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Investigation of the Feasibility of Using Wind Power for Space Heating in Colder Climates

ANNUAL REPORT FOR
THE PERIOD ENDING
JUNE 30, 1978

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ABSTRACT

Current research supporting the development of space and hot water heating by means of the combined use of a wind turbine and solar flat-plate collectors is described in this University of Massachusetts/Amherst (UMASS) annual report for the period ending June 30, 1978. A variety of research activities ranging from economic studies to flow field measurement and analysis are discussed in detail in this report. Also included is a list of publications to date, some of which should become available through the National Technical Information Service (NTIS) when released by the Department of Energy.

Wind Furnace I at the University of Massachusetts - Amherst

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I. EXECUTIVE SUMMARY

The UMass Wind Furnace, a wind and solar powered space heating system, has been operational in a fully automatic mode since September 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.

The on-going work summarized in this report was carried out to continue the wind furnace research begun two years ago under National Science Foundation (NSF) and Energy Research and Development Administration (ERDA) sponsorship. The major objective of this work (for the period of July 1, 1977 to June 30, 1978) was to continue the engineering analysis of the Wind Furnace concept so that a more accurate assessment of the practical and commercial viability of this concept could be made. In order to carry out this analysis, the work was divided into several separate tasks, details of which are summarized in the following sections of this report.

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 (SH-I) during the period from November 1977 through April 15, 1978 (per Table 1.1). For a total heat load of 15,317 kWh during this period, 2464 kWh were supplied by solar and 7396 kWh by the wind turbine or about 64% of the total were supplied by the wind furnace. From this data, the technical feasibility of using wind energy for space heating has been demonstrated.

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. Operation has been successful although the pitch-rate was insufficient to maintain

the rated rotor rpm within the design criteria of $\pm 5\%$.

A microprocessor controller has been designed, built and will be installed when the machine is re-erected following servicing in July, 1978. This controller has the flexibility to be reprogrammed for blade pitch, field current and yaw control to any desired conditions. Evaluation of the controller will be accomplished under the 1978-79 test program.

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, as well as wind speeds at various distances upwind of the turbine, were recorded. These initial results indicate the extent of the flow field in the vicinity of an operating turbine. Much more extensive measurements and analyses 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 papers and reports referenced under each task.

II. INTRODUCTION

This report presents the background and progress to date for the Wind Furnace project at the University of Massachusetts. The organization of the report gives a general description of the Wind Furnace installed at Solar Habitat-I with performance and operational data of general interest.

More 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. Due to the on-going nature of this work, not all of the work of each task could be fully covered by the end of this reporting period. Future technical reports, to be issued by the University of Massachusetts, will document all phases of this work. It should also be noted that, after technical review by DOE, some of the University of Massachusetts technical reports referenced should be available from the National Technical Information Service (NTIS).

GENERAL BACKGROUND

The Wind Furnace project began 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 through funding by Rockwell International, a prime contractor to the Department of Energy.

Solar Habitat I, an energy conservation house designed by Professor Curtis Johnson of the Department of Food and Agricultural Engineering, serves as a demonstration facility for the Wind Furnace. A solar flat-plate collector system was installed on the south side of this house and has been operating since September 1, 1976. The Wind Turbine Generator (WTG)

was erected in November 1976 and underwent component testing and check-out before becoming fully operational in the automatic mode in 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 an auxiliary back-up heating system.

THE WIND FURNACE

Solar Component

Two hundred square feet (18.6 m^2) 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 while water alone is pumped from the tank through the heat exchanger and back to the tank. When the collector temperature exceeds the storage tank temperature by 20°F , the collector pump is automatically turned on by means of a differential thermostat.

Storage

Based on work summarized in Reference 1, a 7570 L (2000 gal) tank is considered to be the correct size for this 148.6 m^2 (1600 ft^2) house with its full basement. The concrete thermal storage tank is fully insulated

WIND FURNACE CONCEPT

FIGURE 1

and covered, with any heat loss from the tank representing a heat gain to the basement. Thermocouples have been placed throughout the house and at various levels within the tank for careful monitoring of the thermal systems.

Wind Turbine Design

A 9.9 m (32.5 ft) diameter, three-bladed downwind rotor is mounted atop an 18.3 m (60 ft) steel stayed pole mast. Designed to operate at a tip-speed-ratio of 7.5, the machine produces 25 kW at 11.6 m/s (26 mph) wind speed. The predicted power output is shown in Figure 2 as a function of wind speed and blade pitch angle, β .

Figure 3 shows the pitch schedule with rotor rpm as a function of wind speed and of pitch angle. From cut-in speed of 2.7 m/s (6mph) to rated speed of 11.6 m/s (26 mph), the rotor rpm continually increases and the 7.5 tip speed/wind speed ratio is maintained. From 11.6 m/s (26 mph) to 22.4 m/s (50 mph), the blades are pitched towards feather thus maintaining a constant rated rpm of 167. At the cut-out speed of 22.4 m/s, the blades are pitched to full feather and the machine stops.

An ac synchronous generator, rated at 31.3 kVA at 1800 rpm, produces variable voltage and variable frequency power that is dependent on the wind 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 framesupports all of the wind turbine components and provides for attachment to the tower via the pole matcher. The pole matcher contains 15 brass slip rings embedded in fiberglass and epoxy.

PREDICTED PERFORMANCE

FIGURE 2

ROTOR RPM AS A FUNCTION OF WIND SPEED

FIGURE 3

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 WTG and enables the wind turbine to yaw with changes in wind direction. A yaw damper consists of a chain-and-sprocket driven electric generator. As the machine yaws, the load on the generator increases with increase in yaw rate, thus more damping in yaw is provided. The yaw damping coefficient can be changed by changing the resistance load placed across the terminals of the generator. The generator also serves as a yaw drive motor if necessary.

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 a 1:11 speed-up from rotor to generator.

Three steel tubes welded to a steel plate assembly serve as the rotor hub which attaches to the lug bolts of the truck rear axle assembly. These tubes provide the bearing support for the blades and a center tube supports the pitch control shaft and linkage. Blade pitch is adjusted by an electrical servo motor driving a shaft, the linear motion of which is changed into synchronized blade rotation by a sprocket and chain linkage.

