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Investigation of the Feasibility of Using Windpower for Space Heating in Colder Climates

Duane E. Cromack

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INVESTIGATION OF THE FEASIBILITY OF USING WINDPOWER
FOR SPACE HEATING IN COLDER CLIMATES

Final Report for the Period
Ending June 30, 1978

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## TABLE OF CONTENTS

Title Page.................................................................................................................. i
Table of Contents....................................................................................................... ii
Abstract..................................................................................................................... iii

I. EXECUTIVE SUMMARY......................................................................................... 1

II. INTRODUCTION.................................................................................................... 3

   General Background................................................................................................. 4
   The Wind Furnace...................................................................................................... 4
   Operation of the Wind Turbine.................................................................................. 8

III. SUMMARY OF TASKS......................................................................................... 24

   TASK 1. Continued Operation of SH-1 Experiment.............................................. 24
   TASK 2. Continued Aerodynamic and Blade Studies............................................ 49
   TASK 3. Continued Controls Design................................................................. 60
   TASK 4. Near Field Measurement......................................................................... 66
   TASK 5. Continued Dynamic Analysis.............................................................. 77
   TASK 6. Continued Design and Test of MOD-4.................................................. 83
   TASK 7. Analytical and Economic Modelling..................................................... 90
   TASK 8. Project Management............................................................................. 99

IV. PARTICIPATING PERSONNEL.............................................................................. 101

V. PUBLICATIONS TO DATE................................................................................... 105
ABSTRACT

A summary of the activities and results of the research on the UMASS Solar Habitat-I and Wind Furnace project is given. A general background and review followed by specific work under each task is presented. Lists of publications to date and participating personnel are included.
I. EXECUTIVE SUMMARY

The UMASS Wind Furnace has been operational in a fully automatic mode since October, 1977. Performance data has been collected, reduced and analyzed for the heating system as a whole as well as for the wind turbine in particular.

Results, although not complete due to instrumentation problems, indicate that the wind furnace provided a significant amount of the heating load for Solar Habitat-I during the period from November 1977 through April 15, 1978. For a total heat load of 15,300 kWh during this period, approximately 2460 kWh were supplied by solar and 7400 kWh by the wind turbine or about 64 percent supplied by the wind furnace.

Experimental wind turbine performance results for the constant tip-speed-ratio operation and purely resistive load, compare very closely to the computer predicted or design conditions. The wind turbine has operated automatically throughout the complete pitch-control range. The results have been successful although the pitch-rate is insufficient to maintain the rated RPM within the design criteria of plus or minus 5 percent.

A microprocessor controller has been designed, built and will be installed when the machine is put back up following servicing in late July. This controller has the flexibility to be reprogrammed for blade pitch, field current and yaw to any desired conditions. Evaluation of the controller will be accomplished during the next year.

A significant aspect of the program has been the wind field measurement and analysis. Five towers and anemometers have been installed and vertical wind velocity profiles recorded as well as wind speeds at various distances up wind of the turbine at axis height. These initial results indicate the
extent of the flow field in the vicinity of an operating turbine. Much more extensive measurements and analysis correlating the wind data with the wind turbine operational characteristics are planned for the coming year.

Further details of the program efforts are discussed in this report and in the technical reports referenced under each task.
II. INTRODUCTION

This report is intended to present in a general manner, the background and progress to date for the Wind Furnace project at the University of Massachusetts. The organization of the report is such as to give a general description of the Wind Furnace as installed at Solar Habitat-I along with some performance and operational data of general interest.

Somewhat greater detail is presented under the summary discussions for each task with referenced technical reports and published papers giving a full description of the specific tasks. Each task summary is separate with its own figures, references and numbering sequence.
GENERAL BACKGROUND

The Wind Furnace project was begun in 1975 under an NSF Grant to investigate the feasibility of using wind power for space heating in a colder climate. This work has continued under ERDA and DOE support as part of the Rockwell International Wind Energy Program.

Solar Habitat 1, an energy conservative house designed by Professor Curtis Johnson of the Department of Food and Agricultural Engineering, serves as a demonstration facility for the Wind Furnace. The house was constructed and the solar flat plate collector system was installed and has been operating since September 1, 1976. The wind turbine was erected in November 1976 and underwent component testing and check-out. The Wind Furnace system has been operating in a fully automatic mode since September 1977.

Conceptually the Wind Furnace is a heating system consisting of a wind turbine, solar flat plate collectors, a storage system and a heat delivery system as shown in Figure 1. Water in the insulated thermal storage tank is heated by the solar collectors and by the electricity generated by the wind turbine. In turn, this water is used to heat the house by conventional baseboard hot water convectors. For this house, a gas fired hot air furnace serves as the auxiliary back-up heating system.

THE WIND FURNACE

Solar Component

Two hundred square feet (18.6 m²) of copper-tube copper-plate water solar collectors are mounted vertically on the south facing wall. Propylene-Glycol and water are circulated through the collector loop and heat exchanger
speed. The automatic field controller is programmed to provide the correct field current to produce but not exceed the maximum power at any given wind speed.

A welded steel main frame supports all of the wind generator components and provides for attachment to the tower via the pole matcher. The pole matcher contains fifteen brass slip rings embedded in fiberglass and epoxy. Electrical power from the generator is brought down through three of the slip rings to the resistance heating load in Solar Habitat-I. The other slip rings are used for the pitch control, field current control, rpm signals and other instrumentation signals. This pole matcher attaches to the top of the pole and provides a bearing surface and attachment support for the wind generator and enables the wind generator to yaw with changes in wind direction. A yaw damper has been incorporated and consists of a chain and sprocket driven electric generator. The yaw damping coefficient can be changed by changing the resistance load placed across the terminals of the generator. The generator can also serve as a yaw motor if necessary for servicing.

The two stages of the speed-up drive train consist of a one-ton truck rear axle connected to the rotor hub and a silent chain drive connected to the generator. This provides approximately an 11:1 speed-up from rotor to generator.

Three steel barrels welded to a steel plate assembly serves as the rotor hub which attaches to the lug bolts of the truck rear axle assembly. The barrels provide the bearing support for the blades and a center tube supports the pitch control shaft and linkage. Blade pitch is accomplished by an electrical servo motor driving a shaft. The linear motion of the shaft is changed into synchronized blade rotation by a sprocket and chain linkage.
The rotor blades are made entirely of GRP. A hollow tapered spar is bonded inside the fiberglass skin which was hand laid up over a twisted and tapered mold. A steel spindle is mechanically fastened to and epoxy bonded over the circular root portion of the spar to form the pitch bearing surface. Each blade weighs 34.47 kg (76 pounds) including the steel spindle and pitch control sprocket. With nearly optimum taper and twist, the blades are designed to operate at a constant tip-speed ratio of 7.5 and to withstand gust loadings of up to four times the thrust at rated speed and power.

A fiberglass nacelle totally encloses the wind generator components, has three access doors for servicing and repair, and supports a wind anemometer.

Pitch Control

Figure 3 defines the pitch control regions in terms of rpm versus wind speed. In Region I, the wind speed is below V cut-in, the rotor is stationary and the blades are pitched to 40 degrees for maximum start-up torque. In Region 2, the blades are pitched to -6 degrees (tip speed ratio of 7.5) for steady operation to produce the maximum power output for any given wind speed. Region 3 begins at 11.6 m/s (26 mph) wind speed, extends to 22.4 m/s (50 mph) and represents a region of constant power at synchronous generator rpm. Throughout Region 3 the blade pitch increases from -6 degrees at 11.6 m/s (26 mph) towards 16 degrees at 22.4 m/s (50 mph), thus maintaining the constant power and constant rpm. When the wind speed reaches 22.4 m/s (50 mph), the blades are pitched to full feather (zero torque at 90 degrees). Region 4 represents all wind speeds greater than 22.4 m/s (50 mph) and a condition of zero power.
Region 3 appears to be the critical control region where the rpm is to remain constant to produce a constant rated power output and thus a constant torque. Thus, region 3 requires a linear blade pitch increase with increasing wind speed (decreasing tip-speed-ratio).

