is blowing and the battery is near a fully-charged state it would be beneficial to employ hot-gas defrosting without the use of auxiliary power.

Hot-gas defrosting should also be employed when refrigeration is definitely needed in the storage area to reduce the amount of time during which refrigeration cannot be provided.

The refrigerated storage of apples (or other fruits or produce) introduces a requirement that is not often found in other alternative energy applications. The requirement that when the temperature in the storage area exceeds the desired temperature by only a few degrees, refrigeration must be supplied without regard to the source of power to reduce the possibility of damage to the fruit. This need may require the mandatory use of auxiliary power.

A prolonged period of temperatures above the desired storage temperature can result in irreparable damage to the fruit [16]. Even minor damage can result in further degradation in fruit quality even though the environmental conditions are corrected quickly and maintained thereafter. Fruit damage can result in large monetary losses, defeating the intended purpose of storage - to delay the marketing of quality fruit until a later date when the supply of freshly harvested fruit has diminished. Of course, some degradation in fruit quality can be expected, but the damage should be minimized.

Several elements of control strategy were developed for the improvement of the control of a wind-powered, refrigerated apple storage similar to thesystem developed at VPI&SU:

i) Never charge the battery with the auxiliary power supply unless absolutely necessary.

ii) When possible, operate the compressor motor to provide refrigeration directly from the battery with any possible

ii) assistance from the windmill and permit any excess power developed by the windmill to charge the battery. Also, employ air defrosting unless there is sufficient wind energy available to raise the system voltage to the upper range of the allowable voltage range of the battery.

iii) Prevent needless charging and discharging of the battery when auxiliary power is required by automatic adjustment of the auxiliary power supply to maintain a zero battery current.

iv) Operate the compressor motor with the assistance of the auxiliary power supply only when necessary, i.e., to prevent fruit damage that would be caused by an elevated storage temperature.

v) Produce ice in the ice storage tank by operation of the compressor motor when refrigeration is not needed in the storage area, but subject to the conditions stated in ii).

vi) Defrost the evaporator coils only when required and for only as long as is needed to restore an adequate flow of air through the evaporator section.

vii) Employ automatic regulation, if possible, to control the field of the windmill generator to optimize the efficiency of the unit for any electrical load.

An improved control strategy would require two thermostats to best utilize any available wind energy. Control of the system would alternate between these two thermostats according to the following plan.

One of the thermostats would be associated with the preferred mode of operation in which the compressor operates from the battery and power developed by the windmill. The compressor motor would be turned on when the temperature in the storage area rose above temperature T_1 and turned off when it dropped below T_2. These two temperatures correspond to the thermostat's end points and define the desired temperature range to be maintained within the storage area. In this mode of operation air defrosting would be employed.

If the temperature of the storage area were to fall below T_2 some provision should be made to continue operation of the compressor motor to produce ice in the ice storage tank. Ice production should only be initiated if the system voltage is sufficiently high which would indicate the production of power by the windmill generator. If ice production were to be initiated it should continue until the voltage dropped below a given value or when the storage area temperature exceeded temperature T_1. Operation would then revert to the normal, preferred mode. To accomplish this ice production a bypass arrangement would be needed to shunt the flow of air through the storage area.

While operating in the preferred mode, the system voltage might drop below the allowable minimum or the temperature in the storage area might continue to rise above temperature T_1. The latter condition would probably indicate a lack of refrigeration effect caused by longer defrost periods associated with air defrosting. In that event auxiliary power should be employed to operate the compressor motor. With the former (low voltage) condition the compressor motor should be turned off until either the latter (temperature) condition is also encountered or until the system voltage has risen above some value indicating that the battery has been charged by windmill produced power.

The change to an alternate mode of operation utilizing auxiliary power can be initiated by the second thermostat with endpoint temperature T_A (upper) and T_B (lower). The upper set point temperature would have to be slightly higher than set point T_1 of the preferred thermostat. Also, the lower set point temperature T_B should lie between set points T_1 and T_2. Thus, should the storage area temperature rise above T_A the auxiliary power would be employed together with hot-gas defrosting. To reduce the need for auxiliary power an automatic system for maintaining a zero battery current would be required. Auxiliary power would be turned off when the storage area temperature was reduced to temperature T_B, and control would revert to the preferred mode.

