1976


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

PHASE II
Final Report for the Period
Ending June 30, 1977

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PREPARED FOR THE UNITED STATES
DEPARTMENT OF ENERGY
DIVISION OF SOLAR ENERGY
UNDER CONTRACT NO. ERDA E(49-18)2365
THE WIND FURNACE (WF-1), DEC. 1976

AT SOLAR HABITAT ONE
UNIVERSITY OF MASSACHUSETTS, AMHERST

A PROJECT SPONSORED BY ERDA, NSF, USDA, U-MASS AND INDIVIDUALS CONTRIBUTING TO THE MARK SWANN ACCT.

GOAL: DEMONSTRATE A COMBINATION OF WIND ENERGY SYSTEM PLUS SOLAR COLLECTOR AND THERMAL STORAGE WHICH CAN ECONOMICALLY SAVE AT LEAST 30 BARRELS OF HEATING OIL EQUIVALENT PER RESIDENTIAL UNIT PER YEAR, SPACE AND DOMESTIC WATER HEATING.
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0. Abstract

A summary of the activities and results of a four year Wind Furnace project is given. The report emphasizes the physical nature of the Wind Furnace-One wind turbine generator and describes the various subsystems. Decisions in the design process are given: shortfalls and inadequacies in the design process are described. The educational component of the project is summarized. Comments on project management and coordination within the academic environment are given.
1. Summary

After considerable preparatory thinking and analysis it was proposed by the University of Massachusetts (Amherst) that some combination of flat plate solar collector heating system plus Wind Turbine Generator (WTG) system, using a shared low-cost thermal storage, might be competitive in many parts of the World (1972). A 32.5 ft diameter three bladed modern high speed wind turbine had already been started as an academic project, funded by gifts and an NSF Undergraduate Research Participation Grant (1973). It was determined that a very tight and heat conservant building designed and built by Professor Curtis Johnson of the Food and Agricultural Engineering Department could be made available as a test site. An NSF Windpower research grant competition was entered and funds were received to carry on in the academic research mode (1974). The University agreed to finance site work and the construction of an oversize-concrete basement at the highest point on the campus, thus creating a laboratory named The Solar Habitat.

The hybrid concept had been described and set up as a system that could be simulated on the computer for any site for which wind (speed and direction) and solar insolation data were available. Wind data for Hartford International Airport (Bradley Field) were combined with insolation data for Blue Hills, Mass. - the only useable data available at that time, recognized from the start as a misfit, but better than nothing. The early computer simulations showed the strong influence which wind wheel diameter, turbine generator rated power and the shape of the power output versus speed characteristic, the area of the solar collectors, the size of the thermal storage, the infiltration losses of the building and the number of air
changes per hour experienced by the building could have on the results. Extensive parametric analyses were made, and it was decided that the initial hardware unit would comprise:

(a) A 32.5 ft diameter windwheel driving a 25 kW generator, cut-in at 7 mph and reaching rated power at 26.1 mph. An overall WTG wind-wheel to generator output mechanical-electrical efficiency of 85% was assumed.

(b) Two hundred square feet of flat plate collector, mounted vertically (simply because the available building could accommodate that array and nothing else).

(c) A WTG axis height of 80 ft was selected originally, but later reduced to 62 ft because of concern about aesthetics - this too was a rather arbitrary choice.

(d) A down-wind, yaw-dampened WTG was decided upon in order to take advantage of centrifugal relief at a ten degree fixed blade coning angle.

(e) It was decided to use water thermal storage because it was thought that it would have more universal appeal in the prospective market than would a hot air system with rock thermal storage. Because of the indicated importance of storage size as a system parameter, it was decided to install five different tanks. It was also thought that separate tanks might be wanted for the flat plate collector system and for the WTG.

(f) It was recognized from the beginning that a number of models of the Wind Furnace existed, and that the generation of electricity, followed by degradation of that high quality energy down to relatively low quality stored hot water was not thermodynamically proper. Therefore, a mechanical churn (Mod Four) was included in the future plans for the Wind Furnace,
replacing the generator. It was also recognized that Gustav Meyer's idea (1934) of combining a wind wheel and a heat pump for heating was thermodynamically very attractive; so a heat pump model was also included in the future plans. At this time the mechanical churn shows strong potential to be more cost effective than the electric generator, but the heat pump system demands that some mechanical hardware (a variable stroke refrigeration compressor) must be developed before that model can make economic sense.

(g) It was decided that the value of a competitive system would be measured only in economic terms: which system would deliver the most useful product in a way that would cost the owner the least money. As stated earlier, each of the models waste a considerable amount of collected energy, but this has been readily accepted, provided the unit cost of useful delivered product decreased despite the waste.

The flat plate collectors and all of their associated hardware were purchased and this subsystem has performed well. The WTG was designed and built within the University. Many of the major parts were obtained as vendor supplied items, but the key parts were home-built. Engineering graduate students accomplished the design work, ordered the material and assisted in building and assembling the parts. The School of Engineering Shops accomplished all of the welding, machining and assembly work. One graduate student constructed the male mold for the blades, another one designed and built all of the tooling and did the preponderance of the work required to make four pre-production blades, then a matched set of four production blades. All of the departmental technicians and some additional research assistants helped in blade construction.
One graduate research assistant did the majority of the structural support detailing, obtained all the material and supervised the total effort of creating the support structures and its foundations.

One graduate research assistant started with a three-phase, separately excited, 31.1 kVA 1800 rpm generator, a gift to the project, and determined all of the requirements of the electrical power subsystems, obtained all the material and either procured or built the parts. It was determined in the early stage of the design - that some kind of load controller would be necessary to prevent even so simple a thing as an attached resistance heating load from overloading and thus stalling the windwheel at low wind velocities. This idea initially took the form of a switching load controller, then became a combination of series-parallel heaters plus a field controller that sensed generator rpm and adjusted field current accordingly.

One undergraduate research assistant took on the job of designing, then building the field controller, the master logic, the pitch controller and the associated power supplies.

One graduate research assistant was responsible for the mechanical engineering of the system from the top of the pole upwards. He designed the pole matcher, the main frame, the slip ring assembly, the brush blocks, the speed-up transmission, and was responsible for the overall shape and balance of the system.

Another graduate research assistant designed the hub and the blades pitching mechanism, from the d.c. motor input to a mechanical push-pull motion that pitches the blades as commanded by the pitch controller. He also designed and supervised construction of a yaw damper device which prevents excessive yawing (angular) velocity and thus prevents
unacceptable bending moments induced by gyroscopic forces.

Two graduate research assistants and two undergraduates laid down the contour lines for fairing the nacelle, decided their structural requirements and concept, then built the nacelle, along with the required tooling.

One graduate research assistant designed and built the lightning rod and the brush blocks.

Another graduate research assistant and an undergraduate designed and built the mechanical-hydraulic brake with its mechanical override.