The rotor blades are made entirely of fiberglass reinforced plastic. 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 lb) 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 loading of up to four times the thrust at rated speed and power.

A fiberglass nacelle totally encloses the transmission, generator and control system components. It has three access doors for servicing and repair, and it supports an anemometer.

Pitch Control

Figure 3 defines the pitch control regions in terms of rpm versus wind speed. In Region 1, the wind speed is below V cut-in, the rotor is stationary and the blades are pitched to 40° for maximum start-up torque. In Region 2, the blades are pitched to -6° (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 speed. Throughout Region 3 the blade pitch increases from -6° at 11.6 m/s (26 mph) towards 16° 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°). 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 indicates in general, a consistent trend towards the operational design condition of -6° pitch over region 2.

OPERATION OF THE WIND TURBINE

The results presented in this section are from continuous recordings on a six-channel strip-chart recorder. These recordings are used more for qualitative than quantitative analysis. That is, it is easier to get a feel for the machine while observing the parameters being traced. Definitions of symbols used are listed in Table 1. Sections of representative runs are shown in Figures 4-8 with accompanying explanations, and comments made concerning specific observations. Details of these runs follow:

A) Figure 4 - 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 5 mph. It has been observed that in light winds (less than approximately 7 mph) the machine will not 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 winds, because 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 can be seen to go from 35° to 4° 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 0 to 0.42 A.

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

TABLE 1 - DEFINITION OF SYMBOLS

- $\bar{V}$ = wind speed observed at the axis height from the house anemometer, approximately 30 ft 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 V at 167 rpm.)
- β = blade pitch angle referenced to the tip. (This is actually the voltage of the feedback pot connected to the ball screw in the pitch change mechanism.)
- 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.)

FIGURE 4. AUTOMATIC START-UP.

B) 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 0° until the rotor speed dropped below 20 rpm. At this point, the pitch controller increased the pitch angle to the start-up angle which had been set to 30° .

The field current trace shows a transition of incremental changes in current level until the rpm drops to 37, the threshold value 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 rotor speed. The maximum voltage generated in this interval was 100 V. 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.

C) Figure 6 - Region 2 Operation: Moderate Breeze

With the winds between 5 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 4° , except at one point where the rotor speed approached 162 (rpm). The pitch controller increased pitch slightly and then returned to 4° , the pitch setting that had been set for Region 2 operation. 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 W.

FIGURE 5. RETURN TO START-UP ANGLE.

FIGURE 6 REGION 2 OPERATION-MODERATE BREEZE.

D) Figure 7 - Region 2 and Region 3 Operation: Moderate Breeze with Higher Gusts

Operation in winds averaging 17 mph with gusts to approximately 25 mph is shown in this chart section. The rated shaft speed has been set to 145 rpm. 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 8%.

E) Figure 8 - Region 2 and Region 3 Operation: Fresh Breeze Winds

Approximately three hours later than the above run, the winds were averaging 20 mph and gusting to 30 mph. 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% over rated (145 rpm). The pitch angle varied from 4° (Region 2) to a maximum angle of 20° (Region 3).

As a result of the higher shaft speeds, the load voltage stayed mainly between 100 to 300 V. A maximum of 330 V was reached at a shaft speed of 173 rpm. This maximum output of 32670 W was the result of a wind gust to approximately 30 mph. Four other times the output reached or exceeded 300 V, or 27 kW.

Figures 9 and 10 show certain data points plotted along with the predicted curves of power output as a function of shaft or wind speed. They illustrate the following points:

- 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% over or under the predicted value. These were most likely caused by the nature of the wind and the settings

FIGURE 7 REGIONS 2 AND 3 OPERATION WITH GUSTS.

FIGURE 8 REGIONS 2 AND 3 OPERATION - HIGHER WINDS.

FIGURE 9 ELECTRIC POWER OUTPUT AS A FUNCTION OF SHAFT SPEED.

FIGURE 10. ELECTRICAL POWER OUTPUT AS A FUNCTION OF WIND SPEED.

of the pitch angle excitation.

- 2) Rated power was exceeded many times. The maximum power of 32.7 kW, 30.7% above rated, occurred at a value of 173 rpm, 3.6% over rated shaft speed. The machine had entered Region 3 operation starting at a pitch angle of 4° and increasing to 18° before returning to 4° . (These traces can be seen in Figure 8.)

For a 3.6% overspeed the predicted power level would be 27 kW. This value has been recorded under the same conditions of pitch angle, excitation and shaft speed for steady winds. The 32.7 kW recorded was for a pitch angle of 16° and gusting winds. The differences between these two cases (i.e. steady or gusty winds) account for the 21% greater output over predicted.

B L A N K

III. SUMMARY OF TASKS

Task 1 Continued Operation of Solar Habitat-I Experiment

The overall objective of this task was to continue the operation of the wind-powered heating system and to experimentally evaluate the wind furnace as a heating concept. This task included work on both the thermal systems and wind machine components and is summarized as follows:

1.1 Thermal Systems

1.1.1 Modification to system components

During the period of testing, several modifications 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 modeled 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.

DOMESTIC HOT WATER PREHEAT SYSTEM

FIGURE 1.1

The second major modification included the installation of new insulation of the 3.8 m^3 (1000 gal) hot water storage tank. As was discovered in the initial testing of the component, the thermal losses were much higher than acceptable (or than predicted from a model of an idealized hot water thermal storage tank). This was because 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. To overcome this problem, 10 to 13 cm. (4 to 5 in.) of urethane insulation ($R = 8/\text{in.}$) 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 Fig 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 190°F . 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 this liner has held water at temperatures up to 80°C .

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

FIGURE 1.2

STORAGE TANK THERMAL PERFORMANCE

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 WTG (electrical systems) is shown in Figure 1.3. The Data Logger System consists of two Data Loggers each coupled to a Digital Cassette recorder and teletype terminal. Transient data acquisition for the WTG system is also provided by a six channel strip chart recorder.