Outside temperature should be monitored to control a sump heater in the compressor to prevent damage during colder weather when refrigerant might condense in the valve assembly. This condensate can severely damage the compressor when it begins operation.

The control strategy that has been outlined above should provide a significant improvement in the utilization of available wind energy and power taken from the auxiliary power supply. Quantitative improvement would depend on the system design and site selection.

This control strategy would be suitable for implementation with a dedicated, microprocessor controller.

XIV. CONCLUSIONS

1. The Elektro 120 WVG windmill operated more efficiently at voltages above 135 VDC.

2. The following control strategy elements can provide for improved system operation:

   (i) Auxiliary power should not be used to charge the battery unless absolutely necessary

   (ii) Operation of the compressor motor from the battery and from windmill developed power with air defrosting is the preferred mode of operation

   (iii) An elevated storage temperature should initiate the use of auxiliary power with automatic control to maintain a zero battery current.

   (iv) Operation with auxiliary power should continue until the storage temperature has been reduced to an acceptable value, then revert to the preferred mode.

   (v) Hot-gas defrosting should be employed when auxiliary power is needed.

   (vi) Ice should be produced in the ice storage tank when possible and when refrigeration is not needed in the storage area.

   (vii) Defrosting should be initiated only when needed and should continue only for as long as is needed to restore an adequate flow of air through the evaporator.

3. A means to optimize the efficiency of a windmill for any system voltage is needed.

XV. RECOMMENDATIONS FOR FURTHER RESEARCH

The research upon which this dissertation was based is only the beginning stage in the eventual development of an optimized control system for wind energy applications of the type considered. There will be ample room for improvement in several areas.

The control of the windmill generator's field should be investigated with the goal of optimizing developed power conversion for any type of electrical load. Such control would most probably require a microprocessor for implementation and could be combined with the basic microprocessor control scheme suggested in this dissertation.

Ways of improving the efficiency of supplying auxiliary power from an alternating current source should be sought. An SCR-based system should be studied for comparison with the variable transformer and bridge rectifier method.

Further research is needed in the control of the refrigeration equipment to maximize the developed refrigeration effect per unit of input energy required, i.e., maximize the coefficient of performance, possibly by control of the expansion valve and condensing pressure.

For the particular application of wind energy discussed in this discourse the effect of partitioning the refrigeration effect between the storage area and the ice storage tank should be investigated. Also, the use of an indirect refrigeration system warrants further study.

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XVII. APPENDICES

APPENDIX A

VPI&SU System Component Specifications

Table A-1

Specifications of the Refrigeration System

Refrigeration System	Direct, vapor compression
Refrigerant	R-12 (CCl_2F_2)
Compressor: Lehigh Manufacturing Co., Model 16791	
Nominal Power	3 Hp
Number of cylinders	2
Bore/Stroke	3-1/4 in./2-1/4 in.
Receiver Refrigerant Capacity	25-1/2 Lb R-12
Air-Cooled Condenser: Lehigh Manufacturing Co., Model 11302	
Nominal Speed	500 rev/min
Capacity	26,000 Btu/hr @ 20°F suction temp.
Compressor Motor: General Electric Co., DC Motor, Model 5B254A19	
Rated Power	5 Hp
Rated Voltage	115 Vdc
Maximum Current	39.1 Amperes
Duty Cycle	Continuous
Rated Speed	1750 rev/min
Expansion Valve: Sporlan Valve Co., Model CFE 3 C	
Type	Thermostatic w/pressure equalizer
Rated Capacity	3-ton
Evaporator: Aerofin Corp., DP DX 144 3NTL	
Circulating Fan: Aerovent Corp., 315 BIA DWDI	
0.12 kW (0.16 Hp) @ 1180 RPM	