One graduate research assistant performed all of the computer programming and simulation studies for the entire system.

Two graduate research assistants designed and built all of the thermal systems which are installed in the solar habitat and then tested and calibrated them. One more graduate research assistant designed, built and installed an integrating pyrheliometer, then took over the job of completing the design of the thermal experiment and the actual accomplishment of the heat loss measurements on the completed Solar Habitat and its subsystems.

Departmental technicians assembled the house on the foundation that was built by an outside contractor. They set up the house framing, installed the floor, wall and roof panels, installed doors and windows, and finished the house inside and outside, including trim and painting. Other technicians installed the plumbing and the electrical wiring.

One graduate research assistant and two undergraduates installed wind data collection instruments in the UMass Wind Data System, collected the resulted and assisted in their analysis.

One graduate research assistant performed dynamic analyses of the support structure and of many competitive configurations of the tower which
were considered, including a tripod tower that was thought to be more cost-effective than the steel stayed pole mast.

Two graduate research assistants and two undergraduates created a model blade testing program that used the University's 4 ft x 4 ft open-throat wind tunnel. They constructed models, tested them and started the correlation of model results with full scale results. Their efforts extended to the comparative analysis of competitive blade systems; Optimum shape versus Constant Chord, Variable Twist versus Linear Taper, Linear Twist versus Linear-Taper Variable-Twist, for example. Those results will be of great value in follow-on designs.

Two undergraduate students prepared wood carving blocks and reduced to a wooden master the team's design for a 35 ft Linear-Taper Linear-Twist blade for the next generation.

All of the supervision of analysis, design, fabrication, construction and erection, plus the administrative details required to accomplish the above was provided by faculty, coordinated by one man called the project engineer, who reported directly to the principal investigator. The paper work and accounting was done by the three secretaries of the Civil Engineering Department. The existing University facilities, Physical Plant, Purchasing and Accounting were used as required. The existing School of Engineering Shops and their competent managing professor were used continuously.

The complete Wind Furnace System at Solar Habitat One now exists, a well-instrumented test facility. Unfortunately not enough data have been collected yet to prove conclusively that the Wind Furnace concept and computer simulation were correct: those data are to be collected over the
period September 1977 through May 1978. It is thought that these conclusions can safely be recorded in summary of the work to date:

(a) The Wind Furnace One, as a wind turbine generator, has performed to its design specification, has withstood winds in excess of 100 mph and has survived lightning strikes at least in the vicinity.

(b) The idea of using blade pitch control to enhance low wind speed start-up of a 3-bladed, high speed, propeller-type machine has been verified. The automatic pitch controller works very well and is probably cost effective.

(c) Hand laminated, glass reinforced plastic blades can be very cost effective for a WTG of this size.

(d) The idea of using a load controller to enhance smoothness of operation and prevent stalling of a WTG has been proven and the hardware and method (field controller) appear to be cost effective.

(e) The stayed pole mast can be cost-effective and aesthetically pleasing as a WTG support structure.

(f) With proper design there need be no vibration or fatigue problems in a cost-effective, high speed propeller type WTG.

(g) The concept of flat plate collector plus wind hybrid heating system may not be cost effective: wind alone or flat plate collector alone, depending upon the site, will probably be better.

(h) The Mechanical Model (Mod 4) of the Wind Furnace will probably be the most cost-effective model wherever the wind system can be placed close to the thermal storage.

(i) The hot air version of the Mechanical Model, in which air is
heated mechanically and a rock bed is used for storage, as proposed by Clarence Kenney of Merton Engineering Company, is worth investigating for homes equipped with hot air heating systems.

(j) The Wind Furnace Project was a very interesting operation within the academic research arena. To some of the scholars on campus it was little other than a vocational school effort: to those who work with their hands in the university (technicians, shop mechanics, purchasing agents, secretaries) it was almost an industrial operation, too much for the institution's facilities and capabilities. For the students supported by it, it was a rare opportunity to learn and use the best of theory, then apply it to the creation of a real product: this discipline was cruelly sobering upon occasions. The opportunity seemed to be relished by all the students who participated. To the faculty who bore the responsibilities of supervision it was a mixed blessing: the need to produce hardware results to a schedule did not always rest easily on the shoulders of the participants. The pride in accomplishment, when all was done and it worked, was universal, however, and the project has had a worthwhile long-term effect on the egos and competence of those who identified with it.

To the university administration, it was a source of desired dollars and the cause for creation of a significant new laboratory. The usefulness of that laboratory in the long-term to the university now remains to be seen. To the U.S. Solar Energy Program, this project should have demonstrated clearly how much of an
impact a sizeable wind-heating program could have on oil consumption in the U.S., if the right people decide to get behind the concept. To the U.S. citizenry, this project should show how significant a contribution wind power utilization, in the near term, could be, if they decide to get on with it.

NSF and the Energy Research and Development Administration (ERDA) invested $280,000 in the two year Wind Furnace Project, for which the UMass team are more than willing to acknowledge with gratitude. Private contributions to the Mark Swann Account invested $45,000 for which we are equally grateful. The University invested $28,000 in the laboratory and the site, principally money diverted from overhead earned on the ERDA grants. The U.S.D.A. funding that supported the design and construction of the Curtis Johnson house amounted to $37,000. For that investment a successfully working and well-instrumented laboratory and demonstration site has been built and set to work.

Four doctoral candidates, 15 master's candidates and 9 undergraduates have received substantial support to date towards the cost of their education, and 10 professors have enjoyed some support of their research interests. It is the opinion of the principal investigator, at least, that those who invested have received good value, and that much more value is yet to be derived if the university is now able to use effectively that which has been erected.
2. The Wind Furnace Concept and the Trial System

In 1934 Gustav Meyer included in his book WINDKRAFT (FACHBUCHVERLAG LEIPZIG) the idea that the improved windmill and the then very new heat pump might be combined to create an effective space and/or water heating system. In 1972 Heronemus and McGowan at the University of Massachusetts asked Darkazalli to work on a project investigating several possibilities for solar and/or wind powered heating of a new secondary school building then under construction in Amherst. One school had already been built to those plans, so two nearly identical possibilities existed.

The same year Stoddard at Amherst completed his first strip theory for aerodynamic analysis of wind wheels, Van Dusen at Amherst showed how his rowing shell strength analysis and its supporting computer programs could be used to design Glass Reinforced Plastic (GRP) blades, and Atwater was put to work laying out blade stations based on the Canadian Brace Institute's 32.5 ft. diam. 3-bladed wind wheel. Cromack indicated a strong interest in the project and said he could use his open-throat wind tunnel to compare scale model wind wheels. Mark Swann gave Heronemus a sizeable sum of money to pursue alternative energy concepts, Kirchhoff made available two 10 week summer appointments in his Undergraduate Research Participation Grant from NSF, and Antoon and Clement Cheung, two aeronautical engineers, joined the effort.