Experimental data shown on Figures 2 and 3 indicate in general a consistent trend towards the operational design conditions of -6 degree(s).

OPERATION OF THE WIND TURBINE

The results presented in this section are from continuous recordings on a six-channel Sanborn strip-chart recorder. These recordings are used more for qualitative analysis than quantitative. It is easier to get a feel for the machine while observing the parameters being traced. Definitions of symbols used are listed on page 9. Sections of runs are shown with accompanying explanations and comments are made concerning specific observations.

Figure 4 11/2/77 Automatic Start-Up:

This strip chart section shows the automatic start-up of the WTG after it has been driven to face the wind. The wind speed was averaging five mph. It has been observed that in light winds (less than approximately seven mph) the machine will now yaw about. This is primarily due to the friction of the yaw damper chains. Observations with the chains disconnected confirm this. Damping is required in higher wind, though, as without it the machine will yaw 360° if there is a sudden stoppage of the wind. This has been observed to happen with the yaw chain disconnected.

Blade pitching from 35 degrees to four degrees occurred when the shaft speed reached 20 RPM.
Field current was automatically applied at a shaft speed of 37 RPM. Due to the low winds, the RPM varied around the on-off speed of the field controller. This is why the field current cycled back and forth from zero to 0.42 amps.

Very little power was generated under these wind conditions as shown by the low load voltage, approximately 30 volts being the maximum attained.

Figure 5 Automatic Return to Start-Up Angle

In this case, the wind decreased from an average of 10 mph to an average of 2.5 mph. The RPM trace shows the same general decrease with a waveform shape similar to the wind waveform. This is to be expected with constant pitch angle operation.

The pitch angle was holding constant at zero degrees until the RPM dropped below twenty. At this point, the pitch controller increased the pitch angle to the start-up angle which had been set to thirty degrees.

The field current trace shows a transition of incremental changes in current level until the RPM drops to 37, the threshold RPM for the field controller. Current cycling (on and off) continues until the RPM drops below 37 at which time the field current is shut off.

The load voltage waveform is also similar in shape to the wind waveform. This is also to be expected as the voltage is a power function of the RPM. The maximum voltage generated in this interval was 100 volts. Once the field current is zero, the voltage decays to a low value determined by the residual magnetism in the field iron and the rotor RPM.
Figure 6 11/17/77 Region 2 Operation: Moderate Breeze

With the winds between five and 25 mph, the average was near 15 mph for this run. Since these were gustier conditions, the waveforms are more jagged in appearance. The pitch angle held constant at four degrees except at one point where the RPM approached 162 (22.3 volts). The pitch controller increased pitch slightly and then returned to four degrees. Region 2 operation had been preset for a blade pitch angle of four degrees. The greater variations in shaft speed led to larger changes in field current as determined by the field controller. The estimated average power level in this run was 4400 watts.

Figure 7 11/27/77 Region 2 and Region 3 Operation: Moderate Breeze with Higher Gusts

Operation in winds averaging 17 mph with gusts to approximately 27 mph is shown in this chart section. The rated shaft speed had been set to 145 RPM (20 volts). When the RPM approached or exceeded this value, the pitch controller sensed the transition to Region 3 and varied the pitch angle in order to maintain rated RPM. The shaft overspeed was held to within eight percent.

Figure 8 11/27/77 Region 2 and Region 3 Operation: Fresh Breeze Winds

Approximately three hours later than the above run, the winds were averaging twenty mph and gusting to thirty. The rated shaft speed was still 145 RPM. The pitch controller operated much of this time due to the shaft speed being near or above rated. The maximum overspeed was held to 20 percent over rated (145). The pitch angle varied from four degrees (region 2) to a maximum angle of 20 degrees (region 3).

As a result of the higher shaft speeds, the load voltage stayed mainly between 100 and 300 volts. A maximum voltage of 330 volts was reached at a shaft speed of 173 RPM. This maximum output of 32670 watts was the result
of a wind gust to approximately 30 mph. Four other times the output reached or exceeded 300 volts, or 27000 watts.

Figures 9 and 10

Figures 9 and 10 show certain data points plotted along with the predicted curves of power output. These graphs show:

1) Even though the data points seem to cluster around the predicted curves, there are some large variations. Some of the variations are as much as 50 percent over or under the predicted value. These were most likely caused by the nature of the wind and the settings of the pitch angle and excitation.

2) Rated power was exceeded many times. The maximum power of 32690 watts, 30.7 percent above rated, occurred at a value of 173 RPM, 3.6 percent over rated shaft speed. The machine had entered Region 3 operation starting at a pitch angle of four degrees and increasing to 18 before returning to four. (These traces can be seen in Figure 8 occurring on November 27, 1977 at approximately 0810 hours.)

For an overspeed of this magnitude, the predicted power level would be 27000 watts. This value has been recorded under the same conditions of pitch angle, excitation and shaft speed. The exceptions were the maximum pitch angle obtained (16°), and the wind speed of the gust. The differences between these two cases accounted for the 21 percent greater output over predicted.
DEFINITIONS OF SYMBOLS

WV = wind velocity observed at the axis height from the house anemometer, approximately 30 feet ENE of the wind turbine. Units: miles per hour.

RPM = shaft rotational speed. This is actually the output voltage of a dc tachometer geared to the pinion shaft. It is geared to produce 23 volts at 167 RPM. (See table below)

B = blade pitch angle measured at the tip. This is actually the voltage of the feedback pot connected to the ball screw. Refer to the accompanying table for conversion between voltage and degrees.

FC = field current applied to the field winding. Units: dc amperes.

LV = load voltage measured at the terminals of the load. This is the line-to-neutral ac voltage. The load resistance per phase (wye-connected) is ten ohms.

CONVERSION TABLES

<table>
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<tr>
<th>RPM</th>
<th>VOLTS</th>
<th>B (degrees)</th>
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<td>4.93</td>
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<td>1.93</td>
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<td>1.90</td>
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<tr>
<td>180</td>
<td>24.80</td>
<td></td>
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</tbody>
</table>
REFERENCES


WIND FURNACE CONCEPT

FIGURE 1
PREDICTED PERFORMANCE

FIGURE 2
ROTOR RPM AS A FUNCTION OF WIND SPEED

FIGURE 3
FIGURE 4

- WIND SPEED (M.P.H.)
- R.P.M.
- $\beta$
- FIELD CURRENT (AMPS)
- L.V. (VOLTS)

TIME (2.5 MN/MIN)
FIGURE 5

- Wind Speed (M.P.H.)
- R.P.M.
- Field Current (Amps)
- L.V. (Volts)
- Time (2.5 mm/min)
Figure 6

- TIME (15 MIN/MIN)
- LV (VOLTS)
- FIELD CURRENT (AMPS)
- R.P.M.
- WIND SPEED (M.P.H.)
SHAFT SPEED (RPM)

ELECTRICAL POWER OUTPUT (KW)

RATED POWER

CURVE REPRESENTS CUBIC EQUATION

\[ \beta = -2.0^\circ \]
\[ \mu = 6.5 \]
\[ \rho = 1.76 \]

FIGURE 9
FIGURE 10

ELECTRICAL POWER OUTPUT (KW)

WIND SPEED (MPH)

CURVE REPRESENTS CUBIC EQUATION

RATED POWER

RATED WIND SPEED
III. SUMMARY OF TASKS

TASK 1 Continued Operation of SH-1 Experiment

The objectives of this task are to install and evaluate the domestic hot water pre-heat system, install and evaluate a new tank insulation and liner, improve the overall data acquisition system and to evaluate the wind furnace as a heating concept.