Table A-2

Specifications of the Windmill System

Manufacturer	Elektro (Switzerland)
Model	Modified 120WVG
Rated Power	10 KW @ 24 miles/hour
Maximum voltage	150 Vdc
Maximum current	60 Amperes
Maximum windspeed	13 m/s (30 mph)
Output	3-phase, 110 or 220 VAC
Rotor Diameter	6,6 m (22 ft)
Field Regulation	Permanent magnet & field rotors
Field current	1.2 - 1.5 Amperes
Field voltage	50 - 80 V
Generator weight	285 kg (625 lb)
Pitch control	Centrifugally actuated
Vane control	Electric drive/hand crank
Tower height	12 m (40 ft) originally 27 m (90 ft)

Table A-3

Specifications of the Storage Battery

Manufacturer	Nife, Inc.
Model No.	C 3600
Cell Type	KB-12, nickel cadmium
Open circuit voltage, V_{oc}	1.33 - 1.35 V/cell
No. of cells	91 (series connected)
Rated capacity/cell	123 A-hr/cell
<u>Discharge:</u>	
Normal Rate	30 Amperes
Normal discharge time	4 hours
Initial voltage	1.3 V/cell
Final voltage	1.0 V/cell
Average voltage	1.2 V/cell
<u>Charge:</u>	
Max. Rate @ constant current	35 Amperes
Time at maximum rate	5 hours
Voltage at maximum rate	1.40 - 1.72 V/cell
Maximum constant voltage charge	1.55 V/cell
Float voltage (trickle charge)	1.42 V/cell

Table A-4

Specifications of the Auxiliary Power System

Isolation Transformer: General Electric Co.	
Model	9T2IA1007
Approx. % Imp.	2.9 %
Rated kVA	5
Primary	120 VAC, 60 Hz
Secondary	120 VAC, 60 Hz
Variable Autotransformer: The Superior Electric Co.	
Type	1156C-3Y
Spec. No.	8P17156
Primary	240 VAC, 3-phase, 60 Hz (only one leg used)
Output	0 - 230 VAC
Maximum Current	45 Amperes
Maximum kVA	21.8
Rectifier	
Type	Full Wave Bridge
PIV	200 Volts
Maximum Current	25 Amperes

APPENDIX B

In Situ Performance Data Tabulation

Table B-1

Performance Test Identification

Test No.	Compressor Operation*	Auxiliary Power
1	OFF	OFF
2	OFF	OFF
3	OFF	OFF
4	OFF	OFF
5	OFF	OFF
6	OFF	OFF
7	OFF	OFF
8	OFF	OFF
9	R	OFF
10	D	OFF
11	R	OFF
12	R	OFF
13	D	OFF
14	R	OFF

* D = Defrost; R = Refrigeration

Table B-1 (cont.)

Performance Test Identification

Test No.	Compressor Operation*	Auxiliary Power
15	R	FIXED
16	D	FIXED
17	R	FIXED
18	D	FIXED
19	D	FIXED
20	R	FIXED
21	R	FIXED
22	R	FIXED
23	R	FIXED
24	R	FIXED
25	R	FIXED
26	R	FIXED
27	R	VARIABLE
28	R	VARIABLE

* D = Defrost; R = Refrigeration

Table B-2

Performance Data Tabulation-Test 1

Auxiliary Power: OFF

Compressor Motor: OFF

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{V}$ (Volts)
7.6	17	1110	124.5
5.8	13	540	124
6.0	13.5	660	124.5
5.8	13	600	125
5.4	12	480	125
6.5	14.5	720	126
5.4	12	390	126
5.4	12	510	127
7.6	17	1140	131
6.9	15.5	1230	136
6.9	15.5	1050	136
5.1	11.5	360	135
7.6	17	1020	134