The first goal was the design and construction of a 32.5 ft. diam. wind turbine. Heronemus, Djaferis and Poole calculated the productivity of the wind turbine in both the raw energy mode and in Heronemus' hydrogen-link storage sub-system configuration at many sites across the country and for various islands. The results, compared against Darkazalli's early results
suggested that one machine of this size could produce enough energy during the heating season at many sites to supply 60% or more of the heating and hot water required for an ASHRAE well-insulated house at that site.

Many on-lookers had already suggested the concept that flat plate solar collectors and a wind powered heater might take turns (bright sun/no wind versus dull sky/good wind) at providing heating, and Darkazalli's results corroborated that theory. Therefore, the concept of the hybrid system, wind turbine plus solar flat plate collectors, emerged as the Wind Furnace. It was called the NEWF - the New England Wind Furnace - until ERDA money was accepted, at which time the name was changed to the more general - Wind Furnace.

The second goal of the concept was rooted in economics. It was clear that electricity produced by a wind system, firmed up with chemical storage batteries, would be competitive only under the most unusual circumstances. It was also clear that electric costs for the heating of space and water are considerably more than normal electric costs in the non-electric heated home, and that a storage system considerably less expensive than batteries could store heat. It was decided to use a liquid system because most New England buildings use liquid heating (baseboard water).

The size of the thermal storage was shown to be a major parameter. All of the computer simulations showed considerable overflow or wastage of windpower over an entire year, but this was accepted because the economics still favored the system that provided only heating. The UMass team, concerned about the global heating problem associated with energy practices that convert matter into heat, adopted the attitude that wastage of solar-provided energy was entirely different from wastage of fossil, fission or fusion-provided energy, from many points of view. It was to let simple
economics determine which wind furnace system was best.

The heat pump of Gustav Meyer was still in the minds of the team, but no one seemed to be able to show that its addition to the system would be economically viable. It was agreed, repeatedly, that if there were some practical way of directly coupling the heat pump to the wind wheel, and some way of storing both heat and cold, or perhaps a flywheel storage of reasonable cost between wind wheel and heat pump compressor, then perhaps Meyer's original concept might become viable. At the time of this writing, Curtis Johnson may have a concept that will integrate the heat pump effectively provided Heronemus' variable stroke compressor can be built at reasonable cost: but all that remains to be demonstrated.

The mechanical churn model, the large scale Joule-Thompson "mechanical equivalent of heat" physics lab experiment, was identified early as a strong contender for the best model of the Wind Furnace. That belief has been substantiated during the project, and as of August 1977, a cost effective set of Model Four hardware has been demonstrated on the diesel powered bench test rig. The mechanical systems of the first Wind Furnace wind machine (WF-1) were compromised to some extent to make possible the easy changeover from an electrical generator version to a down-pole mechanical drive connected to a churn.

The Wind Furnace concept was entered into an R & D competition which ERDA authorized the Agricultural Research Service to conduct for wind systems up to 50 kW a size thought to be useful for rural or isolated premises. A two year program sized at $232,000 was proposed: an initial grant of $130,000 was made, followed by a second year's grant of $150,000.
A policy as to the nature of this sizeable experimental system had to be established. The first thought was to demonstrate in the first model, real hardware at the lowest possible system cost. On the other hand, it was thought to be unwise to take any chance of compromising the wind systems capability by purchasing or building anything that was of marginal quality, even though low in cost. There was also the realization that the parts and pieces being designed at UMass were in most instances novel and would be the first product of that nature produced by recently graduated engineers, and there was, therefore, a need to be conservative with factors of safety and design assumptions. The design process required a careful balancing of the need to succeed with the first of a brand new product with the need to keep costs as low as possible.

The path out of the dilemma was that which was originally proposed: insure that the program scope was large enough and timed so that each participant would produce two designs; the first one for WF-1, then his own improved design for a second generation machine. Support for that path was not forthcoming, however, so some of the experienced design team members have gone on their ways before their many excellent design improvement ideas could be placed on paper. WF-1 represents a continued compromise between those conflicting demands. Most of the parts and the raw materials were purchased in very small lots at retail prices, and all of the machinery and fabricating was first-time, custom-built work.

The original Wind Furnace concept centered on that which could be done at a residence by the owner of that residence. As the project progressed however, it became apparent that multiples of that machine, in vertical planar arrays, might do an excellent job for multiple unit dwellings,
institutional buildings, shopping centers and small industrial/commercial installations. The concept of 3, 5, 10, 16 or even more windwheels, driving either electric generation or Model-4 water-brake churns has been looked at in some detail, and the concept appears to be sound. One advantage held by wind systems over the photo-thermal solar systems is this opportunity to expand in vertical planes, and the higher they go, the richer this wind resource becomes. So, the Wind Furnace concept, on paper, has grown to multiple unit systems, and by the work of Heronemus has grown to very large scale. The Urban Furnace concept is envisioned, wherein large urban areas would be supplied part of their heating needs from large numbers of electricity-generating arrays of wind turbines located around the urban area, either on land or afloat. Dr. Lilljidahl of the U.S. Dept. of Agriculture has said that there are at least 3 million rural or isolated residential premises where the Wind Furnace concept might be applied. Our own analyses of the heating (alone) requirements of farms tells us that arrays of 3 to 10 wind systems could be appropriate on many farms. The Wind Furnace concept could be reduced to commercially available hardware in 18 to 24 months. The expected sales price could be such that millions of units could be sold. The impact of 3 million Wind Furnace installations in the United States would exceed the petroleum-saving effect of one hundred percent consumption of all remaining natural U.S. uranium ore used in the LWR process. The impact of 3 million individually owned Wind Furnaces on the existing energy industry of this country (and the World) would constitute a potential that could never be matched by governmental regulations of that industry.
3. The Habitat

When the Wind Furnace Project was first proposed to ERDA for additional funding, it was thought that a laboratory space within the School of Engineering would be heated thereby. Professor Ambs pointed out the existence of the prefabricated and yet unassembled energy conservant house designed and built by Professor Curtis Johnson in the Dept. of Food and Agricultural Engineering. Negotiations between individuals, departments and schools lead to a statement of willingness in the College of Food and Natural Resources to join Engineering and contribute the Johnson House for a period of at least three years. From the decision point onward there was complete and continuing harmony in the joint effort, established and maintained by the project engineer and a comprehensive set of interface control drawings established via conferences and conversations. The Habitat is in reality more than the Johnson Building, however: it is also an oversized concrete basement laboratory, a very fine set of instrumentation, an excellent site with improved grounds, and a permanent line item in any future university budget (perhaps).