1.1 Thermal Systems

1.1.1 Modifications to system components

During the period of testing, several modification to heating system subcomponents were made in order to improve the overall energy delivery performance of the heating system.

One of these modifications included the addition of a domestic hot water supply system during January 1978. As shown in Figure 1.1, this system was modelled after conventional closed-loop solar heating system designs, using the wind and solar hot water storage tank as the energy source for the hot water preheat. This subsystem used a 0.3 m$^3$ (80 gal) hot water preheat tank with a 1.86 m$^2$ (20 ft$^2$) finned heat exchanger coil. The differential thermostat senses the storage tank and preheat tank temperatures and turns on the circulating pump when the storage tank temperature is 5.6°C (10°F) above the preheat tank temperature. It should be noted that, except for an initial checkout period, this subsystem was not in use during the heating period when the overall system tests were carried out.

The second major modification included the installation of new insulation on the 3.8 m$^3$ (1000 gal) hot water storage tank. As was discovered in the initial testing of this component, the thermal losses were much higher than acceptable (or then predicted from a model of an idealized hot water thermal
storage tank). This was due to the fact that much of the energy loss from the concrete storage tank (insulated on the outside) occurred via conduction along the concrete walls to adjacent concrete walls that were exposed to ambient air or ground temperatures. In order to overcome this problem, 1.6 to 2 cm. (4 to 5 inches) of Owens Corning High R Sheathing (R = 8/inch) were placed inside the tank and then a 30-mil PVC vinyl tank liner was used. The performance of the improved tank insulation over the previous experimental data is shown in Figure 1.2. This newly insulated tank was put into operation on January 25, 1978 and an especially severe winter storm (with heavy winds) brought the water in the tank up to a temperature over 90°C. Shortly after this period the tank liner developed several leaks in the manufactured seam, causing a loss of the entire hot water stored. After repeated attempts at patching, the liner was replaced with a seamless 6 mil polyethylene liner in March 1978, and has held water at temperatures up to 80°C.

Other system component changes included minor modifications to the solar collectors and the baseboard convector system. Specifically, the inner cover of the collectors was changed from Tedlar to 1/8 inch glass and extra vents were added to the baseboard convector flow loop.

1.1.2 Experimental testing and data acquisition

A schematic of the overall data acquisition system for the thermal heating system in Solar Habitat I and the wind turbine generator (electrical systems) is shown in Figure 1.3. The Data Logger System consists of two separate Fluke Model 2240A Data Loggers each coupled to a Texas Instrument 733 ASR Digital Cassette recorder and teletype terminal. Transient data acquisition for the WTG system is also provided by a six channel Sanborn strip chart recorder.
Thermal systems data was collected on the data logger at 15 minute intervals and included 20 channels of temperature signals, five channels for system electrical components (such as pumps and WTG), solar pyranometer output, and wind speed. After collection of 4 days data, the cassettes were processed by a digital data reduction program (Figure 1.4) and inputed to another digital program from which the resulting output was a daily summary of thermal system performance. This second program (see Figure 1.5) produced hourly and daily averages of the following parameters:

1) Ambient temperature
2) Upstairs and basement house temperature
3) Storage tank temperature
4) Solar insolation
5) Wind speed
6) Percent time of collector operation
7) Percent time of WTG operation

In addition, daily degree days were calculated and a complete hourly and daily summary of solar collector performance, including total daily energy input to the storage tank was produced. Figure 1.6 shows a typical output from this program. A kilowatt-hour meter was planned for the WTG but was not installed during the 1977-78 heating season, due to the necessity to design an entirely new meter.

Monitoring of data from the thermal systems started on November 1, 1977, and continued to April 15, 1978. (The late start in the heating season was due to damage of the data acquisition system and other thermal system logic controls by a lightning strike in August 1977). At this time
complete reduction of the thermal performance data have not been completed, but some preliminary results and a comparison with predicted results can be made. (A detailed technical report giving a summary of all the experimental data will be completed in August 1978.) Due to some experimental difficulties, a complete data set for the full year with fully automatic operation of the house was not obtained. However, most of these difficulties were of a minor nature and consisted of small missing sections of thermal systems data (in the early part of the heating season most of these were due to the use of the thermal systems data logger for WTG data acquisition), or non-continuous operation of major system subcomponents. In the later category this included short periods when the WTG, storage tank, or baseboard convectors were out of normal operation. For the case of missing weather data, use was made of National Weather Service data from Bradley Field, Connecticut, which has a similar climate.

In general, the heating system performed well and was able to supply energy for heating the house from the hot water storage system. For example, Figure 1.7 shows the operation of the house for a day and a half period during a winter storm in February 1978. As can be seen the winds were quite strong during this period (with basically zero solar collector input). The slight dip in the storage tank temperature during the second day is due to the effects of thermal stratification in the tank. That is, the tank liquid was manually stirred by the large solar collector pumps in an attempt to uniformly distribute the thermal energy as maximum allowable tank temperature was approached during this windy period. Unfortunately, not shown on this graph, the storage tank liner failed shortly after this time period and the heated contents of the tank were lost.
As the thermal heating experiments were originally planned, a kilowatt-hour meter was supposed to be available to monitor the WTG energy input, while the input from the solar collector was determined from temperature difference measurements (with known collector system flow rates). Technical development difficulties forced the delay of construction of the kilowatt-hour meter, so that the WTG power input could not be determined from direct measurements. Therefore, in order to determine the windpower energy input, the experimentally calculated solar and auxiliary energy inputs must be subtracted from the house heating requirements (calculated from previous work on the residence. Specifically, based on an assumption of 0.4 air changes per hour for SH-1, the residential heating energy requirements/degree day was approximately 1.63 Kwhr/°C-day (10,000 BTU/°F-day). Also, the previously developed analytical modeling program could be used to predict the heating requirements and required auxiliary energy input.

Table 1 presents a summary of the initial energy flow estimates on a month-by-month basis using both analytical models and experimental data. Although the results are subject to some change, when the site wind data is fully analyzed, it can be seen that the WTG provided a significant amount of the residential heating load.
<table>
<thead>
<tr>
<th>Month</th>
<th>$Q_{\text{House}}$</th>
<th>$Q_{\text{Solar}}$</th>
<th>$Q_{\text{Aux}}$</th>
<th>$Q_{\text{Wind}}$</th>
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<td>Nov</td>
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<td>15,317</td>
<td>2,464</td>
<td>5,477</td>
<td>7,376</td>
</tr>
</tbody>
</table>

Table 1.1 Energy Balance for SH-1 (kWhr)
1.2 Wind Turbine

1.2.1 Introduction

During the past year, the wind turbine has, in general, been under fully automatic operation, i.e. left unattended to control itself under all wind conditions. The energy generated has been fed into the water storage tank by means of the emersion heaters. Interruptions of the automatic operation have been due to minor problems or for specific operational tests.

Considerable experimental data has been obtained along with valuable operational experience. Details of the performance data will be presented in the technical report, (1), some of which has already been presented in refs. 2 and 3.

A few problems with the wind turbine have plagued the project. Specifically, oil leaks both from the truck differential and from the second-stage speed up lube case have been annoying but have not caused any down time. The yaw damper, however, has bound-up on several occasions and resulted in some down-time. Chain sprockets, two in particular, would loosen and slide along their mounting shaft thus binding the chain and preventing the machine from yawing. Both the oil leaks and yaw damper problems were corrected during the general maintenance and repair period while the machine was down (June 27th through Aug. 2nd).

The unlubricated flexible coupling connected to the generator wore considerably and finally in late May failed, resulting in the machine being shut down. A replacement coupling (lubricated) has been installed and careful generator alignment and check-out should correct this problem.