Table B-3

Performance Data Tabulation-Test 2

Auxiliary Power: OFF

Compressor Motor: OFF

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{V}$ (Volts)
5.8	13	510	114
6.0	13.5	600	118
6.5	14.5	870	119.5
6.7	15	810	120.5
5.4	12	450	120
4.9	11	240	119.5
6.5	14.5	720	121
5.4	12	420	121
4.7	10.5	210	119.5
4.7	10.5	270	121
5.8	13	630	122
6.5	14.5	750	122
6.3	14	720	122
4.7	10.5	180	121.5
5.6	12.5	510	122.5
6.5	14.5	840	124
6.9	15.5	930	124.5
7.8	17.5	1080	126.5
7.2	16	930	127
6.9	15.5	930	127
5.8	13	930	127
5.6	12.5	660	126

Table B-4

Performance Data Tabulation-Test 3

Auxiliary Power: OFF

Compressor Motor: OFF

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{V}$ (Volts)
3.8	8.5	90	113
4.8	10.75	360	113
3.2	7.25	0	113.5
4.2	9.5	120	114
4.0	9	120	114
4.2	9.5	150	114
3.8	8.5	60	114
3.8	8.5	90	114.5
4.5	10	330	115
4.5	10	210	115
3.8	8.5	60	115
4.5	10	210	116
3.8	8.5	120	116
4.5	10	210	116
4.7	10.5	360	116
5.4	12	570	116
6.3	14	750	116
4.5	10	210	116.5
3.8	8.5	120	116

Table B-5

Performance Data Tabulation-Test 4

Auxiliary Power: OFF

Compressor Motor: OFF

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{V}$ (Volts)
4.0	9	90	124
3.8	8.5	90	123
3.8	8.5	150	123.5
4.0	9	120	124
3.8	8.5	90	123.5
2.5	5.5	0	123.5
4.7	10.5	390	123.5
4.9	11	540	124
4.5	10	270	124
5.1	11.5	390	123.5
4.7	10.5	270	123.5
3.6	8	60	123.5
3.1	7	0	123
4.9	11	510	123.5
4.0	9	150	123.5
3.4	7.5	30	123
3.8	8.5	120	123
4.0	9	180	123

Table B-6

Performance Data Tabulation-Test 5

Auxiliary Power: OFF

Compressor Motor: OFF

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{V}$ (Volts)
5.4	12	360	126
5.8	13	480	131
5.4	12	360	135
7.8	17.5	1290	139
8.0	18	1350	143

Table B-7

Performance Data Tabulation-Test 6

Auxiliary Power: OFF

Compressor Motor: OFF

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{V}$ (Volts)
6.0	13.5	840	144
5.6	12.5	630	143
6.5	14.5	960	144
5.6	12.5	630	143
5.6	12.5	630	143
7.4	16.5	1470	143

Table B-8

Performance Data Tabulation-Test 7

Auxiliary Power: OFF

Compressor Motor: OFF

$\overline{W}$		$\overline{P}_W$	$\overline{V}$
(m/s)	(mph)	(Watts)	(Volts)
2.9	6.5	30	133
4.5	10	300	137
3.8	8.5	150	135
3.8	8.5	210	138
3.8	8.5	270	135
3.6	8	180	135
2.7	6	0	133
3.1	7	60	134
2.9	6.5	0	133
3.1	7	30	133
2.0	4.5	0	132
3.6	8	0	132
3.8	8.5	120	134
2.9	6.5	0	133
2.7	6	0	132
1.6	3.5	0	132
2.0	4.5	0	131

Table B-9

Performance Data Tabulation-Test 8

Auxiliary Power: OFF

Compressor Motor: OFF

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{V}$ (Volts)
4.9	11	420	137
4.5	10	330	136
4.0	9	180	137
3.6	8	60	136
3.1	7	60	135
3.1	7	30	134
2.9	6.5	0	134
4.5	10	360	140
3.6	8	90	137
3.1	7	90	136
2.7	6	60	136
2.9	6.5	0	134
2.0	4.5	0	132
4.5	10	480	137
4.7	10.5	480	138
4.7	10.5	450	138
3.6	8	240	138