The habitat building itself has been described in great detail in the several technical reports referred at the end of this section. One major flaw exists in Habitat construction, and the method of correction is not yet clear. The design called for screened louvers at ceiling height, all around the house, which could be opened in the summer to acquire cross-ventilation. For lack of money, they were not built in to the house and their need has been sorely felt during the hot summer days of 1977. None of the windows in the house can be opened for ventilation, and ventilation through opened doors is inadequate.
Few comments have been received to date regarding replication of the house. It was designed to be transportable in sections over the highway following factory construction, and it was designed specifically as a substitute for the inadequately insulated mobile homes that comprise a large fraction of today's house output. It is hoped that one or more companies will take seriously the many splendid features of this house and its overall remarkable thermal properties, and put it into production. It would be ideally suited for Wind Furnace heating if built and erected in its original configuration concept, a timber house atop a treated timber foundation enclosing a crawl space. The required thermal storage and a small equipment space could easily be built under the house in that crawl space, and the Wind Furnace could be erected close to the structure as done in Amherst.
4. **The Solar Collector, Thermal and Storage Systems**

The extent of the solar collector system was decided quite arbitrarily: how many square feet of collector, and in what unit size, could be fastened to the Johnson House without spoiling its appearance? Ten collector units of the size being made in 1975 by Dixon Energy Systems, Inc., seemed to be exactly correct, their pedigree was excellent (based on actual, careful testing) and the price was right. A heat exchanger, pumping system Rho-Sigma\(^\text{c}\) control and the necessary piping were integrated and arranged so that the collectors could discharge their heated water to any of several storage tanks.

The vertical arrangement of the collectors was chosen simply to match the home. A complete new roof line would have been required to place the collectors on the roof, requiring a change in shape of the house and considerable expenditure. A sloping wall type array separated from the house wall was considered, but rejected because of added expense plus the conclusion that the vertical orientation was really not that bad when maximized heating season input was the goal. All-in-all, the solar collector system is a standard liquid (anti-freeze) type system except for the added complexity of extra piping and instrumentation required.

The habitat was fitted with three distinct heating systems:

(a) baseboard convectors, arranged in three zones, each with its thermostat and pump.

(b) baseboard electric, arranged in three equal electric loads, substitutable by switching from the resistance heating elements immersed in the liquid storage.
(c) peripheral-slot hot-air heating with the gas fired furnace blowing heated air down under the floor, spreading it out toward the slot all around the periphery of the floor.

The third system is the one that was to have heated the Johnson House and is now used as the fossil fueled back-up or auxiliary space heating system for the habitat.

Baseboard electric was installed to complete the Model One Wind Furnace in which heating electricity generated by the wind turbine is fed directly into baseboard heaters whenever the house wants heating. This model was at one time thought to be the least expensive to install, but the rather serious mismatch between available wind and required heating led to its deemphasis and the placing of more faith in the systems with storage.

Baseboard convector heating is thought to be the best of the heating systems when combined with reasonable thermal storage.

Three different schemes for insulating and lining the concrete water storage tanks were tried, and none was truly successful. The one scheme for waterproofing a concrete tank by installed troweled-on neoprene to the interior proved a near disaster: the task of applying the material was very tedious and extreme safety precautions were required while it was being done. In retrospect, the storage tanks should not have been cast with one side common with the foundation, and a vinyl or other fabric pool type of liner inside block construction should probably have been used. It has been noticed recently that an excellent 2000 gal. storage tank has been constructed from standard sheets of exterior grade plywood, 2 in x 4 in lumber, a vinyl pool-type linear and a wrapping of fiberglass insulation.
bats, all enclosed with an external sheathing of sheet rock or Homasote(R). Unfortunately, the concrete walls of the Solar Habitat One storage tanks very effectively conduct heat to the surrounding earth.

The ideal thermal storage may be one built essentially free-standing in a compartment external to the basement, a compartment which can be ventilated to the basement during the heating season, or, ventilated outboard to the atmosphere during the summer.

It has been shown that vapor rising from an open-top storage tank can be a problem, and that the thermal storage tank top should be essentially vapor tight. It was also shown that Amherst water, when allowed to sit for a few weeks in a thermal storage tank, would produce a substantial bloom of algae and other heat exchanger and pump clogging flora. Chlorination stopped that growth, but when used to excess the chlorine caused a few other problems.

The solar collector system was carefully instrumented and calibrated and it has performed very well.

The entire Habitat was carefully instrumented and a series of tests were performed to measure all elements of heat loss from the house. Those tests corroborated Curtis Johnson's design assumption: the Habitat requires only about one-half the heating required by the ASHRAE well-insulated standard house.

A Fluke data logging system was obtained with grant funds, and a new level of large-scale data collection and experimentation was established therewith. This system was energized from the local WMECO lighting mains, and during a period of electrical storms in August, 1977, lightning entered the Habitat via the electric power mains and caused
major damage to the Fluke system. The wind turbine generator was protected from lightning strikes at that time by its lightning rod system.

The details of the numerous and conclusive tests of thermal systems and their design and fabrication are given in the published technical reports.
5. The Wind Machine

5.0 General

The words "wind machine" are used here because this is not only a "wind turbine generator" (WTG in ERDA parlance) but also a wind turbine mechanical shaft work deliverer. WTGE, for wind turbine generator/electrical, and WTGM for wind turbine generator/mechanical might be used, but those are no more appropriate than wind machine.

This wind machine is of the modern, high-speed propeller type fitted with three blades, designed to operate at a tip-speed ratio of 7.5 and to achieve a power coefficient of 0.42 at design condition. It is a down wind machine with ten degree static blade coning angles. The windshaft's rotation, 167 rpm at rated wind speed (26.1 mph) and wind wheel power (50 horsepower), is geared up by a ratio of 11:1 in two stages of speed increases, so that the generator will turn at 1800 rpm at rated conditions.

The second stage speed-up drives a three-phase synchronous generator which produces variable voltage, variable frequency power between a cut-in rotational speed of about 40 rpm and rated rpm. When the wind velocity exceeds 26.1 mph, the machine is governed on rpm, being allowed an upward excursion to 180 rpm by that governing. The governor (pitch controller) adjusts the pitch of the blades to prevent speeds in excess of 180 rpm. That same pitch controller also holds the blade pitch angle at 40° when the machine is standing idle waiting for the breeze to freshen. When the wind reaches a little over 6 mph and holds, or continues to rise, the windwheel will start, accelerate to about 30 rpm, then the blades pitch quickly to about -60° for operation at maximum power coefficient anywhere between 30 rpm and rated 167 rpm.
The wind machine, when driving a generator, is protected from overload stall-out by a field controller which limits the generator output power to a value slightly below that which the wind wheel is capable of extracting from the wind. When operating in the mechanical churn mode (Mod 4), the driven device will have a cube law power characteristic of the same shape as the output characteristics of the wind wheel, so control will be automatic except for start-up and overload feather.

The wind machine is statically balanced about the vertical axis around which it yaws (turns in azimuth). The blades themselves serve as the machine's wind vane, and once started to rotate, they will pull the machine quickly to a down-wind position and thereafter will follow shifts in wind direction with ease.