Instantaneous thermal systems data was collected on the data logger at 15 minute intervals and included 20 channels of temperature signals, 5 channels for system electrical components (such as pumps and WTG), solar pyranometer output, and wind speed. After collection of four days data, the cassettes were processed by a digital data reduction program (Figure 1.4) and inputted 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) Percent time of collector operation
- 6) Wind speed
- 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

FIGURE 1.3
BLOCK DIAGRAM - DATA ACQUISITION SYSTEM

FIGURE 1.4

FLOW CHART FOR DATA REDUCTION PROGRAM

(Note: All temperatures in °F)

SOLAR HABITAT 1

JULIAN DATE = 64

HOUSE PERFORMANCE

HOURLY--

HOUR	AMB. TEMP.	HOUSE TEMP.	BSMT. TEMP.	TANK TEMP.	INSOL (B/H-F2)	%COLL OPER.	WIND SPEED (MPH)	WIND DIR
0	13.7	70.4	63.5	148.8	.3	0.	6.5	.25
1	13.3	69.9	63.6	147.4	.3	0.	3.6	0.
2	12.6	69.3	63.6	146.1	.3	0.	2.2	0.
3	11.7	68.7	63.5	144.9	.4	0.	2.9	0.
4	11.1	68.4	63.3	143.7	.4	0.	5.1	0.
5	10.2	67.7	63.4	142.6	.4	0.	5.2	.25
6	10.3	68.0	62.8	141.6	3.3	0.	13.0	.75
7	10.2	68.8	62.3	140.2	87.8	0.	13.8	.75
8	11.2	71.1	61.9	139.3	168.8	0.	12.0	.75
9	13.8	72.2	62.2	136.8	247.4	.75	8.7	.75
10	15.7	73.7	62.6	137.7	291.2	1.00	15.2	.75
11	16.4	75.7	63.0	138.0	311.3	1.00	15.2	1.00
12	18.2	76.0	63.1	139.1	311.9	1.00	12.8	.50
13	20.0	76.7	64.1	140.1	290.4	1.00	9.8	.50
14	22.1	76.9	64.2	140.6	214.8	1.00	10.5	1.00
15	22.5	77.6	64.7	140.5	182.4	1.00	10.9	1.00
16	22.6	77.4	65.1	140.8	89.0	0.	11.2	1.00
17	20.4	77.9	64.3	140.6	21.9	0.	12.3	1.00
18	19.6	76.3	63.7	140.6	.3	0.	8.7	.75
19	19.9	76.7	63.1	140.6	.3	0.	10.9	1.00
20	20.4	75.1	63.0	140.1	.3	0.	8.3	1.00
21	19.9	74.2	62.9	140.2	.4	0.	9.8	.75
22	18.6	73.5	62.6	140.0	.2	0.	9.8	.75
23	17.2	72.2	62.5	139.8	.2	0.	5.4	.75

AVERAGED DAILY PERFORMANCE--

AMB. TEMP.	HOUSE TEMP.	BSMT. TEMP.	TANK TEMP.	INSOL (B/H-F2) AV. TOT	TOTAL COLL. HOURS	WIND SPEED (MPH)	TOTAL WINDMCH HOURS
16.3	73.1	63.3	141.3	185.1	6.75	9.4	15.25

2220.7

DEGREE
DAYS

48.7

FIGURE 1.5

SAMPLE OUTPUT FROM

THERMAL DATA REDUCTION PROGRAM

COLLECTOR PERFORMANCE

HOURLY-

HOURLY	INSOL (B/H-F2)	%COLL OPEP.	ENERGY COLL. (B/HR)	COLL. PARAM (F-H/B)	EFF.	AVER. FLUID TEMP.	FLUID TEMP. RISE	PLATE TEMP.
0	.3	0.	0.	0.	0.	0.	0.	0.
1	.3	0.	0.	0.	0.	0.	0.	0.
2	.3	0.	0.	0.	0.	0.	0.	0.
3	.4	0.	0.	0.	0.	0.	0.	0.
4	.4	0.	0.	0.	0.	0.	0.	0.
5	.4	0.	0.	0.	0.	0.	0.	0.
6	3.9	0.	0.	0.	0.	0.	0.	0.
7	97.8	0.	0.	0.	0.	0.	0.	0.
8	168.8	0.	0.	0.	0.	0.	0.	0.
9	247.4	.75	6503.8	.49	.13	139.5	4.7	161.7
10	291.2	1.00	15129.3	.41	.26	142.4	8.2	173.2
11	311.3	1.00	19133.4	.38	.31	144.7	10.4	179.9
12	311.9	1.00	19133.4	.37	.31	145.5	10.4	179.5
13	290.4	1.00	17153.8	.40	.30	146.1	9.3	177.5
14	214.3	1.00	10825.7	.54	.25	144.3	5.9	166.3
15	182.4	1.00	2029.5	.65	.06	141.4	1.1	149.4
16	39.0	0.	0.	0.	0.	0.	0.	0.
17	21.9	0.	0.	0.	0.	0.	0.	0.
18	.3	0.	0.	0.	0.	0.	0.	0.
19	.3	0.	0.	0.	0.	0.	0.	0.
20	.3	0.	0.	0.	0.	0.	0.	0.
21	.4	0.	0.	0.	0.	0.	0.	0.
22	.2	0.	0.	0.	0.	0.	0.	0.
23	.2	0.	0.	0.	0.	0.	0.	0.

AVERAGED DAILY PERFORMANCE-

AVER/ TOTAL INSOL (B/F2)	TOTAL COLL. HOURS	TOTAL ENERGY COLL. (BTUS)	AVER. COLL. PARAM (F-H/B)	AVER. EFF.	AVER. FLUID TEMP.	AVER. FLUID TEMP. RISE	AVER. PLATE TEMP.
185.1	6.75	90083.9	.46	.23	143.6	7.2	169.8
2220.7							

DAILY
COLL.
EFF.

.20

FIGURE 1.6

SAMPLE OUTPUT FROM THERMAL DATA
REDUCTION PROGRAM (COLLECTOR PERFORMANCE)

was not installed during the 1977-78 heating season, due to the necessity to design a 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. (The lightning caused a rapid and large voltage surge in the utility supplied ac power.) At this time complete reduction of the thermal performance data has 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 during the next contract). Due to some experimental difficulties, a complete set of data for the full year with fully automatic operation of the house was not obtained. However, most of these difficulties were minor consisting 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 latter category this included short periods when the WTG, storage tank or baseboard convectors were out of normal operation. National Weather Service data from Bradley Field, Connecticut, which has a similar climate, was substituted for missing weather data.