Table B-10

Performance Data Tabulation-Test 9

Auxiliary Power: OFF

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\overline{V}$ (Volts)
7.2	16	900	1830	---
6.3	14	630	1830	---
6.3	14	690	1800	119
6.5	14.5	660	1830	118
6.9	15.5	750	1770	118.5
7.8	17.5	930	1800	118
6.9	15.5	720	1800	117
6.5	14.5	630	1740	117
7.2	16	840	1740	113
6.5	14.5	630	1680	111
7.2	16	780	1680	109
5.6	12.5	450	1650	107
6.5	14.5	570	1620	106
8.6	19.25	870	1650	106
8.6	19.25	810	1650	105
7.9	17.75	660	1620	104.5
7.9	17.75	690	1620	104
8.7	19.5	780	1620	103
6.0	13.5	510	1590	102
7.4	16.5	630	1560	101
7.8	17.5	630	1560	100
8.5	19	720	1560	98
8.7	19.5	660	1560	97

Table B-11

Performance Data Tabulation-Test 10

Auxiliary Power: OFF

Compressor Motor: ON, Defrost Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\overline{V}$ (Volts)
4.2	9.5	180	1650	117
5.8	13	540	1680	117
5.4	12	330	1620	115.5
6.3	14	630	1650	115
5.1	11.5	390	1590	113
4.5	10	240	1530	109
5.4	12	450	1560	106
5.6	12.5	480	1530	105
6.3	14	570	1500	105
6.3	14	630	1530	105
6.5	14.5	570	1470	104
5.4	12	330	1470	102
8.0	18	720	1470	102
9.2	20.5	810	1440	102
10.1	22.5	930	1470	101
7.6	17	660	1440	99
6.7	15	570	1410	97.5
5.4	12	390	1380	96

Table B-12

Performance Data Tabulation-Test 11

Auxiliary Power: OFF

Compressor Motor: ON, Refrigeration Mode

$\bar{W}$ (m/s)	$\bar{W}$ (mph)	$\bar{P}_W$ (Watts)	$\bar{P}_C$ (Watts)	$\bar{V}$ (Volts)
4.2	9.5	180	2670	110
4.5	10	270	2700	109
4.5	10	270	2670	108.5
3.8	8.5	180	2655	108
4.2	9.5	210	2655	107.5
4.7	10.5	360	2670	106.5
3.6	8	120	2610	105
4.7	10.5	360	2640	104
4.7	10.5	330	2610	104
4.7	10.5	390	2610	103
4.7	10.5	270	2610	102.5
3.4	7.5	60	2475	101
3.8	8.5	90	2655	99.5
3.8	8.5	90	2550	98
3.6	8	30	2520	97
3.8	8.5	150	2490	96.5

Table B-13

Performance Data Tabulation-Test 12

Auxiliary Power: OFF

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\overline{V}$ (Volts)
5.8	13	510	2610	118
4.7	10.5	180	2580	116.5
5.1	11.5	330	2580	116
5.1	11.5	330	2550	115.5
4.9	11	270	2490	114.5
4.7	10.5	210	2550	113
5.1	11.5	270	2520	112
5.4	12	360	2505	112
5.4	12	450	2505	112
6.0	13.5	540	2520	111.5
6.0	13.5	630	2520	111.5
4.7	10.5	210	2460	110
5.1	11.5	300	2460	108
5.8	13	540	2460	105.5

Table B-14

Performance Data Tabulation-Test 13

Auxiliary Power: OFF

Compressor Motor: ON, Defrost Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\overline{V}$ (Volts)
7.6	17	960	1600	121.5
7.4	16.5	870	----	120
7.2	16	870	1550	119
6.0	13.5	480	----	118.5
6.7	15	780	----	118.5
6.9	15.5	780	----	118
7.2	16	840	----	118
7.6	17	870	----	118
6.9	15.5	690	----	118

Table B-15

Performance Data Tabulation-Test 14

Auxiliary Power: OFF

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$		$\overline{P}_W$	$\overline{P}_C$	$\overline{V}$
(m/s)	(mph)	(Watts)	(Watts)	(Volts)
7.4	16.5	1050	2730	121
7.2	16	990	2700	120
8.0	18	1170	2550	119.5
6.7	15	930	2640	118
5.4	12	570	2610	117
6.3	14	720	2670	116.5
5.1	11.5	600	2670	116
4.0	9	270	2610	114.5