The machine sits atop a steel pipe stayed-pole mast with the rotor axis 65 ft above ground. The four cable stays are preloaded in tension to prevent any one from going slack when off wind. This support system experiences one critical speed (wind wheel-support system frequency resonance) between cut-in and rated speed, but has shown no unsatisfactory motion at that speed. Because the stays were attached to the pole about 15 ft below the top, the upper portion of the pole with the machine will move as a cantilever system, and excursions can be seen under certain circumstances. No motion has been excessive. The machine is remarkably quiet when operating at proper pitch setting. The support system is free from noise of any detectable type save the occasional clanking of the safety climbing guide wire that runs down the pole to the bottom rungs.

The wind machine is enclosed in a large faired nacelle made from glass reinforced plastic. It provides no strength to the wind machine except
where it supports the lightning rod. The size and shape of the nacelle were strongly influenced by the need for the machine to work in either the electrical generator mode or in the mechanical-shaft to ground Mod-4 mode. Despite its size and somewhat unusual shape, the nacelle does not seem to be objectionable in appearance, and its sizeable interior has made top-of-pole maintenance excursions rather pleasant. A second model of this machine would have a much smaller nacelle. The spinner portion of the nacelle is streamlined, in the wrong direction from a fluid flow point of view, but the shape seems to be appropriate to the eye.

The entire wind machine with blades and nacelle in place weighed 2300 lbs. Hindsight has suggested that at least 1000 of those pounds could be shed in the second model of the same size machine.

The blades were laminated from glass reinforced plastic and the blade stocks or spindles were then covered inside and out with steel. Roller bearing sets carry each of the blades. The design called for the aerodynamic axis, control axis and mass axis to be coincident, and this seems to have been achieved. The spar-stock of the blades is a monolithic lamination and the skin is a separate, vacuum bagged and squiegeed, high quality lamination.

The controllers are located down in the basement laboratory to make them easily accessible for this experimental program: in a second model they would be located up in the nacelle. Space and ballast weight were also allowed in the nacelle for an auxiliary power battery and a charging system.

Main power is carried across the yaw axis via slip rings and brushes. A large number of instrumentation and control slip ring-brush combinations were also provided in this first model. A very large graphite lightning
rod brush is rigged to ride on the steel main frame, wiping the pole matcher flange, providing lightning rod continuity to ground.

The entire machine was assembled in the shop without blades. Blades were earlier assumed into the hub, lying with its windshaft axis vertical, and were then removed. The entire machine was connected via a torsion meter to the Power Take off of a large tractor diesel engine in the laboratory, run-in and calibrated for mechanical and electrical losses. An overall mechanical-electrical efficiency of 85%, between windshaft and generator output, was measured, reproducibly - a remarkable and welcome result, exactly equal to the value assumed when the design was started.

The entire machine was rolled over on its side and bolted to the top flange of the pole. The pole and machine were then hinged up into the air using a crane. It was originally planned to design and build a telephone pole A-frame lifting rig which would have permitted brawn power erection of the entire system, but resources and time did not permit completion of that subsystem. A very large portable servicing platform can be erected at the pole top, piece by piece, and has been used twice. One cannot reach the pitching linkages inside the spinner from that platform however. In accordance with Murphy's Law, the first casualty experienced by the machine occurred inside that spinning nacelle. The Amherst Fire Department Hook and Ladder came to the rescue, and the loosened piece was tightened back in place in short order.

5.1 The Support Structure

It was decided to investigate the stayed pole mast as well as three-legged and four-legged towers. Considerable interest was taken in the
centrifugally cast concrete pole (stayless) support selected by Grumman for their first Windstream 25(R), but the cost seemed to be too great.

A search of the literature revealed very little pertaining to the design, strength or stability of stayed pole masts. The U.S. Navy Design Data were available, but that did not include theory. It was decided to take advantage of this opportunity and build the pole mast so that it could be observed working in a perfect ball and socket bottom end condition, then in a pinned bottom end configuration. The ball and socket were quite expensive, but the resulting contribution to the literature was worth it.

From a fear that somehow or other the blades might spring back into the wind and foul a stay, the stay connection point was ordered placed below the blade-swept circle. The decision then controlled the rest of the design which became much heavier and was characterized by a much lower first mode natural frequency than would have been the case with the stays carried all the way to the pole top. From a combination of aesthetic considerations and limitations on space between the Habitat eaves and the desired pole location (the tunnel leading from the basement to the center of the tower foundation was placed when the house foundation was poured, long before the support structure details became finalized, a rather steep angle was selected for the guys. The appearance of the resulting geometry has been ruled as "acceptable," "beautiful," "statuesque," by observers, so those choices weren't all wrong.

Ten inch steel pipe was used in considerable quantity for stanchions as well as steam and water piping in older mill buildings, and a large supply at ten cents per pound was found in Quincy, Ma. In retrospect, eight
inch pipe would probably have sufficed, but that strong fear of failure was particularly present as the support structure was being designed. Very generous wire rope stays were made up from standard commercial components, including turn buckles, clevises and rings. The stays were calculated to a thousandth of an inch in length: each piece of the support structure went into place without any misfit or adjustment of any kind, a full year after all parts were available. Pretension was set in each stay using a torque wrench rig, then the turn buckles were covered to prevent undesired adjustments thereto. A rat guard was fitted twelve feet above ground around the pole following a Saturday night attempt by a hyperactive undergraduate to climb to the top.

Oversize deadweight anchors were cast in forms, and the rather complicated central foundation which had to straddle the tunnel like a bridge was cast in place.

A second model of the stayed pole mast would extend the attachment for the stays all the way to the pole top, use three instead of four stays, have only one turn buckle, use concrete dead-man anchors instead of deadweight anchors, and have a simplified central foundation and a fixed end of pole in that foundation. Eight inch pipe would be used rather than ten inch pipe, and perhaps a 65 ft. Class I wood pole would be used if weight comes down to 1300 pounds and nacelle size comes down to 60% the diameter of that of the first model. The cost of the support structure and its installation must be reduced significantly in a production-line wind furnace.

5.2 The Windwheel

The windwheel was started as an almost complete copy of that designed
and built by the Brace Institute for the 50 hp wind pumper that they operated at Barbados, except that it was decided early on that a pitch controlled windwheel was wanted for the first UMass machine. One reason for that decision was the problem that Oklahoma State University had with the Brace blades: they could not get them to start up readily and smoothly, so they abandoned them and went back to the multi-bladed configuration. Another reason was a preliminary analysis which suggested that vibration and excessive noise could be experienced with this kind of high-speed windwheel if required to operate in a fixed pitch mode. The compelling reason, however, lies in the argument that one could always evaluate a controlled pitch windwheel in a fixed pitch mode, but one could in no way evaluate controlled pitch operation of a fixed pitch windwheel. The choice evoked considerable ERDA criticism, but UMass was permitted to continue with this design. Experimental results reinforce the wisdom of that choice.