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 thermal performance 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

FIGURE 1.7 DAILY OPERATION OF SOLAR HABITAT - I

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 the 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, to determine the windpower energy input, the experimentally calculated solar and auxiliary energy inputs must be subtracted from the house heating energy 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 $1.63 \text{ kWh}/^{\circ}\text{C-day}$ ($10,000 \text{ BTU}/^{\circ}\text{F-day}$). Also, the previously developed analytical modeling program could be used to predict the heating requirements and required auxiliary energy input.

Table 1.1 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.

Month	Q_{House}	Q_{Solar}	Q_{Aux}	Q_{Wind}
Nov	1666	341	0	1325
Dec	3289	349	1690	1250
Jan	4032	427	1875	1730
Feb	2559	360	1532	667
Mar	2394	521	380	1493
<u>Apr</u>	<u>1377</u>	<u>466</u>	<u>0</u>	<u>911</u>
Totals	15,317	2,464	5,477	7,376

Table 1.1 Energy Balance for SH-I (kWh)

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 immersion heaters. Interruptions of the automatic operation have been due to minor problems or for specific operational tests.

Despite this, considerable experimental data has been obtained along with valuable operational experience, some of which has already been presented in References 3 and 4.

A few problems with the wind turbine have plagued the project. Specifically, oil leaks from the truck differential and from the second-stage speedup lube case have been annoying but have not caused any downtime. The yaw damper, however, has bound-up on several occasions and resulted in some downtime. 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 failed in late May, resulting in the system 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 Data Logger has greatly speeded up this process. During the 1978-79 contract year, a much higher speed data acquisition system, connected directly to the University computer for data reduction, will greatly speed up the process.

1.2.2 Results

Data is currently collected by either of two systems depending on the type of data desired. The analog (or continuous) 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 shows a typical strip chart data trace. This figure illustrates a period of decreasing wind with the corresponding decrease in rpm and subsequent increases in blade pitch angles as the rotor drops below 20 rpm. Other examples of this data were previously shown in Figures 4 through 8.

CHART SPEED (2.5 MM/MIN)

FIGURE 1.8

The other means of recording WTG performance data is the digital acquisition system using the second Data Logger. A modification to this system, 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, either in the order in which 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 1.9 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 1.10. Each curve represents constant tip-speed-ratio operation. Also shown by asterisk is the design point of 25 kW at 11.7 m/s for a tip-speed-ratio of 7.5.

FIGURE 1.9 POWER AS A FUNCTION OF ROTOR SPEED

FIGURE 1.10 POWER AS A FUNCTION OF WIND SPEED FOR
CONSTANT TIP-SPEED-RATIO

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

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 ± 0.2 m/s. The front ends 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.

DATA COLLECTION CYCLE

FIGURE 1.12

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 5.33 m (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 References 5 and 6. 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 for the same power output and design tip-speed-ratio.

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 bending stresses are the limiting design conditions.

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

BENDING MOMENT DIVIDED BY CHORD CUBED

FIGURE 2.1

CODE 1=COMPACT 2=GENERAL
? 2

READS,RADIUS,TWIST,BLADES
? 17.5,18.75,3

READS,PITCH,TIPSPEED,C10,C100
? -3.1,7.5,2.43,.27

TAPE 30
17.50 1.75 3 -3.10
7.50 4415 10
100 .27 0.
90 .51 2.08
80 .75 4.17
70 .99 6.25
60 1.23 8.33
50 1.47 10.42
40 1.71 12.50
30 1.95 14.58
20 2.19 16.67
10 2.43 18.75

RADIUS TWIST SOLIDITY TAPER RATIO
17.50 18.75 .0693 .1111
END.

ENTER VALUES FOR U, DR, 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
INCREMENTAL PERCENTAGE-----	.10
HUB 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
ALTITUDE OF SITE ABOVE SEA LEVEL IN FT=	0.
CONING ANGLE IN DEGREES-----	10.00
NUMBER OF DATA STATIONS ALONG SPAN----	10
NACA PROFILE USED-----	4415
RPM OF THE BLADE-----	150.06

STANDARD AXIAL INTERFERENCE METHOD USED

NO TIP LOSS MODEL USED

NO HUBLOSS MODEL USED

PERCENT RADIUS	CHORD IN FT	TWIST ANGLE IN DEG
100.0	.27000	0.
90.0	.51000	2.08000
80.0	.75000	4.17000
70.0	.99000	6.25000
60.0	1.23000	8.33000
50.0	1.47000	10.42000
40.0	1.71000	12.50000
30.0	1.95000	14.58000
20.0	2.19000	16.67000
10.0	2.43000	18.75000

DATA OUTPUT RECORD

AXIAL INTERFERENCE FACTOR	-----	A
ANGLE OF ATTACK IN DEGREES	-----	ALPHA
ANGULAR INTERFERENCE FACTOR	-----	AP
DRAG COEFFICIENT	-----	CD
LIFT COEFFICIENT	-----	CL
POWER COEFFICIENT	-----	CP
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

FORCE-X-DIR/BLADE IN LBS/FT ----- FX
 FORCE-Y-DIR/BLADE IN LBS/FT ----- FY
 MOMENT-X-DIR/BLADE IN FT-LBS ----- MX
 MOMENT-Y-DIR/BLADE IN FT-LBS ----- MY
 POWER IN KILOWATTS ----- P
 PERCENT RADIUS ----- PC-R
 ANGLE PHI IN DEGREES ----- PHI
 RADIUS IN FEET ----- R
 REYNOLDS NUMBER ----- RE NO
 TORQUE IN FT-LBS ----- Q
 THRUST IN LBS ----- T
 RELATIVE VELOCITY IN FT/SEC ----- W