Table B-16

Performance Data Tabulation-Test 15

Auxiliary Power: ON (fixed)

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\hat{P}_{AUX}$ (Watts)	$\overline{V}$ (Volts)
3.8	8.5	210	2610	2820	103
4.2	9.5	285	2610	2790	102.5
3.8	8.5	135	2610	2940	102.5
3.8	8.5	150	2610	2940	102
3.6	8	120	2610	2970	102
3.6	8	150	2610	2940	102
3.6	8	180	2610	2970	102
3.1	7	30	2610	3030	102
3.4	7.5	120	2640	3030	101.5
3.4	7.5	120	2610	2940	102
3.6	8	210	2670	2970	102.5
4.0	9	210	2610	2910	102
3.6	8	120	2610	3030	102
3.6	8	150	2700	2970	103

Table B-17

Performance Data Tabulation- Test 16

Auxiliary Power: ON (fixed)

Compressor Motor: ON, Defrost Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\hat{P}_{AUX}$ (Watts)	$\overline{V}$ (Volts)
8.9	20	870	1500	----	103.5
8.7	19.5	870	1500	----	104
8.0	18	840	1500	----	104
7.6	17	750	1500	----	106
9.4	21	900	1530	----	105.5
7.2	16	690	1470	----	105
6.7	15	600	1500	----	104
7.6	17	720	1500	----	104

Table B-18

Performance Data Tabulation-Test 17

Auxiliary Power: ON (fixed)

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\hat{P}_{AUX}$ (Watts)	$\overline{V}$ (Volts)
6.3	14	570	2610	2820	118.5
5.6	12.5	480	2580	2880	119
5.4	12	450	2610	2910	118.5
4.7	10.5	240	2580	2940	118
5.4	12	450	2580	2880	119
5.1	11.5	330	2580	2850	119
5.6	12.5	420	2610	2820	118.5
6.3	14	540	2580	2760	120
4.7	10.5	240	2610	2790	118.5
4.5	10	180	2610	2850	118
6.3	14	660	2310	2280	122
8.0	18	1080	2640	2460	121

Table B-19

Performance Data Tabulation-Test 18

Auxiliary Power: ON (fixed)

Compressor Motor: ON, Defrost Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\hat{P}_{AUX}$ (Watts)	$\overline{V}$ (Volts)
8.0	18	960	1800	1170	119.5
7.8	17.5	960	1800	1140	120
6.5	14.5	660	1740	1170	119.5
5.4	12	330	1710	1290	118
4.7	10.5	300	1710	1260	118

Table B-20

Performance Data Tabulation-Test 19

Auxiliary Power: ON (fixed)

Compressor Motor: ON, Defrost Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\hat{P}_{AUX}$ (Watts)	$\overline{V}$ (Volts)
5.1	11.5	540	1830	1500	119.5
4.9	11	360	1740	1470	119.5
6.0	13.5	750	1830	1380	119.5
5.4	12	540	1770	1410	-----
4.5	10	330	1740	1560	-----
4.5	10	330	1770	1560	118
4.7	10.5	270	1740	1560	-----
6.9	15.5	1020	1800	1350	-----
5.4	12	450	1770	1410	120

Table B-21

Performance Data Tabulation-Test 20

Auxiliary Power: ON (fixed)

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\hat{P}_{AUX}$ (Watts)	$\overline{V}$ (Volts)
4.9	11	330	2745	4230	127.5
6.3	14	660	2745	4080	128
5.8	13	450	2760	4080	127.5
5.1	11.5	300	2760	4110	127
5.4	12	420	2745	4020	127.5

Table B-22

Performance Data Tabulation-Test 21

Auxiliary Power: ON (fixed)