Early in 1972, long before Wilson and Lissaman published their aerodynamics report, Stoddard set up a computerized strip theory analysis for blade performance based on his earlier helicopter engineering experience. That theory reproduced the observed Brace Institute experimental results, so considerable confidence was felt in the design. Within another twelve months Stoddard and Edds, working in the wind tunnel using a 200 W Wincharger(R) as a test device, were able to again confirm experimentally those strip theory methods and results. Later Lefebvre re-confirmed that theory and the subsequent Wilson and Lissaman computer program, using a family of small blades, special hubs and a small prony brake test rig. It was during the Stoddard-Edds testing of the Wincharger that the need for the load controller was also demonstrated.
the slightest bit of excess load applied to the operating Wincharger, load requiring power in excess of that which the windwheel could extract from the oncoming wind, would stop the rotor.

So the shape and characteristics of the blades were set. Atwater and Van Dusen laid out full scale sections, and a hollow, mahogany veneer male master blade with aluminum trailing edge was built, minus the stock. Stoddard then took over the job of conceptualizing, designing and building tools, molds and fixtures in which blades could be produced. There were several false starts and the Mark Swann account paid for considerable resin and glass. Then the ideas fell together and three good blades (but without stocks) were produced. Steel stocks were designed and material purchased: but the design simply didn't look right even though it calculated well. Heronemus proposed a concept for making a monolithic spar-stock, laminate, and after some considerable discussion, it was adopted.

A whole new set of spar-stock tooling and assembly jigging was required, together with rubber bag work that no one here had ever done before, and the job took on the ominous features of the infinite sink. But thanks to the fortitude of Stoddard it was finally furnished - the Van Dusens, father and son, furnishing a major assist - and one day the first of four new blades had been laminated and cured. It was a thing of beauty, and three more followed soon despite the exhaustion of the key man. Then the steel was applied to the stock, the trailing edges were sealed and a set of four blades were statically balanced. Cromack took one and designed and executed a classical static deflection test: observed results matched Van Dusen's predictions with great accuracy. Three blades and one spare were
ready for the windwheel hub and the rest of the machine.

Much was learned about aerodynamic theory, about resins and reinforcements, and, sadly, about how some of the solvents and vehicles used in the laminating processes could cause severe skin rash and stomach disorders. At one critical point in this basic operation it was commented that the major ingredient that went into those blades was "love": that comment will never be forgotten. They now flash through the air in splendid beauty with the sun able to create a translucent amber color as it shines through them.

5.3 Electrical Power and Control

When the design of the windmill was first started it was planned to purchase a war surplus high speed ac generator (400 Hz) and use a three-stage transmission to bring windshaft speed up to about 5000 rpm. However, when the generator was ordered, there was none remaining in stock. Then Mr. Russell Wolfe, President of MKS Instruments, Inc., offered to trade a brand new LIMA ELECTRIC 33.1 kVA 1800 rpm three phase self excited (SER) synchronous generator for our first three blades (the ones without stocks). The offer was quickly accepted, recognized as very generous to UMass, and the design of the electrical power system was tied squarely to that machine. Michael Edds and Dr. Sheckels took over. Very little could be found in the literature pertaining to the part-speed, part-load, under-frequency characteristics of a three phase synchronous generator. The manufacturer could supply nothing: a synchronous generator is supposed to be operated only at synchronous speed! The new machine was set up in the electrical machinery lab, driven by a 15 kW dc motor, and the wealth of instruments and equipment available in that lab were brought to bear. Everything that could be learned
within the limitations of the drive motor and output dynamometer was learned: the complete set of results could not be had until the machine was driven in the diesel bench test rig.

It had been thought that a stepping switch type of load controller would be required to prevent overloading and stalling. It was soon decided, that spare electric water heater elements could be purchased in an adequate variety of sizes to make such a series-parallel switching operation rather simple. But more work suggested that a fixed load could be controlled with a rather simple field controller inserted into the self-excited feature of the machine, converting it essentially into a controlled externally excited machine. The analyses looked very good, and some experiments confirmed the analytical results. Dan Handman and Dr. Monopoli then assisted in the design of the controller theory, converted that into a hardware design, and built the controller in time for it to be tested when the machine was driven by the diesel. The resultant field controller has worked extremely well since its first run.

The spare electric water heater elements were integrated with piping, flanges, gaskets and wire, into three identical heater trees that could be immersed in any one of the storage tanks. A total of 25 kW of heaters, divided evenly into three identical sets, one for each phase of the generator's output, were installed. Later on, after the designed capability and overload capability of the gift generator were more fully understood, it was realized that as many as 35 kW of heaters might safely have been installed.

The baseboard electric heaters were also purchased, modified and installed to present the same identical three resistance loads to the generator.
as presented by the immersed heaters.

The brushes, slip rings and their required insulation were all calculated and appropriate components were purchased. The down-pole power wiring and the in-laboratory wiring was designed and installed. A battery back-up power system was installed for all controllers and instruments, but their primary power was taken from the utility mains. This proved to be costly because lightning entered the instruments via the utility power connection and caused considerable and expensive damage.

Two other controllers were required: the pitch controller and the Master Logic, and Handman designed, built and tested them. The first pitch controller was designed to control on tip speed ratio. It was initially thought that a pattern of tip speed ratio varying between field cut-in wind speed and rated wind speed would be appropriate to maximize productivity. After that controller had been built and packaged, it was decided that control on rotor rpm would be safer in the control region between rated wind speed and furling wind speed (control Region 3). It was also decided that one value of tip speed ratio, namely 7.5, should apply across the entire wind speed spectrum between cut-in and rated, and that control on rpm would be simple for Region 2 as well. For Region 1, start-up, it was decided that the windwheel should be standing at the pitch angle for maximum torque coefficient whenever waiting for a wind (40° Pitch Angle), and that there should be no adjustment to pitch until the windwheel had been able to acquire a certain amount of inertia, enough to withstand the counter torque associated with cutting in the field. This condition was estimated to occur between 30 and 40 rpm. Once that speed was reached, however, the pitch controller
should quickly drive the pitch to its value for optimum performance (-6° Pitch Angle).

This change in control philosophy required a major rebuilding of the Pitch Controller - the first one was never really given a fair test. Handman took on the redesign job and built the bread board. The bread board was not secure or reproducible enough to entrust long-term automatic control to it. In July, 1977, the completed and properly packaged new Pitch Control on RPM Controller was in place, automatic operation was resumed, and all seems to be well. All major design parameters were built into this newest controller in such a way that adjustments in value can be made with trimmers. The rpm boundaries of the several control regions can be changed, cut-in speed can be changed and furling speed can be changed. It has thus been possible to evaluate at relatively low wind speeds the ability of the controller to prevent a high wind-speed runaway.