PC-R= .95	J= 11	A= .1988515	AP= .0026911
PC-R= .90	J= 11	A= .2459609	AP= .0035367
PC-R= .85	J= 14	A= .2825828	AP= .0043492
PC-R= .80	J= 12	A= .3072568	AP= .0051775
PC-R= .75	J= 15	A= .3260574	AP= .0059620
PC-R= .70	J= 8	A= .3293622	AP= .0069073
PC-R= .65	J= 13	A= .3261726	AP= .0080139
PC-R= .60	J= 8	A= .3196873	AP= .0093672
PC-R= .55	J= 11	A= .3122477	AP= .0110925
PC-R= .50	J= 7	A= .3060704	AP= .0133821
PC-R= .45	J= 10	A= .3027275	AP= .0165588
PC-R= .40	J= 6	A= .3031689	AP= .0211487
PC-R= .35	J= 9	A= .3082503	AP= .0290956
PC-R= .30	J= 7	A= .3185741	AP= .0391965
PC-R= .25	J= 10	A= .3342587	AP= .0581956
PC-R= .20	J= 8	A= .3551014	AP= .0940815
PC-R= .15	J= 51	A= .3400531	AP= .1522000
PC-R= .10	J= 7	A= .2342855	AP= .0358970

R	PC-R	ALPHA	Q	T	P
15.51	.90	7.372	232.539	148.895	4.954
13.79	.80	5.483	517.593	346.796	11.027
12.06	.70	4.004	774.105	536.532	16.492
10.34	.60	3.194	998.279	701.672	21.268
8.62	.50	2.916	1190.167	838.390	25.356
6.89	.40	3.294	1349.160	948.409	28.743
5.17	.30	4.706	1474.665	1034.811	31.417
3.45	.20	8.331	1564.620	1099.100	33.334
1.75	.10	29.154	1608.757	1136.943	34.274
0.	0.	0.	0.	0.	0.

R	FX	FY	MX	MY	W
15.51	3.61	37.346	69.132	716.493	246.085
13.79	3.85	38.098	152.792	1567.216	219.195
12.06	3.85	34.594	226.720	2274.889	194.459
10.34	3.89	29.196	289.769	2796.534	167.681
8.62	3.94	23.760	341.921	3150.102	141.003
6.89	4.00	18.906	382.956	3371.537	114.510
5.17	4.05	14.571	412.650	3495.934	88.273
3.45	3.98	10.247	430.463	3551.832	62.432
1.75	.47	4.076	435.835	3564.015	39.259
0.	0.	0.	0.	0.	0.

R	PHI	F	CL	CD	RE NO
15.51	6.35	1.000	1.038	.016	802128.181
13.79	6.55	1.000	.908	.014	1050705.003
12.06	7.15	1.000	.794	.012	1230413.462
10.34	8.42	1.000	.727	.012	1318184.033
8.62	10.24	1.000	.704	.012	1324753.750
6.89	12.69	1.000	.736	.012	1251493.842
5.17	16.19	1.000	.849	.013	1100146.064
3.45	21.90	1.000	1.098	.019	873852.063
1.75	44.77	1.000	.735	.582	608794.709
0.	0.	0.	0.	0.	0.

END.

SRU 5.633 UNITS.

RUN COMPLETE.

R	PM	CP	CT	CX	CY
15.51	0.	.065	.097	.098	1.017
13.79	0.	.144	.226	.090	.890
12.06	0.	.216	.349	.087	.778
10.34	0.	.278	.456	.095	.710
8.62	0.	.332	.545	.113	.684
6.89	0.	.376	.617	.150	.709
5.17	0.	.411	.673	.224	.807
3.45	0.	.436	.715	.392	1.010
1.75	0.	.448	.740	.105	.917
0.	0.	0.	0.	0.	0.

2.3 Blade Structural Analysis

Early design and analysis work on the Wind Furnace blades was done by Stoddard and Van Dusen and appears in references 7 and 8. 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 inputted, 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 lb applied at $r/R = 0.95$ and at 25% of the chord resulted in a measured tip deflection of $2.96 \pm .04$ inches in the flapwise direction and $0.36 \pm .14$ inches in the lead direction. The predicted deflections for this loading were 2.99 in. and 0.57 in. respectively. There was no detectable angular rotation of the blade.

Agreement between measured and predicted blade strains has been shown to be good. 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.

DESCRIPTION OF BLADE COMPONENTS

BLADE STOCK

FIGURE 2.2

FIGURE 2.3

FIG. 2.4 SCHEMATIC PROGRAM MOMENTS

WF-1 TEST BLADE, 1/2 RATED LOAD,
SKIN STRAINS AT 475 RADIUS STATION

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

FIGURE 2.6

Details of this experimental arrangement and of its results as well as the analysis, including flapping, will be presented in future technical reports.

Task 3 Continued Controls Design

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 UNASS wind turbine became operational under fully automatic control in September 1977. This control system is described in detail in Reference 9. Lightning damage to the instrumentation prevented testing of the system until November.

The blade pitch controller varies the pitch angle, β , 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 output 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 causing the rotor 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 in this mode was logged during the past year. A sample of this automatic mode of operation was shown in Figure 7 at 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 Reference 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°/s pitch rate for the blades is insufficient to maintain a given rpm within $\pm 10\%$. 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 7, the field current fluctuates rapidly and when the generator fluctuates around 40 rpm, the field current is continually cycling 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 micro-processor 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 planned maintenance and repair. This controller is described in detail in Reference 10.

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 3.1):

FIGURE 3.1 CONTROL SYSTEM BLOCK DIAGRAM

1. Signetics ABC 1500 microprocessor board.
2. Blade pitch system motor interface.
3. Yaw motor interface.
4. Generator field current interface.
5. Sixteen analog input channels interface.
6. Eight digital inputs interface.
7. Eight digital outputs 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 10A and is adjustable in 3.9A increments.

The blade pitch system and the yaw direction system use 24 V dc motors. The interfaces between the microprocessor 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 microprocessor.

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 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.

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 the Wind Furnace 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 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 the manufacturer for some revisions. These changes are detailed in Reference 11. The anemometers were again mounted on the towers and finally became operational at the end of February 1978.