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\hat{P}_{AUX}$ (Watts)	$\overline{V}$ (Volts)
3.6	8	0	2700	3210	122.5
4.0	9	30	2700	3240	122.5
4.2	9.5	120	2700	3210	123
5.6	12.5	450	2730	3090	123
4.5	10	120	2730	3060	122.5
4.9	11	270	2715	3090	122
4.9	11	240	2745	3090	123
6.5	14.5	630	2730	3000	123.5
4.5	10	90	2700	3120	122.5
5.4	12	480	2700	2940	124.5
5.1	11.5	390	2670	2940	124

Table B-23

Performance Data Tabulation-Test 22

Auxiliary Power: ON (fixed)

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\hat{P}_{AUX}$ (Watts)	$\overline{V}$ (Volts)
6.7	15	780	2670	1770	122
6.9	15.5	780	2640	1860	122
5.1	11.5	300	2640	1950	121.5
5.8	13	420	2640	1920	121
6.7	15	720	2640	1920	121
4.9	11	210	2640	2010	120.5

Table B-24

Performance Data Tabulation-Test 23

Auxiliary Power: ON (fixed)

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\hat{P}_{AUX}$ (Watts)	$\overline{V}$ (Volts)
6.7	15	690	2610	1170	119.5
5.8	13	510	2610	1260	119
7.8	17.5	900	2580	1260	118.5

Table B-25

Performance Data Tabulation-Test 24

Auxiliary Power: ON (fixed)

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\hat{P}_{AUX}$ (Watts)	$\overline{V}$ (Volts)
5.1	11.5	300	2520	2220	114.5
5.6	12.5	390	2550	2220	114.5
4.9	11	270	2520	2280	115
5.6	12.5	480	2580	2160	115
6.7	15	630	2550	2130	114.5
5.1	11.5	390	2550	2190	115
6.5	14.5	600	2550	2130	115.5
5.6	12.5	450	2520	2130	115.5

Table B-26

Performance Data Tabulation-Test 25

Auxiliary Power: ON (fixed)

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\hat{P}_{AUX}$ (Watts)	$\overline{V}$ (Volts)
2.9	6.5	0	2790	1920	115
3.1	7	0	2775	1890	115
3.8	8.5	90	2775	1890	114.5
4.5	10	180	2790	1920	114.5
3.1	7	30	2760	1980	114.5
4.5	10	180	2790	2010	114.5
4.5	10	210	2790	1980	114.5
4.9	11	360	2790	2040	114
4.2	9.5	150	2760	2040	114
3.1	7	30	2790	2100	114
4.9	11	450	2790	2070	114
4.5	10	270	2760	2070	114
4.2	9.5	240	2760	2100	114
3.6	8	60	2760	2070	114
4.0	9	210	2745	2070	113.5
4.5	10	150	2745	2040	113.5
5.4	12	510	2760	2040	113.5

Table B-27

Performance Data Tabulations-Test 26

Auxiliary Power: ON (fixed)

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\hat{P}_{AUX}$ (Watts)	$\overline{V}$ (Volts)
4.5	10	300	1920	1530	129.5
6.0	13.5	750	1950	1950	129
7.4	16.5	1080	2010	2070	130.5
6.5	14.5	900	1860	2040	130.5
4.7	10.5	240	1920	1830	129.5

Table B-28

Performance Data Tabulation-Test 27

Auxiliary Power: ON (variable)

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\hat{P}_{AUX}$ (Watts)	$\overline{V}$ (Volts)
7.2	16	1170	1890	.810	127
7.2	16	990	1890	1050	126
5.6	12.5	600	1860	1500	126
5.5	12.25	630	1860	1440	126
4.8	10.75	330	1890	1770	126
4.7	10.5	330	1860	1800	126
6.9	15.5	990	1890	1050	126

Table B-29

Performance Data Tabulation-Test 28

Auxiliary Power: ON(variable)