5.4 The Wind Furnace Mechanical Subsystems

5.4.1 The Pole Matcher

The Pole Matcher is that upward extension of the support structure about which the entire aloft system rotates in azimuth (yaws) and across which the slip rings and brushes provide rotatable or sliding continuity in the electrical circuits. The pole matcher is fitted with two bearings, a tapered roller bearing at the top which carries the entire weight of the aloft system with minimal friction, and the skirt bearing at the bottom, a plastic bearing against which the main frame wipes or leans when it reacts to windwheel trust or nacelle drag. This pole matcher was made with a very large inside diameter
so that a vertical line shaft and universal joint, as well as the offset of the hypoid pinion shaft of the first stage transmission could fit in the Mod 4 configuration. The steel pipe vertical case of the pole matcher was covered with laminated glass and epoxy resin into which stepped rings and milled slots were then machined to carry the slip rings and their lead wires. When completed the Pole Matcher was a very substantial home-made slip ring assembly.

The slip rings were tediously machined from a billet of naval bearing bronze. Commercial slip rings of a size large enough to fit outside of the very large diameter vertical pipe were available only at prohibitive cost: but the home made slip rings were not inexpensive either. The slip rings are grossly oversized: it was decided not to "waste" the material already paid for, and it was decided not to take a chance on brazed and machined copper base bands which would probably have been adequate at one-tenth the cost. The machining was a work of perfection and the brushes have always tracked without friction or wear.

The brushes were purchased from a vendor complete with brush holders and pigtails. The brush holders were press-fit located in holes boared in the hand-made glass and epoxy brush holder pans, then secured with a little epoxy, and those subassemblies were bolted into the openings left for them in the main frame. The entire assembly resting on the tapered roller bearing at the top of the pole matcher could be rotated in yaw with a few ounces of push on the bow of the nacelle. A large diameter special nut holds the main frame down on the pole matcher, the nut rubbing on a Bos Bronze washer.
5.4.2 The Main Frame (Drawing p. 35)

The Main Frame is a simple box-beam steel foundation welded from pieces of 3/16 in. thick steel plate. It was designed to withstand the various bending and shear loads which thrust and drag can impose on it. All parts of it are very strong compared against need, and the heavy steel gives no indication of deflection under any loading. It was designed so that the main axle housing, the rear axle assembly which provides the first stage speed-up could effectively serve as the top flange of the beam. A second model of the Main Frame would call for a much lighter, less expensive but equally stiff structure.

5.4.3 The Hub and Windshaft (Drawing p. 36)

After considerable debate, primarily because of predicted cost and lack of positive knowledge of expected pitching moments, it was decided to carry the blade stocks in pairs of top-quality tapered roller bearings, and to make those stocks a full inch larger in diameter than required by calculation. Experience has shown the ample stocks and bearings to be beautiful in service but far more expensive than they needed to be. Experience has also shown the blade pitching moments, including those caused by friction of blade stock in its bearings, to be one order of magnitude smaller than those for which the system was designed: Again, much less weight and cost would suffice here.

The hub is a machined steel weldment made from pipe and flat plate. It was machined and balanced to a high degree. The three blade stock bearing barrels are supported by gussets which also provide working surfaces for the pitch changing mechanism. These blade stock bearing barrels load on to
NOTE:
1. MATERIAL IS STEEL
2. ALL WELDED CONSTRUCTION
an axially arranged length of pipe which serves to tie the entire structure together and provides axial support and alignment for the pitch changing linkage.

There is one major defect in this design which should not be repeated. To save cost of bearings and tooling it was decided to make the inner and outer bearing on each stock of the same diameter. The result is a rather long parallel stock subassembly which must be fed into the barrel with exact alignment or binding will occur. This results in very lengthy periods of time for blade insertion. A smaller diameter inner bearing and stepped boring could have prevented that.

The windshaft is the wheel hub and axle of the rear axle assembly of a one-ton truck. A 5/8 in. diameter axial hole was rifle bored down the soft center of the axle to carry the pitch controlling axial motion across the rotating windwheel to main frame boundary. This windshaft was accepted after a prolonged comparison between a home-built two stage speed up drive and a drive whose first stage is the rear axle assembly running backwards. Economics at that time clearly favored the rear axle assembly. It was recognized that the axle windshaft would be the weak point in the entire drive, but a factor of safety of 2.4 was used on the yield strength of axle material when loaded with the rated power torque. This was accepted, however in later months the strength (or alleged lack of it) of that hollow small diameter axle became the key element in a loss of nerve which kept the machine from operating for three long months. A second model windmachine would probably not use an automotive rear axle assembly in its drive train.
5.4.4 The First Stage Speed-Up Transmission (Drawings pgs. 39, 40)

The rear axle assembly of a one ton Ford truck was purchased and modified for use as a 4.88 to 1.0 ratio speed-up in the first stage of the windmachine drive. It is driven backwards from the wheel to the differential input pinion. The differential has been locked and the other axle and most of the other axle housing removed. The retained axle housing is clamped to the top of the main frame so that it is effective in strength and rigidity of that structural part. The pinion shaft housing tube was modified by the addition of a laminated and bonded epoxy and glass flange to which the lube case of the second stage speed up fastens in a flat gasketed oil-tight joint. That flange was built somewhat hastily and has permitted some oil to leak out. The standard compression gasket between the differential housing and its cover plate has leaked rather badly and has required replacement.

When tested on the diesel bench test rig this part of the transmission seemed to absorb about 7 hp of windshaft power at rated speed, all of which has to be given up as heat lost first to the lubricant, then to the housing, then to ambient air. Out of concern for this heat and the possibility that it might degrade the differential housing lubrication, an air inlet scoop and directing duct were built into the bottom of the nacelle and outlets were cut into the bulkhead between the stationary nacelle and the spinning nacelle.

The run-in given to the system on the bench test rig reduced markedly the break-out torque of the transmission. It would appear that this run-in polished the gears and faced up the bearings in a most satisfactory manner.
A machined steel tube, designed primarily as a housing and support for the pitching drive, was press-fitted into the sawed-off end of the removed axle housing, then secured to the axle housing with substantial tack welds. That tube, acting as an integral part of the axle housing, completes the structural flange across the top of the main frame.