4.2 Experimental Results

As of June 1978 the following measurements had 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 V 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 $n = 0.02$

FIGURE 4.1 SITE PLAN

FIGURE 4.2 WIND SHEAR PROFILES

WIND SPECTRA AT SOLAR HABITAT I

FIGURE 4.3 POWER SPECTRAL DENSITY.

WIND FURNACE TRANSFER FUNCTION

FIGURE 4.4 TRANSFER FUNCTION.

FIGURE 4.5 WIND SPEED HISTOGRAM (Data of 4/2/78)

Hz. Above this "cut-off frequency," the transfer function is 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 the more general terms of wave number.

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 (12).

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 Ref. 12.

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 (12) 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 WFl 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 at about $1\frac{1}{2}$ blade radii (7 m) upstream of the blade disc, the influence of the wind turbine is no longer felt. Figure 4.7

FIGURE 4.6 STREAMLINE PLOT

FIGURE 4.7 STAGNATION STREAMLINE VELOCITY

FIGURE 4.8 VELOCITY PROFILES

shows the stagnation streamline velocity profile upstream of the nacelle body and figure 4.8 shows the x and y components of the velocity field upstream of the turbine blade disc. Note that in Figure 4.8, the presence of the wind turbine (or nacelle) considerably affects the flow velocity.

The program presented in Reference 12 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.

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 18.3 m (60 ft) in height and made from 254 mm (10 in.) diam., 3/8 in.-wall steam pipe. It is supported at the base with a ball and socket and is guyed at the 14 m (46 ft) height with four guys. The wind turbine applies a vertical load of 2100 lb and the design horizontal load at the top is 3500 lb.

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 a technical report in progress.

5.2 Discussion of Results

Figures 5.1 through 5.5 show the first five mode shapes, frequencies and periods for the WF-I 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.

FIGURE 5.1 GUYED POLE TOWER BENDING MODE SHAPE

FIGURE 5.2 GUYED POLE TOWER - SECOND BENDING MODE SHAPE

FIGURE 5.3 GUYED POLE TOWER - THIRD BENDING MODE SHAPE.

FIGURE 5.4 GUYED POLE TOWER - FOURTH BENDING MODE SHAPE

FIGURE 5.5 GUYED POLE TOWER - FIFTH BENDING MODE SHAPE

TASK 6 Continued Design and Test of MOD-4

6.1 Introduction

The objectives of this task are to conduct laboratory tests on two sizes of a mechanical water churn, to evaluate trade-offs between shaft-driven, ground-located, and aloft-mounted water churns 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^R, a 12 in. and a 14 in. 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 shows conceptually the arrangements for the shaft-driven and the aloft water churns.

Laboratory tests have been conducted using both the 12 and 14 in. 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 absorbed by the Twister as a function of tip speed 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, water churns are ideally suited to be matched to wind turbines which also exhibit 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. Mounting the mechanical churn aloft (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. Antifreeze 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.

Greater detail on the tests conducted and conceptual evaluations will be presented in a technical report to be available at a later date.

FIGURE 6.1 CUT-AWAY OF WATER TWISTER^R

WIND FURNACE
MODEL FOUR

FIGURE 6.2

VERSION A

WIND FURNACE
MODEL FOUR
VERSION C

FIGURE 6.3

FIGURE 6.4

RELATIONSHIP OF POWER AND TIP SPEED FOR WATER TWISTER^R MODEL 12
AND MODEL 14

FIGURE 6.5

RELATIONSHIP OF POWER AND TIP SPEED FOR WATER TWISTER^R MODEL 12
 AND MODEL 14

TASK 7 Analytical and Economic Modeling

The overall objective of this task is to improve the analytical wind heating performance models developed in the past two year's work.

7.1 Advanced Wind Furnace Concept

Work under this task has been completed and is presented in the technical report of Sarkisian and McGowan (13). 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.

7.2 Systems Studies of Large Wind Furnace Designs

This work pertains to the investigation of the suitability of using multiple wind turbine systems to satisfy the thermal or thermal and electrical needs of an industrial, institutional or a commercial user. One analytical model used is a modification of the one developed by Sarkisian and McGowan (13) for the study of advanced wind furnace system concepts. One WTG system studies (the Improved Wind Furnace System, IWF) was based on a design that provided conditioned electric power or sent energy into a low temperature thermal storage component. A machine shop, local regional school and a commercial greenhouse were used for the case studies for the three types of user application. The Improved Wind Furnace wind energy conversion system was used 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 WTG's is expected to be issued in the near future.

Another object of this study is the refinement of the economic analysis used for previous analytical wind energy system studies (14). A life-cycle costing approach will be 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 a forthcoming 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 Solar Habitat-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 during the past year has been 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 and a technical report to be issued during the next contract year will summarize this work.

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 wind 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, the performance information will allow economic feasibility assessments of wind heating systems in general.

In predicting the available wind power, it is necessary to know the characteristics of both the wind system 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.

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 distance 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 meteorological station to gage the site's long term applicability. A number of areas have been separated from each other for the purpose of analysis:

FIGURE 7.1 ANALYTICAL MODEL OUTLINE

- 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% (15,16,17). Accordingly, no correction factor has yet been applied to the hour-by-hour computer model due to the uncertainty surrounding this effect. Figure 7.2 presents power as a function of frequency and indicates which frequencies have the most energy. The curve (18) is a composite derived from data taken over a variety of sampling periods. For example, the low frequency portion of the spectrum was obtained by an analysis of 24 hour average winds over an interval of 200 days. For the high frequency end, data were taken during a hurricane with winds averaging 13 m. The effect of the high wind speeds was to greatly increase the amplitude of that end of the spectrum. More normal situations such as discussed by Van der Hoven and Panofsky (19) seldom show a spectral amplitude above 1.0 m^2 in this range.

The low frequency peaks are a result of frontal passage (about every four days) and diurnal variations (in this case, two per day). The high frequency peak is due to boundary layer turbulence. A drop-off in intensity beyond the peak is typical of behavior in the inertial subrange, but the location of the peak does not change much with varying wind speeds, although the magnitude does.

On the time scale of greater than one hour, variability in the wind speed can have considerable effect on the power output.. Other work at UMASS (20) indicates that application of the Weibull probability distribution, using the

FIGURE 7.2
HORIZONTAL WIND SPEED POWER SPECTRUM AT 100 m. (FROM VAN DER HOVEN, 1957)

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-I as a function of the average wind speed for various degrees of variability.