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$		$\overline{P}_W$	$\overline{P}_C$	$\hat{P}_{AUX}$	$\overline{V}$
(m/s)	(mph)	(Watts)	(Watts)	(Watts)	(Volts)
4.9	11	270	2730	2730	122
4.0	9	120	2730	3090	122
4.9	11	360	2730	2790	122
4.9	11	300	2730	2880	122
4.7	10.5	420	2760	2760	122
4.7	10.5	300	2760	2850	122
2.9	6.5	30	2760	3240	122
2.2	5	0	2835	3300	122
3.4	7.5	30	2715	3240	122
4.9	11	210	2700	2910	122
3.8	8.5	60	2730	3150	122
4.9	11	330	2730	2820	122
4.2	9.5	120	2730	3120	122
6.5	14.5	660	2760	2400	122
4.9	11	270	2700	2850	122
2.9	6.5	0	2730	3210	122
3.8	8.5	60	2790	3210	122
4.9	11	330	2640	2700	122
4.7	10.5	240	2700	2880	122
4.9	11	330	2730	2820	122
5.1	11.5	360	2700	2700	122
5.1	11.5	450	2700	2610	122
4.7	10.5	150	2700	3000	122
4.5	10	150	2790	3000	122
5.8	13	600	2700	2490	122

Table B-29 (Cont.)

Performance Data Tabulation-Test 28

Auxiliary Power: ON(variable)

Compressor Motor: ON, Refrigeration Mode

$\overline{W}$ (m/s)	$\overline{W}$ (mph)	$\overline{P}_W$ (Watts)	$\overline{P}_C$ (Watts)	$\hat{P}_{AUX}$ (Watts)	$\overline{V}$ (Volts)
7.4	16.5	930	2700	2010	122
6.9	15.5	930	2670	1980	122
5.6	12.5	510	2700	2550	122
4.9	11	150	2700	2970	122
5.4	12	450	2760	2670	122
3.8	8.5	30	2700	3180	122
6.9	15.5	780	2700	2220	122
4.7	10.5	270	2700	2880	122

XVI. VITA

John D.C. Baldwin was born in Long Branch, New Jersey on March 30, 1948. He attended several schools while his father was with the U.S. Army, including one in Ankara, Turkey.

After graduating from Staunton Military Academy in Staunton, Virginia where he had received several awards for outstanding leadership and academic achievement, he entered Virginia Polytechnic Institute and State University where he received a B.S. degree in Mechanical Engineering in 1971.

Following graduation he was employed as a mathematics teacher at a small, private boy's school in Virginia. He returned to VPI&SU the following year to begin graduate work.

He received his M.S. degree in Mechanical Engineering in 1973 and took a position as an Engineer/Scientist Specialist with McDonnell Douglas Astronautics Co.-West in Huntington Beach, California. While in their employ, he conducted studies in high-speed particle erosion and nose tip materials development.

The author returned to VPI&SU in 1975 to begin work towards a Ph.D. degree in Mechanical Engineering. While with the Department of Mechanical Engineering, he was employed as an Instructor, teaching Engineering Thermodynamics and a senior level mechanical engineering laboratory course. He also assisted Dr. A.G. Szeless in the analysis of his novel ship's hull design, MONOFORM.

In 1976 the author transferred his Ph.D. efforts to the Environmental Sciences and Engineering multi-disciplinary program to concentrate his efforts in agricultural engineering and to develop his area of specialization - alternative energy systems.

With the Department of Agricultural Engineering he obtained financial support during his program as a Graduate Research Assistant and as a Research Associate. His work has involved research projects in the areas of forestry, solar energy, and wind energy.

John Derouet Couper Baldwin

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AN IMPROVED CONTROL STRATEGY FOR WIND-POWERED

REFRIGERATED STORAGE OF APPLES

by

John Derouet Couper Baldwin

(ABSTRACT)

The need for an improved control strategy for the operation of a wind-powered refrigeration system for the storage of apples was investigated. The results are applicable to other systems which employ intermittently available power sources, battery and thermal storage, and an auxiliary, direct current power supply.

Tests were conducted on the wind-powered refrigeration system at the Virginia Polytechnic Institute and State University Horticulture Research Farm in Blacksburg, Virginia. Tests were conducted on the individual components of the system. In situ windmill performance were also conducted. The results of these tests have been presented.

An improved control strategy was developed to improve the utilization of available wind energy and to reduce the need for electrical energy from an external source while maintaining an adequate apple storage environment.