The tedious data reduction procedure necessitated by the analog strip-chart recording of performance data has been so time consuming as to delay the reporting. However, the somewhat higher data acquisition rates on the
Fluke Data Logger has greatly speeded up this process. During the 1978-79 contract year, the truly high speed data acquisition system, connected directly to the CYBER computer for data reduction, will greatly speed up the process.

1.2.2 Results

Data is currently collected by two systems dependent on the type of data desired. The analog (or continuous) Sandborn data recording system collected the following analog signals (DC voltages) during transient tests of the WTG:

1) Wind speed
2) Shaft RPM
3) Field current
4) Load voltage
5) Pitch angle

Due to the form of data and the time required to reduce the data, this system is used primarily for demonstration purposes or for a single event record.

Figure 1.8 and 1.9 are reproductions of Sandborn strip chart data. Fig. 1.8 shows a period of decreasing wind with the corresponding decrease in RPM and subsequent increase in blade pitch angle as the rotor drops below 20 RPM.

Figure 1.9 shows a condition of high gusty winds with speeds exceeding 25 mph, hence the blade pitch angle being increased towards feather to prevent excessive RPM.

The primary means of recording wind turbine generator performance data is the digital acquisition system using the second 2240A Fluke Data Logger. A modification to the Fluke permitting a 1200 baud rate allows
sampling of five channels every second. The digital data is stored on cassette tapes and then processed to give instantaneous values of the following parameters:

1) Wind speed
2) Rotor RPM
3) Tip-speed ratio
4) Blade-pitch angle
5) Field current
6) Load voltage
7) Electrical power produced
8) Available power from the wind
9) Overall efficiency

One computer program is used to analyze the data and list all parameters in the order they occurred or chronologically. A second program sifts through the data and sorts it into different "bins" according to the value of a particular parameter. This program also contains curve fitting routines for linear equations or power curve fits.

Figure 1.10 shows measured electric power output (for the purely resistance load) as a function of rotor shaft RPM for automatic control operation. This same data was reduced using the "method of bins" to sort the data for constant tip-speed-ratio operation, and is shown in Figure 1.11. Each curve represents constant tip-speed-ratio operation. Also shown is the design point of 25 kW at 11.7 m/s for a tip-speed-ratio of 7.5.

1.2.3 Expanded Data Acquisition

Higher speed and expanded capability for data acquisition have become essential. Higher speed is needed for the adequate resolution of the blade strain data. Speed and expanded capacity are needed in order
to correlate the wind speed and direction, blade strains and rotor indexed position, rotor shaft torque, wind turbine power output, etc.

This expanded data acquisition system is being installed along with the blade-strain system while the wind turbine is down for servicing and repair.

Figure 1.12 is a block diagram of the ground portion of this high speed data acquisition system. The data collection cycle is shown in Figure 1.13 and the data format is shown in Figure 1.14.

Data that is collected for this system is available as either binary coded decimal - two digit, or natural binary 8-bit words. The system provides a "real time" clock to (1) uniquely identify collection blocks, (2) compute "angle-time" to "absolute-time" data adjustments, (3) provide clock/strobe for anemometer boards and (4) enable automatic "alarm" system operation.

Anemometer signals are processed completely digitally, i.e. without analog conversion. Accuracy is approximately ±.2 m/s. The front end of the boards are optically isolated to prevent high voltage transients entering the system from lightning or other electrostatic effects.

This system should be installed and operational in early September.
DOMESTIC HOT WATER PREHEAT SYSTEM

FIGURE 1.1
FIGURE 1.2
STORAGE TANK THERMAL PERFORMANCE
FIGURE 1.3

BLOCK DIAGRAM - DATA ACQUISITION SYSTEM
Fluke Data Logger - Samples 26 stations at 15 min. intervals

TI 700 ASR - Records information from Fluke onto cassette

TI 700 ASR
Recorded cassettes read into storage space of UMASS CDC Computer System

CDC - STAPE file created and saved

RSDATA - Reads in 15 min. interval data (on STAPE), averages it over hourly intervals provides summary print-out of hourly data and writes hourly data onto TAPE 2

TAPE2 saved as files jJDTeJD; JD = initial Julian Date of Data, eJD = ending Julian Date of Data, T = thru

SOLCAL - provides formatted printout of hourly data if desired and calculates daily average component performance of i) house ii) collectors

House Temp. and control signals data

Edit program prepares data for RSDATA program

Previously undiscovered error in STAPE causes RSDATA to abort

FIGURE 1.4
FLOW CHART FOR DATA REDUCTION PROGRAM
SOLAR HABITAT

JULIAN DATE = 64

HOUSE PERFORMANCE

HOURLY-

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AVERAGED DAILY PERFORMANCE-

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DEGREE DAYS

48.7

FIGURE 1.5

SAMPLE OUTPUT FROM

THERMAL DATA REDUCTION PROGRAM
### COLLECTOR PERFORMANCE

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### AVERAGED DAILY PERFORMANCE-

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#### FIGURE 1.6

SAMPLE OUTPUT FROM THERMAL DATA REDUCTION PROGRAM (COLLECTOR PERFORMANCE)

---

DAILY COLL. EFF. .20
Figure 1.7 Daily Operation of Salar Habitat - I
FIGURE 1.8

WIND SPEED (M.P.H.)

R.P.M.

β

FIELD CURRENT (AMPS)

L.V. (VOLTS)

CHART SPEED (2.5 MM/MIN)
WIND SPEED (M.P.H.)

R.P.M.

$\beta$

FIELD CURRENT (AMPS)

L.V. (VOLTS)

CHART SPEED (5 MM/MIN)

FIGURE 1.9
FIGURE 1.10 POWER AS A FUNCTION OF ROTOR SPEED

RATED POWER: 25 kW AT 167 RPM.

\( kW \propto (\text{R.P.M.})^m \)

\( 2.6 < m < 3.0 \)
FIGURE 1.11  POWER AS A FUNCTION OF WIND SPEED FOR CONSTANT TIP-SPEED-RATIO
FROM WIND TURBINE AND TOWER

ANALOG INPUTS

3 ADDABLE

ANEMOMETER BOARD 1

"REAL TIME" CLOCK

3 CONTROL

TERMINAL

MODEM

SERIAL DATA TO COMPUTER

BOSSES EXTEND TO OTHER USES

HIGH SPEED DATA ACQUISITION SYSTEM OVERVIEW

4K WORDS RAM

4K WORDS RAM

4K WORDS RAM

4K WORDS RAM

10° TO 360° (absolute position)

SERIAL TRANSMISSION OF BLADE STRAIN GAGE AND TORQUE BRIDGE DATA

"FAST" PORT C

2650 BASED ADAPTABLE BOARD COMPUTER 1500

PROGRAMMABLE COMMUNICATIONS INTERFACE

TO WIND TURBINE

16 CHANNEL ANALOG TO DIGITAL BOARD

16 ANEMOMETER BOARD 5

5 DEVICE ADDRESS BUS

5 ANEMOMETER INPUTS

ADAPTABLE AND TORQUE BRIDGE DATA
DATA COLLECTION CYCLE

FIGURE 1.13
12 Gages with Torque:
468 Words (3744 bits)

\[ (468 \times 28) \frac{\text{words}}{\text{rev}} \times 33 \text{ rev} = 16368 \text{ words} \]

\[ 2^{16} = 16384 \text{ words} \]

(uses nearly all of the memory)
References


TASK 2 Continued Aerodynamic and Blade Studies

2.1 Introduction

The objectives of this task are to complete the study of blade shapes, to layout and construct a 17.5 ft radius Linear Taper Linear Twist (LTLT) model blade, and to conduct a blade structural analysis program with experimental verification.

2.2 Blade Shape Studies

The blade study has been completed with a portion of it appearing in refs. 1 and 2. Results of this study show the optimized LTLT blade to be as or nearly as efficient as the aerodynamically optimum (non-linear taper and twist) blade.