Various techniques are available for estimating wind speed as a function of height. The most common method is to assume that wind speed varies with height according to a power law relation of the form (21):

$$V_1/V_2 (Z_1/Z_2)^P$$

where the exponent is assumed to be a constant and a function solely of the surface of the surrounding landscape. According to Justus, et al. (22), a better fit to actual data is found by assuming that the exponent varies with wind speed. Also, Touma (23) points out that the exponent is a strong function of the atmospheric stability as well as surface conditions. In the forthcoming report summarizing the analytical hour-by-hour program (to be issued during the next contract year) more details will be given on this subject; however, preliminary results indicate a substantial discrepancy between models. Current thoughts indicate that wind speeds at proposed sites should be monitored at design hub height.

The second area of major concern involves prediction of the heating load. It is often assumed that the heating load is directly proportional to the difference between the inside and outside ambient temperature. That approach, however, implicitly assumes that the effect of the

FIGURE 7.3

PERFORMANCE OF WIND FURNACE I

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 50 percent. Recent work (24) 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 effect. 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 effect portion, which is believed to vary approximately as the wind speed to the 1.3 power.

Future work (to be reported during the next contract year) 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. This input, combined with a life cycle economics program, will provide the necessary information required to assess the economic feasibility of wind heating systems. Work is in progress on this phase of the project and will be the subject of several papers and technical reports to be issued during the next contract year.

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, provide for the submission of monthly, six month and annual progress reports and to edit and submit all technical reports.

8.2 Reporting

The contract period of this report was originally from July 1, 1977 to June 30, 1978 but was 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 Systems project group at Rocky Flats on June 9, 1978 when presentations were made by Drs. Cromack, McGowan and Kirchhoff. This report constitutes the annual 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 special, as opposed to a general, workshop. It is the firm belief of many that special 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 who have graduated 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 were 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 Fiberglas, 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.
4. Barry Liebowitz, M.S. candidate, Mechanical Engineering Dept. Teaching Assistantship, thermal systems.
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.
7. Koorosh Modarresi, M.S. candidate, Mechanical Engineering Dept. Teaching Assistantship, analytical flow field studies.
8. Paul Murphy, M.S. candidate, experimental flow field studies.
9. Frederick Perkins, M.S. candidate, blade structural analysis, to join SERI, Golden, Colo.
10. Martin Rolland, M.S. candidate, MOD-4 design and analysis
11. Paul Sarkisian, M.S. candidate, Mechanical Engineering Dept. Teaching Assistantship, Solar Energy Div., Carrier Corp.
12. Walter Sass, M.S. candidate, Electrical and Computer Engineering, School of Engineering Teaching Associate, instrumentation and controls.
13. James Sexton, M.S. candidate, supported by Mark Swann Account, wind turbine design, joined Rockwell International, Rocky Flats Plant, Golden, Colo.
14. Forrest Stoddard, Ph.D. candidate, Ocean Engineering, Mechanical Engineering Dept. Teaching Assistant, wind turbine dynamics, joined U.S. Windpower Assoc., Burlington, MA.

15. Lawrence Sullivan, M.S. candidate, Northeast Solar Energy Center Assistantship, Solar Habitat-I demonstration.
16. Christopher Tomashofski, M.S. candidate, blade analysis and testing.
17. Jay Turnberg, M.S. candidate, Mechanical Engineering Dept. Teaching Assistantship, blade analysis and LTLT model.
18. Edward S. Van Dusen, Ph.D. candidate, Ocean Engineering, unsupported, vertical axis wind turbine analysis, owner of Composite Engineering Incorporated, Cambridge, MA.
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.
2. Michael Evans, B.S.M.E. candidate, draftsman.
3. Richard Geikie, B.S.C.E. candidate, Undergraduate Research Assistant Summer 1978.
4. Thomas Gorman, B.S. candidate in Wood Technology, Undergraduate Research Assistantship Wood Technology, wood blade construction.
5. Daniel Handman, B.S.E.C.E. candidate, Undergraduate Research Assistantship, microprocessor controller design, to join Graphic Sciences, Danbury, CT.
6. Anne Mason, B.S. candidate, Smith College, Summer Research Participation Assistantship, wind data reduction and analysis.
7. Cathy McElkinney, B.S. candidate, Smith College, Summer Research Participation Assistantship, computer analysis and data acquisition.
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

1. "Stability of Wind Power Support Structures," by A. Chajes was presented at the Annual Column Research Council Meeting, Toronto, Canada, June 1975 (published in Proceedings Column Research Council, P.B. 247 678-1975).
2. "Prefabricating Buildings Adapted to Solar and Wind Energy Utilization," by C.A. Johnson, presented at the 1975 Annual Meeting North Atlantic Region ASAE, Cornell Univ., Ithaca, NY, August 1975.
3. "Wind and Solar Thermal Combinations for Space Heating," by J.G. McGowan, W.E. Heronemus, G. Darkazalli, presented at the Tenth Intersociety Energy Conversion Conference at Newark, Del., August 1975.
4. "Switching Logic - Wind Furnace Experiment," by William E. Heronemus, et al., SH-I-07.01.001 TR/75/2, Oct. 1975.
5. "Blade Structural Design: Wind Furnace Experiment," by E.S. Van Dusen, SH-I-2.10, TR/75/3, Jan. 1976.
6. "A First Economic Analysis of the Wind Furnace," edited by W.E. Heronemus, SH-I-09.01.001, TR/76/1, Jan. 1976.
7. "Discussion of Momentum Theory for Windmills," by Forrest S. Stoddard, TR/76/2, April 1976.
8. "An Approach to Preliminary Systems Optimization of the New England Wind Furnace," by Forrest S. Stoddard, TR/76/3, April 1976.
9. "Preliminary Report on Optimizing the Windmill Rotor," by Paul Lefebvre and Duane Cromack, TR/75/4, April 1976.
10. "Field Controller for the UMass Wind Furnace," by Daniel Handman, TR/76/5, April 1976.
11. "A General Description of the Blade-Pitch Controller," by Bruce A. Caccamo, TR/76/6, April 1976.
12. "Preliminary Report - Thermal Systems - Wind Furnace Project," by Jon G. McGowan and Ghazi Darkazalli, TR/76/7, April 1976.
13. "Preliminary Report - Wind Data Collection and Analysis - Wind Furnace Project," by Frank C. Kaminsky, TR/76/8, April 1976.