Figure 2.1 is a plot of blade bending moment divided by the cube of the chord for the three blade shapes of optimum (OPT), Linear Taper Linear Twist (LTLT), and Constant Chord Zero Twist (CCZT) blades. The significance of this figure is that the bending moment divided by the cube of the chord is at least proportional to the stress. As can be seen, the LTLT blade has a material (chord) distribution that gives the lowest stress levels.

The 17.5 ft (5.33 m) radius model blade has been completed and the following pages give the characteristics and computer predicted performance for that blade based on the Wilson and Lissaman performance program.
2.3 **Blade Structural Analysis**

Early design and analysis work on the WF blades was done by Stoddard and Van Dusen and appears in ref. 3 and 4. These blade characteristics are also described in Figures 2.2 and 2.3.

An extensive computer program (MOMENTS) has been written (APL language) to better determine the structural behavior of blades of varying geometry and construction. A block diagram of the program is shown in Figure 2.4. Blade section characteristics are inputed, calculated and stored for use throughout the program. Blade deflections and stresses are calculated for specified loads and for varying blade pitch angles.

The program has been verified both by inserting known beam characteristics and by experimental measurements.

A load of 15.5 lbs. applied at r/R = .95 and at 25% of the chord resulted in a measured tip deflection of 2.96 ± .04 inches in the flapwise direction and .36 ± .14 inches in the lead direction. The predicted deflections for this loading was 2.99 inches and .57 inches respectfully. There was no detectable angular rotation of the blade.

Agreement between measured and predicted blade strains has been shown to be good (see Figures 2.5 and 2.6). Figure 2.5 shows the results of static tests of strains as a function of percent chord measured at the .475 radius station for distributed loads of one-half rated. (Strain gages are mounted around the blade section.) Figure 2.6 shows the blade skin stress at 40% of the chord as measured along the blade. (These gages are mounted at every 10% radius station along the 40% chord line.) The gage at 10% radius station is mounted on the circular cross-section portion of the spar.

Details of this experimental arrangement and of these results as well as the analysis, including flapping, will be presented in technical reports which will be available in late August.
CODE 1=COMPACT 2=GENERAL

? 2

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READS: PITCH TIPSPEED C10 C100
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RADIUS TWIST SOLIDITY TAPER RATIO
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END.

ENTER VALUES FOR V, BR, H, AND SI

? 25.1 0.10

ENTER CODES FOR GO, HL, AND TITLE

? 2 0 1

THEORETICAL PERFORMANCE OF A PROPELLER TYPE
WIND TURBINE

DATA INPUT RECORD

RADIUS IN FT-----------------------------= 17.50
INCREMENT PERCENTAGE-------------------= .10
HUE RADIUS IN FT------------------------= 1.75
PITCH ANGLE IN DEGREES------------------= -3.10
NUMBER OF BLADES------------------------= 3.00
WIND VELOCITY IN MPH--------------------= 25.00
TIP SPEED RATIO-------------------------= 7.50
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NUMBER OF DATA STATIONS ALONG SPAN-----= 10
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STANDARD AXIAL INTERFERENCE METHOD USED

NO TIP LOSS MODEL USED

NO HUBLOSS MODEL USED.

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DATA OUTPUT RECORD

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ANGULAR INTERFERENCE FACTOR ------ AP
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LIFT COEFFICIENT --------------- CL
POWER COEFFICIENT --------------- CF
THRUST COEFFICIENT ------------- CT
COEF OF FORCE-X-DIR -------------- CX
COEF OF FORCE-Y-DIR -------------- CY
TIP LOSS FACTOR ---------------- F
NORMAL FORCE ------------------- FN
TANGENTIAL FORCE ----------------- FT
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RU 5.633 UNTS.

RUN COMPLETE.

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X = 8
CCZT, OPT, LT LT

BENDING MOMENT DIVIDED BY CHORD CUBED

FIGURE 2.1
DESCRIPTION OF BLADE COMPONENTS

TYPICAL SECTION
(NACA 4415)

SPAR WEB

SKIN

SPAR

TRAILING EDGE STIFFENER

BLADE STOCK

FIBERGLASS EPOXY

STEEL SLEEVE

FIGURE 2.2
WF-I PLANFORM AND TWIST

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FIGURE 2.3
I
PROGRAM MOMENTS

SECTION PROPERTIES

OUTPUT

TRANSLATE TO BENDING AXIS

ROTATE COORDINATES

COMPUTE DEF INPUTS

COMPUTE STRESS

CHANGE PITCH ANGLE

SUBROUTINES

INPUT

INDEX

INTEG

DEF

CALCULATES SECTION PROPERTIES

FIG. 2.4 SCHEMATIC PROGRAM MOMENTS
WF-1 TEST BLADE, 1/2 RATED LOAD, SKIN STRESS AT .475 RADIUS STATION

TENSION

\[ 1399 \text{ psi} \]

\[ \beta_0 = -1^\circ \]

LOWER AERODYNAMIC (HIGH PRESSURE) SURFACE

\[ 1714 \text{ psi} \]

PER CENT CHORD

L.E. 10 20 30 40 50 60 70 80 90 T.E.

UPPER AERODYNAMIC (LOW PRESSURE) SURFACE

\[ \mu \text{ STRAINS (INCHES/INCH)} \]

TRIAL 1

TRIAL 2

ERROR BARS
WF-1 TEST BLADE (STATIC TESTS)
1/2 RATED LOAD, SKIN STRESS AT 40% CHORD

PER CENT RADIUS

HUB 10 20 30 40 50 60 70 80 90 TIP

0

psi

COMPRESSION

-200

-400

-600

-800

-1000

-1200

-1400

-1600

-1800

UPPER AERODYNAMIC (LOW PRESSURE) SURFACE

\( \beta = -1^\circ \)

ERROR BARS

Ab. ± 40 psi
References


3. Van Dusen, E.S., "Blade Structural Design; Wind Furnace Experiment," Energy Alternatives Program, Univ. of Massachusetts, Amherst, MA 01003, TR/76/2, January 1976.

3.1 Introduction

The objectives of this task are to test the existing controller under fully automatic operation and to design, build and test a micro-processor controller incorporating blade pitch control, generator field control and yaw control.

3.2 Existing Controller

The UMASS wind turbine became operational under fully automatic control in September 1977. This control system is described in detail in ref. 1. Lightning damage to the instrumentation prevented testing of the system until November.

The blade pitch controller varies the pitch angle, $\beta$ of the blade (defined as the angle between the blade chord at the tip of the blade and the plane of rotation) to maximize the power out of the rotor for any operational wind conditions. It also serves to set the blades at the angle for maximum start-up torque (minimum cut-in speed) and to feather the blades to shut down in high winds.

The Field Controller varies the generator field current to match the load of the generator to the power being produced by the rotor.

Fully automatic operation means that the wind turbine is allowed to run unattended and considerable operating time was logged during the past year. A sample of this automatic mode of operation is shown in Figure 3.1, a condition of gusty winds exceeding 25 mph at times with a consequent brief increase in blade pitch angle. It should be noted that the field current fluctuated in response to the abrupt changes (or spikes) in the wind and RPM.
Similar curves are presented in ref. 2.

The control system was tested throughout the full range of operational conditions from start-up (Region-1) through shut-down (Region 4) and back. Region 3 operation, that of constant power constant RPM is the most severe and the 6 degrees/sec pitch rate for the blades is insufficient to maintain a given RPM with \( \pm 10 \). Furthermore, the concept of the field current being pre-scheduled as a function of generator RPM appears to cause some problems. As can be seen in Figure 3.1, the field current fluctuates rapidly and when the generator fluctuates around 400 RPM, the field current is continually going on and off. This condition puts an unnecessary strain on the flexible coupling and is believed to be the main cause for its failure. Both of these problems will be corrected with the installation of the microprocessor controller.

3.3 Microprocessor Controller

A microprocessor controller for the UMASS Wind Turbine has been designed and built and will be installed by the time the wind turbine is erected following the maintenance and repair. This controller is described in detail in ref. 3.

The control scheme for the system is determined by the microprocessor program. As such, the control system can be used to truly optimize the Wind Furnace control or to simulate various types of controllers simply by re-programming.

The system has the following nine basic components (a block diagram is shown in Figure 3.2):

1. Signetics ABC 1500 microprocessor board.
2. Blade pitch system motor interface.
4. Generator field current interface.
5. Sixteen analog input channels interface.
8. System power supply.
9. Low battery voltage feather circuit.

The field current interface supplies current to the generator field proportional to an 8-bit number sent from the microprocessor. The interface can supply field current in the range of 0 to 1 amp and adjustable in 3.9 milliamp increments.

The blade pitch system and the yaw direction system use 24 volt DC motors. The interfaces between the ABC 1500 and the motors consist of a pulse width modulator and a switching transistor bridge amplifier with the pulse-width controlled by a word sent from the ABC 1500.

Initially the control system has five sensors to produce analog outputs sensing:

1. Rotor RPM (DC tachometer).
2. Pitch angle with a potentiometer geared to the pitch linkage.
3. Yaw direction with a potentiometer geared to the yaw drive system.
4. & 5. Wind speed and direction - DC signal from an R.M. Young anemometer.

This system will be installed and its operation checked out by mid-August. Its full operation will be evaluated during the next contract year but its full capability will not be evaluated until such time as many different control schemes can be programmed and tested.
FIGURE 3.1

CHART SPEED (5 MM/MIN)

WIND SPEED (M.P.H.)

R.P.M.

FIELD CURRENT (AMPS)

L.V. (VOLTS)
FIGURE 3.2 CONTROL SYSTEM BLOCK DIAGRAM
References


TASK 4 Wind Field Analysis and Measurement

4.1 Introduction

The objective of this task is to measure and analyze the wind field in the vicinity of WF1 and to measure the dynamic interaction between the wind and the turbine operation.

Five R.M. Young anemometers have been purchased and mounted on five towers in the vicinity of the wind turbine as shown on Figure 4.1. Prior to their mounting, the anemometers were all tested in the wind tunnel and their speed was found to be within 2% of the manufacturer's calibration. The anemometers were first operational in mid-January 1978. However they immediately stopped working and had to be returned to R.M. Young Corp. for some revisions. These changes are detailed in (1). The anemometers were again mounted on the towers and finally became operational at the end of February 1978.

4.2 Experimental Results

By the end of the contract period the following measurements are representative of what has been made: The vertical wind shear profile Fig. 4.2, the power spectral density of the horizontal wind gustiness Fig. 4.3, the transfer function between the wind speed and the generator power Fig. 4.4, and a typical wind speed histogram Fig. 4.5. Figures 4.3, 4.4, and 4.5 were all made for the same conditions on April 2, 1978 of average wind speed 7.29 m/s, average generator voltage 139.68 volts during a 1/2 hour period.

The most interesting and useful of these measurements is the transfer function in Figure 4.4. This measurement indicates that the wind turbine can follow the wind speed fluctuations up to a frequency of about $n = 0.02$ Hz. Above this "cut-off frequency," the transfer function if rapidly
attenuated indicating that the machine is no longer following fluctuations in wind speed above $n = 0.02$ Hz.

It is proposed that this concept of a cut-off frequency be used as a general measure of wind turbine performance. The higher the cut-off frequency, the more energy the turbine extracts from the wind; thus the best wind turbine would have the highest cut-off frequency. It should be noted that this whole concept of cut-off frequency can be made in terms of wave number - which is more general.

The details of the measurements and the data processing, and further analysis of data like Figures 4.2 through 4.5 are all contained in the forthcoming technical report (1).

The other facet of this task completed during the contract period was the construction of a potential flow model for the flow field upstream of a horizontal axis wind turbine. The full details of the model are given in Reference 2.

The most valuable part of the model is that it can be applied to any wind turbine with any nacelle body shape. The results in (2) are presented as a FORTRAN Program which can be run by anyone for any wind turbine. The model will give the complete velocity field and flow streamlines for the wind field upstream of any wind turbine.

A few representative results for the UMASS WF1 are shown in Figures 4.6, 4.7 and 4.8.

Figure 4.6 shows the streamlines upstream of the turbine and nacelle body. Note that in about 1 1/2 blade radii upstream of the blade disc, the influence of the wind turbine is no longer felt. Figure 4.7 shows the $x$ and $y$ components of the velocity field upstream of the turbine blade disc, and Figure 4.8 shows the stagnation streamline velocity profile upstream of the nacelle body.
Note that in Figure 4.8, the presence of the wind turbine considerably affects the flow velocity.

The program presented in (2) should be useful to wind turbine designers in estimating the effect of a particular nacelle shape and in choosing where to mount an anemometer in the wind field.
FIGURE 4.2 WIND SHEAR PROFILES

WIND PROFILES AT
U. MASS. SOLAR HABITAT I
MARCH 1978

HEIGHT, METERS

WIND TURBINE AXIS (19.8 m.)

BLADE DISC

WIND SPEED, METERS/SECOND

1 2 3 4 5 6 7

FIGURE 4.2 WIND SHEAR PROFILES
WIND SPECTRA AT SOLAR HABITAT I

FIGURE 4.3 POWER SPECTRAL DENSITY

DATA OF 4/2/78 — ©

THEORY OF DAVENPORT

LUMLEY AND PANOFSKY

FREQUENCY, $n$, Hz.

POWER SPECTRA, $S(n)$, $m^2/Hz$. 

FIGURE 4.3 POWER SPECTRAL DENSITY
WIND FURNACE TRANSFER FUNCTION

DATA OF 4/2/78 - ○

FREQUENCY, \(n\), Hz.

FIGURE 4.4 TRANSFER FUNCTION
FIGURE 4.5 WIND SPEED HISTOGRAM
\[ \psi_0 = 309.5 \text{ m}^3/\text{s} \quad \rho_\infty = 2.9 \text{ m} \]

\[ \psi = \psi_0 / 2 \quad \rho_\infty = 2.04 \text{ m} \]

\[ \psi = \psi_0 / 8 \quad \rho_\infty = 1.04 \text{ m} \]

**Figure 4.6** Streamline Plot

**Figure 4.7** Stagnation Streamline Velocity
References


TASK 5 Continued Dynamic Analysis

5.1 Introduction

The objective of this task is to conduct a dynamic analysis of the guyed pipe tower to obtain the tower mode shapes, frequencies and periods in bending.

The UMASS Wind Furnace is supported by a guyed pipe tower. The tower is 60 ft (18.3 m) in height and made from 10 inch (25.4 cm) 3/8"-wall steam pipe. It is supported at the base with a ball and socket and guyed at the 46 ft (14 m) height with 4-guys. The wind turbine applies a vertical load of 2100 lbs and the design horizontal load at the top is 3500 lbs.

Dynamic equations of motion for the tower and guys have been written including the effect of damping due to the guys. These equations were then solved by computer to obtain the first five bending modes, frequencies and periods.

Details of this analysis, the computer program and the results will be presented in the technical report UM-WF-TR-78-10 to be available in early August.

5.2 Discussion of Results

Figures 5.1 through 5.5 show the first five mode shapes, frequencies and periods for the WF tower. The deflections shown are the results due to a unit deflection at some point. The first mode can be observed without difficulty and the lowest frequency of vibration is passed through at a fairly low rotor RPM.
GUYS 46' -.262

21.5' -.195

1st. Mode
$F = 1.09 \text{ Hz.}$
$T = .9/6 \text{ sec.}$

Figure 5.1 Guyed Pole Tower Bending Mode Shape
FIGURE 5.2 GUYED POLE TOWER - SECOND BENDING MODE SHAPE

2ND MODE

\[ F = 2.59 \text{ Hz.} \]

\[ T = 0.386 \text{ sec.} \]

GUYS

28.0'

0.609

0.113
FIGURE 5.3 GUYED POLE TOWER - THIRD BENDING MODE SHAPE

3RD MODE
F = 4.30 Hz.
T = 0.232 sec.