14. "Dynamics of the New England Wind Furnace," by Merit P. White, TR/76/9, April 1976.
15. "Wind Tunnel Test Program of a 200-Watt, 12-Volt Wind Generator System," by F.S. Stoddard and M. Edds, TR/76/10, April 1976.
16. "Design and Installation of Heating System for UMass Solar Habitat-I," by Ward D. Wells and Jon G. McGowan, UM-WF-TR-76-10, Dec. 1976.
17. "Wind and Solar Residential Heating System: Energy and Economic Study," by Ghazi Darkazalli and Jon G. McGowan, UM-WF-TR-77-1, Jan. 1977.
18. "Three Probability Densities (Log-Normal, Gamma, and Weibull) and their Application to Modelling Average Hourly Wind Speed," by Frank Kaminsky, UM-WF-TR-77-2, Dec. 1976.
19. "Design and Operational Aspects of the UMass Wind Furnace," presented at the AWEA Conf., Boulder, CO, May 12-14, 1977, UM-WF-TR-77-3.
20. "Optimum and Near-Optimum Blade Configurations for High Speed Wind Turbines," by D.E. Cromack and P.E. Lefebvre, Proc. 1977 Annual Meeting of the American Section of the International Solar Energy Society, Orlando, Fla., June 6-10, 1977, Vol. 1, pp. 19-16 through 9-19.
21. "Four Probability Densities (Log-Normal, Gamma, Weibull, and Rayleigh) and their Application to Modelling Average Hourly Wind Speed," by F.C. Kaminsky, Proc. 1977 Annual Meeting of The American Section of the International Solar Energy Society, Orlando, Fla., June 6-10, 1977, Vol. 1, pp. 19-6 through 19-9.
22. "Analytical Performance and Economic Evaluation of Residential Wind or Wind and Solar Heating Systems," by G. Darkazalli and J.G. McGowan, Proc. 1977 Annual Meeting of the American Section of the International Solar Energy Society, Orlando, Fla., June 6-10, 1977, Vol. 1, pp. 24-20 through 24-24.
23. "Design of Hub and Pitching System for Wind Furnace I (WF-1)," C.B. Butterfield, Jr., June 1977, UM-WF-TR-77-4.
24. "Design and Operational Aspects of a 25 kW Wind Turbine Generator for Residential Heating Applications," by D.E. Cromack, W.E. Heronemus, and J.G. McGowan, presented at the 12th Inter-society Energy Conversion Engineering Conference, Washington, D.C., Aug. 28-Sept. 2, 1977.

25. "Structural Analysis of Wind Turbine Support for Wind Furnace I," by A. Chajes, Sept. 1977, UM-WF-TR-77-7.
26. "Instrumentation and Initial Experimental Testing of Solar Habitat-I," by L.S. Socha and J.G. McGowan, July 1977, UM-WF-TR-77-8.
27. "A Comparative Study of Optimized Blade Configurations for High Speed Turbines," by P.L. Lefebvre and D.E. Cromack, Aug. 1977, UM-WF-TR-77-9.
28. "The Working Drawings and Bills of Material for Wind Furnace One as Installed at Solar Habitat-I, Orchard Hill University of Massachusetts, Amherst, MA, 01003," Edited by W.E. Heronemus, Sept. 1977, UM-WF-TR-77-10.
29. "Wind Power for Space Heating," by D.E. Cromack and W.E. Heronemus, Proceedings of the 3rd Wind Energy Workshop, Washington, D.C., September 1977.
30. "New Designs and Applications of Medium Sized Wind Systems," by D.E. Cromack and J.G. McGowan, Proceedings 14th Annual Meeting, Society of Engineering Science, Lehigh Univ., Bethlehem, Pa., November 14-16, 1977.
31. "The UMass Wind Furnace Blade Design," by D.E. Cromack, Proceedings Wind Turbine Dynamic Specialists Conference, NASA Lewis Research Center, Cleveland, OH, November 16-18, 1977.
32. "A Preliminary Investigation of Three Advanced Wind Energy Systems for Residential and Farm Applications," by P.H. Sarkisian and J.G. McGowan, Jan. 1978, UM-WF-TR-78-1.
33. "Control Systems for the UMass Wind Furnace-1," by D. Handman, Jan. 1978, UM-WF-TR-78-2.
34. "Summary Proceedings - 1978 Wind Turbine Blade Workshop," edited by D.E. Cromack, Jan. 1978.
35. "Operational Aspects of the UMass Wind Furnace," by D.E. Cromack and M. Edds, Proceedings of the American Wind Energy Association National Meeting, Amarillo, Texas, March 1-4, 1978.
36. "Wind Turbine Design, Performance, and Economic Analysis," by James H. Sexton, May 1978, UM-WF-TR-78-3.
37. "A Two-Dimensional Analysis of Vertical Axis Windmills," by E.S. Van Dusen and R.H. Kirchhoff, July 1978, *M-WF-TR-78-4.
38. "Operational Evaluation of a Wind Powered Heating System," by J.G. McGowan, D.E. Cromack, M. Edds and D.C. Lewis, Proceedings of the 1978 International Solar Energy Society Meeting, Denver, Colo., Aug. 28-Sept. 2, 1978.

39. "The Flow Field Upstream of a Horizontal Axis Wind Turbine," by Koorosh Modarresi and R.H. Kirchhoff, July 1978, UM-WF-TR-78-5.
40. "Measurement of the Interaction Between the Wind and the UMASS Solar Habitat I Wind Turbine," by Paul Murphy and R.H. Kirchhoff, August 1978, UM-WF-TR-78-6.
41. "A Microprocessor Based Control System for the UMASS Wind Furnace I," by D. Handman and R. Monopoli, July 1978, UM-WF-TR-78-7.

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