GUYED POLE TOWER - THIRD BENDING MODE SHAPE

3RD MODE
F = 4.30 Hz.
T = 0.232 sec.
4TH MODE
$F = 4.32$ Hz.
$T = 0.252$ sec.

FIGURE 5.4 GUYED POLE TOWER - FOURTH BENDING MODE SHAPE
FIGURE 5.5  GUYED POLE TOWER - FIFTH BENDING MODE SHAPE

5TH MODE
F = 7.70 Hz.
T = 0.130 sec.
6.1 Introduction

The objectives of this task are to conduct laboratory tests on two sizes of a mechanical churn, to evaluate trade-offs between shaft driven and aloft water twisters and to evaluate belt drive, transmissions, rotary fluid joints and general installation concepts.

The MOD-4 Wind Furnace embodies the concept of providing hot water for domestic and space heating by means of a wind driven mechanical churn. Two models of the All American Engineering water twister\textsuperscript{R}, a 12 inch and a 14 inch model, have been borrowed and tested in the laboratory. Figure 6.1 shows a cut-away view of the water twister. Figures 6.2 and 6.3 show conceptually the arrangements for the shaft driven and the aloft water twisters.

Laboratory tests have been conducted using both the 12 and 14 inch models connected to the diesel-powered test stand.

6.2 Results and Conclusions

Laboratory test results are shown in Figures 6.4 and 6.5. Both curves show power in kw absorbed by the twister as a function of tip speed in m/s with Figure 6.5 presented on a log-log plot. The solid lines are for a least-square fit through the experimental data points.

These tests show the power to be a cubic function of tip-speed, hence of RPM. Therefore, the water twister is ideally suited to be matched to a wind turbine which also exhibits a cubic power relationship.

The shaft-driven mechanical churn (version A) has the disadvantages of gearing losses and the need for bearing supports for the long rotating shaft going down the full length of the tower. The aloft mechanical churn
(version C) does away with the long shaft problems but has the disadvantages of requiring a fluid-joint at the yaw-axis tower interface and the heat loss from the piping up and down the tower. Concentric well insulated pipes with the hot water carried down the inside pipe reduces these losses. Anti-freeze is needed to prevent freezing for the aloft version.

These trade-offs appear to very nearly balance out with no clear advantage of one version over the other.

A simulation tower is being installed adjacent to the laboratory to further evaluate the two-versions, problems and installation concepts. Greater detail on the tests conducted and conceptual evaluations will be presented in a technical report to be available in late August.
FIGURE 6.1  CUT-AWAY OF WATER TWISTER®
OFFSET PROVIDES TORQUE ELIMINATING NEED FOR YAW DRIVER

TRUCK TRANSAXEL WITH HYPOID GEARS

MODIFIED SEAL IS ABOVE FLUID LEVEL

UNIVERSAL JOINT

LINE SHAFT

BEARING

SPLINE

WIND FURNACE MODEL FOUR VERSION A

FIGURE 6.2
THERMOSTAT

INSULATED WATER BRAKE WITH OR WITHOUT SPEED UP TRANSMISSION

DEUBLIN DUO FLOW FLUID COUPLING

INSULATED COAXIAL PLASTIC PIPE

WIND FURNACE MODEL FOUR

FIGURE 6.3 VERSION C
FIGURE 6.4
RELATIONSHIP OF POWER AND TIP SPEED FOR WATER TWISTER R MODEL 12 AND MODEL 14

Δ - MODEL 12
○ - MODEL 14

Least Square Fit
FIGURE 6.5
RELATIONSHIP OF POWER AND TIP SPEED FOR WATER TWISTER® MODEL 12 AND MODEL 14

From Least Square Fit
slope = 3.0168
intercept = 0.01264

Δ - MODEL 12
○ - MODEL 14
TASK 7 Analytical and Economic Modeling

7.1 Advanced Wind Furnace Concept

Work under this task has been completed and is presented in the technical report of Sarkisian and McGowan, "A Preliminary Investigation of Three Advanced Wind Energy Systems for Residential and Farm Applications," UM-WF-TR-78-1 (under current revision - to be reissued in Aug. 1978). A paper summarizing this work will be presented at the Intersociety Energy Conversion Engineering Conference in August. The work completed under this task represented an extension of previous research on wind powered heating systems and extends the wind energy application to the supply of electricity as well as space and hot water energy loads for rural residences and farms. It was shown that some of these systems are competitive with conventional energy systems, if the wind turbine generators are mass produced. In order to continue the work of this initial investigation, future experimental and analytical research is recommended.

7.2 Systems Studies of Large Wind Furnace Designs

This work pertains to the investigation of the suitability of using multiple wind turbine generators (WTG) to satisfy the thermal or thermal and electrical needs of an industrial, institutional, and a commercial user. One analytical model used is a modification of the one developed by Sarkisian, et al. for the study of advanced wind furnace system concepts. That is, multiple WTG systems studied based on this design was one that provided conditioned electric power, either conditioning the electrical output of the WTG's through an inverter or sending energy into a low temperature thermal storage component (called the Improved Wind Furnace System IWF). A machine shop, a local regional
school, and a commercial greenhouse were used for the case studies for the three types of user application. The wind energy conversion system was the Improved Wind Furnace where the electrical and thermal loads were to be satisfied and the original wind furnace concept where only thermal loads were needed. A detailed technical report showing the predicted performance of the various WTGs is in preparation and is expected to be finished by late August 1978.

Another object of this study was the refinement of the economic analysis used for previous analytical wind energy system studies. A life-cycle costing approach has been used, including the purchaser's rate of opportunity and effects of tax deductions for interest, operating expenses and depreciation. Also, a sensitivity analysis to determine the important economic parameters will be made for each case study. Results using this economic approach will be presented in the August technical report.

7.3 Improvement of Current Analytical Models and Development of Simplified Analytical Models

In conjunction with Task 1, the analytical model for the thermal performance prediction of SH-1 has been updated to reflect design changes and improved analytical simulation techniques. Thus the current digital computer model for simulation of wind (and solar) heating systems has been used as an engineering tool for the analysis of experimental data from SH-1.

A major effort has been expended during the past year on the development of simplified design models for wind heated residences. The main objective of this work is to develop simplified design models that can be used by a wide spectrum of people who would like to know what the predicted performance of wind systems would be - without requiring the expertise, time, and cost
demands of the current hour-by-hour computer model.

Considerable progress on this subtask has been made during the past year (a technical report summarizing the work through July 1978 will be issued in August).

The methodology of this work is outlined in Fig. 7.1. It was of primary concern to consider what information is needed to evaluate a proposed win furnace application and what sort of data is most readily available to provide a basis for that evaluation. The basic information needed is the expected power output of the wind machine, the heating load of the home, and how the two are matched, that is, what quantity of storage and/or auxiliary heating is necessary.

Together with the economic characteristics of the system, this information will allow intelligent decisions to be made regarding the appropriateness of the proposed wind furnace.

In predicting the available wind power it is necessary to know the characteristics of both the wind machine and of the wind regime. For the purpose of the model it has been assumed that the cut in speed rated speed, power, and cut-out speed will be available for any given wind machine. This is not quite correct as will be discussed later.

The wind regime is considerably more difficult to quantify. Wind data is available for numerous locations throughout the country, but these are seldom directly relevant to a specific site some distances away. The discrepancy appears less noticeable in flat terrain, but can be quite significant in hilly or mountainous regions or where the surface characteristics vary. However, it does not appear unreasonable to monitor wind speed for a relatively short period at the proposed site and use long term data from a nearby
meterological station to gage the site's long term applicability. A number of areas have been separated from each other for the purposes of analysis:

1) Short term variability of the wind
2) Long term availability of the wind
3) Variation of wind speed with height.

Spectral analysis of the wind has indicated that power is underestimated by assuming the wind speed is constant at its averaged or sampled value during an hour. The underestimation appears, however, to be significantly less than 10%. Accordingly, no correction factor has yet been applied to the hour by hour computer model due to the uncertainty surrounding this effect. Fig. 7.2 represents power as a function of frequency and indicates which frequencies have the most energy. (For this example the magnitude of the high frequency gust energy is higher than would be normally expected as the example data was taken during hurricane winds.)

On the time scale of greater than one hour, variability in the wind speed can have considerable effect on the power output. Work here indicates that application of the Weibull probability distribution, using the average wind speed and standard deviation allows a good estimate of energy production. A computer program has been prepared which predicts power output from any wind machine as previously characterized, using only those two sample measures. Close agreement has been found on a monthly basis between power predicted from hour by hour calculations and those predicted using the Weibull distribution. As an example, Fig. 7.3 indicates the plant factor for UMASS WF-1 as a function of the average wind speed for various degrees of variability.

Various models are available for estimating wind speed as a function of height. Several computer programs were written in order to compare predictions
from the various models with actual data taken on electric utility weather towers. Preliminary results indicate a substantial discrepancy between models. The best relief seems to be to emphasize that wind speeds at proposed sites should be monitored at design hub height, and that whenever possible meteorological stations should be encouraged to take data which would allow determination of an appropriate power law exponent.

The second area of major concern is the heating load. It is often assumed that the heating load is directly proportional to the temperature difference. That approach, however, implicitly assumes that the effect of the wind and infiltration are both essentially constant. It does appear from these analytical models that in a properly designed building, wind has a relatively small effect on the conduction losses. However, infiltration can contribute a substantial amount to the heating load, even more than one half. Recent work has provided a method for estimating infiltration on an hour by hour basis, as a function of both temperature difference and wind speed, using an experimentally determined or calculated flow coefficient. The UMASS hour by hour model has been modified to include that affect. In addition, procedures have been worked out to allow prediction of monthly average infiltration as a function of average temperature and wind speed. The Weibull distribution was used in evaluating the wind affect portion, which is believed to vary as the wind speed to the 1.3 power.

Depending on the meteorological condition, it is conceivable that augmenting the wind system with solar collectors as in Solar Habitat I would be economically attractive, especially for heating domestic hot water during windless months. A computer subroutine has been prepared which allows a collector which has been tested according to NBS standards to be modeled
in the hour by hour program. Techniques for predicting monthly solar contributions from a few parameters should be forthcoming.

Future work will involve using actual and synthetic data in conjunction with the hour by hour model to predict the fraction of the heating load supplied by the wind furnace system. The results will then be correlated with the monthly parameters to provide a simplified engineering design method for obtaining performance predictions.
OBJECTIVE -
General Design
of WF Systems

Wind Power Input

(monthly)

(Characterize wind regime)

Characterize weather regime

Home heating load

Heating system performance

Economic characteristics

Economic performance
FIGURE 7.2
HORIZONTAL WIND SPEED POWER SPECTRUM AT 100m.

(FROM VAN DER HOVEN, 1957)
FIGURE 7.3
PERFORMANCE OF WIND FURNACE I
25 kW. AT 26.1 M.P.H.
$V_{\text{cut in}} = 6.0 \text{ M.P.H.}$, $V_{\text{cut out}} = 50 \text{ M.P.H.}$
TASK 8 Project Management

8.1 Introduction

The objectives of this task are to provide the project management and coordination necessary for the smooth and timely conduct of all research and testing as well as to provide for the submission of monthly, six month and final progress reports and to edit and submit all technical reports.

8.2 Reporting

The contract period was originally from July 1, 1977 to June 30, 1978 but as subsequently extended to August 15, 1978. During this period monthly progress reports were submitted for July - September, October, November and December 1977 and for January, February, March and April, 1978.

Telephone conference calls served to keep the project monitor abreast of progress on a weekly basis. A year end project review was held for the Wind-power project Group at Rocky Flats on June 9, 1978 when presentations were made by Drs. Cromack, McGowan, and Kirchhoff. This report constitutes the final contract progress report.

Numerous presentations, papers and technical reports have resulted from this contract year's work and are listed, along with previously published work under the report section titled "Papers and Publications to Date."

A Wind Turbine Blade Workshop was held on January 17, 1978 at the University of Massachusetts. There were a total of 62 people in attendance for the one-day program of presentations, lab tours and discussions. The workshop was deemed highly successful due partly to the relatively small size and partly to the fact that it was a speciality as opposed to a general workshop.
It is the firm belief of many that speciality workshops can serve a very worthwhile purpose in advancing the technology and understanding of wind energy conversion systems.
IV. PARTICIPATING PERSONNEL

A significant part of the wind power program at the University of Massachusetts is the educational aspect for the students involved in the research and demonstration program. Several students both graduate and undergraduate, beyond those supported directly by this contract have enhanced their education by their association with the program. Nearly all of these students to graduate have continued in energy related work or studies.

Following is a list of all the personnel involved in the wind power program during the past year. Also shown after each name is the type of appointment or assignment and the source of support, if any.

I. Faculty
1. Dr. Duane E. Cromack, Associate Professor, Mechanical Engineering Department, Principal Investigator
2. Prof. William E. Heronemus, Professor of Civil Engineering.
3. Dr. Robert H. Kirchhoff, Associate Professor of Mechanical Engineering.
4. Dr. Jon G. McGowan, Professor of Mechanical Engineering.
5. Dr. Richard V. Monopoli, Professor of Electrical and Computer Engineering

II. Other Professional Staff
   Michael G. Edds, Research Engineer

III. Graduate Students
(Students were all supported under this contract and all in the Mechanical Engineering Department unless otherwise noted.)
1. Thomas Broderick, M.S. candidate, School of Engineering Teaching Associate, analytical and economic studies, to join Owens Corning Fiberglass, Columbus, Ohio.
2. Bruce Johnson, M.S. candidate, Civil Engineering, School of Engineering Teaching Associate, tower dynamics.
3. Daniel Lewis, Ph.D. candidate, thermal systems, joined TEA, Harrisville, N.H.
5. Louis Manfredi, M.S. candidate in Ocean Engineering, supported primarily under Mark Swann Account, wind turbine design.
6. James Manwell, Ph.D. candidate, School of Engineering Teaching Associate, analytical studies.
8. Paul Murphy, M.S. candidate, experimental flow field studies.
10. Martin Rolland, M.S. candidate, MOD-4 design and analysis
12. Walter Sass, M.S. candidate, Electrical and Computer Engineering, School of Engineering Teaching Associate, instrumentation and controls.

16. Christopher Tomashofski, M.S. candidate, blade analysis and testing.


19. Paul Wendlegass, M.S. candidate, economic analysis and thermal systems.

IV. Undergraduate Students

1. David Driver, B.S.M.E. candidate, Undergraduate Research Assistant, thermal systems, to attend Graduate School at the Univ. of California at Berkeley.


5. Daniel Handman, B.S.E.C.E. candidate, Undergraduate Research Assistantship, microprocessor controller design, to join Graphic Sciences, Danbury, CT.


8. Jeff Squire, B.S.M.E. candidate, work study, general maintenance.
9. Richard Surko, B.S.E.C.E. candidate, Undergraduate Research Assistant, 
microprocessor controller construction and installation.

10. Paul Zanolli, B.S.M.E. candidate, work study, wind turbine maintenance and 
servicing.
V. PAPERS AND PUBLICATIONS TO DATE