The brake drum, brake shoes and hydraulic/mechanical actuating mechanism were retained on the windshaft end of the rear axle housing and were used for awhile as a mechanically actuated or centrifugally tripped spring-actuated brake. The spring loading system was not quite able to hold the shoes against the drum tightly enough to prevent rotation, so it was removed. Because this "wheel" rotates in the direction of backing-up if installed in a truck as intended, the star wheel brake adjuster slowly but surely tightened up the brake to the point where it finally stopped the windmill. This second casualty to the heating system was corrected at the expense of cutting an access hole in the steel of the main frame. At that point it had been demonstrated that the feathered windwheel would turn no more than a few degrees in a very strong wind, and even then it would rotate in a very slow and erratic mode, so the entire brake system was abandoned in favor of feathering. The centrifugal overspeed trip mechanism was modified to trip a switch which would override all the control signals to the pitching mechanism and cause it to drive the blades to the full feather stops. Reset from full feather is possible only by climbing the tower and resetting. This feature was incorporated deliberately in this experimental machine to encourage a thorough inspection of circumstances following an emergency feathering: it would not be tolerated in a production machine. Some experts have decried the lack
of a positive brake, however WF-1 gets along well without one.

5.4.5 The Second Stage Speed-up Transmission (Drawing p. 43)

The second stage speed up is a fabricated silent chain drive contained inside a sealed lube case which provides continuous splash lubrication of the sprockets, chain and the outboard steady bearings housed inside that case. One outboard bearing is fitted at the pinion shaft end and a bearing is fitted on each side of the case at the generator end with a flexible coupling fitted between the generator shaft and the shaft inside the driven sprocket inside the lube case. This drive was very generously sized - it is perhaps twice as strong as need be. It required precise alignment before it would track well. Once that alignment was achieved and maintained it tracks beautifully and quietly.

The differential pinion end presented the most difficult design and construction tasks because some positive lub seal joint at the differential housing/lube case boundary was required, and a special spline had to be broached into the short shaft extension that mates to the pinion shaft. The carefully machined spline was severely damaged at one point and the damage was not discovered until the chain decided to growl and jump off the sprocket teeth. A new part and careful realignment removed that problem. The pinion shaft extension pierces the outboard face of the lube case via an oil seal to provide a drive for the control tachometer. This constitutes a potential lubricant leakage point but could not be easily avoided.

The generator shaft was isolated from the extension shaft in the lube case with a flexible coupling simply because the generator shaft as received had a .005 inch run out, and the second stage chain drive would not tolerate
the resulting wobble without a growl. Thus two extra bearings were installed at the generator end. The lube case is made from sheet iron welded at the corners, and it developed several tiny but annoying leaks in those welds after three months' operation. They were closed by peening. There is a sight glass in the lube case, a filling hole and a drain hole.

The lube case and second stage speed up are carried structurally on pedestal foundations that reach outward from the left side of the main frame weldment. Their location was established by the shape of the rear axle assembly differential housing and its pinion shaft end determined the half-breadth of the surrounding nacelle. Even though the nacelle was deliberately made elliptical to accommodate that large half breadth, that dimension had a controlling influence on the shape and size, thus weight and cost, of the nacelle. In a second model wind machine, two stages of home-built speed-up transmission or one commercial shift-line speed reducer run backwards would relieve that dimension markedly and result in a much smaller and less expensive nacelle.

5.4.6 The Pitch Linkages (Drawing p. 45)

The pitch controller causes a d.c. drive motor to rotate, and its speed of rotation is proportional to the sensed pitch error. That motor drives through a commercial worm and wheel speed reducer into a ball-nut home-built linear actuator. A pitching rod is moved fore and aft to change pitch. That axial force is applied forward in the spinner nacelle, via a rotary joint and a three-armed cross head, to three sliding cars, each of which is fastened to the links of a link chain. Each blade stock has fastened to it a chain sprocket on which a pitching chain mates, and the
closed loop of chain idles around a tension-adjusting idler sprocket carried on an excentric bearing at the far end of the hub standpipe member. Fore and aft motion of the ball-nut manifests itself as rotation in pitch of all three blades. A mechanical-electrical feedback on the ball-nut actuator reduces the pitch sequel error as pitch angle is created, reducing the speed of pitch changing and finally nulling out the control signal when zero error is measured. This system may sound complicated and expensive and in a sense it is. It would certainly be simplified dramatically in the second model but it works beautifully, reliably and accomplishes exactly that which must be done. Two casualties have been experienced in it:

(a) the special locking nut at the far end of the axial push-pull rod worked loose and pitch control was lost. As stated earlier, that part of the mechanism is not accessible from the tower servicing platform, so failure there was pre-destined. When retightened that nut was secured in a to date satisfactory manner.

(b) the oil seal in the worm-wheel speed reducer was gradually worn to the point where it became twisted and dragged on the shaft so severely that the device motor could not overcome it. A new oil seal and repair job solved that problem.

If there is any inadequacy remaining in this pitching mechanism, it might be the lack of secondary centrifugally thrown weights at the blade stocks capable of overdriving the entire pitching mechanism in the event of a run away, thus bringing each blade to feather. It is clearly established that a fully feathered windwheel will not rotate: the most reliable protection against an overspeed casualty would thus be an overriding pitching drive
fastened directly to each blade. The second model of the wind machine would incorporate such a feature.

5.4.7 The Yaw Damper (Drawing p. 48)

In the early stages of the design it was decided to incorporate only a very simple wiper type yaw damper between the pole matcher and the main frame, probably spring loaded. As the design progressed it was decided to install a variable damping yaw damper using a second d.c. motor identical to that installed in the pitching drive. The yaw damper is a chain and sprocket speed-increaser which drives that d.c. machine as a generator. The load placed across the generator terminals determines the rate at which the machine can yaw thus giving control over the yawing moment, and preventing structural failure in the windshaft. The yaw damper works well, but has been the source of a number of small but aggravating casualties. Because it had to be crammed into left-over space of an undesirable shape, the chains require tensioners which don't work as well as desired. Perhaps the major problem associated with this yaw damper relates to the hole cut in the main frame to permit its installation. A tight enclosure had been created around the slip-ring and brush assembly to prevent fouling of those critical surfaces. The yaw damper opening has permitted leaked lubricant to foul the slip-rings and brushes. A second model would be fitted with a yaw damper that does not violate the enclosure around brushes and slip-rings.

5.4.8 The Model Four Wind Furnace

The Wind Furnace has not yet been operated in the mechanical churn (Model Four) configuration and probably will not be until data have been
collected for at least one full heating season. Because the Model Four is felt to have great potential for reducing the installed cost of production-line wind furnaces, a rather lengthy progress report on it is included here in this final report.

The second year of the Wind Furnace Project came to an end with the Model Four Project partially completed, and agreement that its completion would extend into the third year. The Model Four is the Wind Furnace configuration in which wind shaft mechanical work is delivered to a rotating device in which that energy is expended via frictional and momentum exchange to heat a circulating fluid. The heated fluid then transfers its warmth to the contents of a low temperature thermal storage from which space heating baseboard circulating water is drawn.

Several home-built churns of the paddle-wheel and rotating disc were designed, and conversations were held with ENERCON of Long Island investigating the feasibility of their heat generating hysteresis clutch in the churn role. It was concluded in October, 1976, that this churn could be a very simple, inexpensive device, of a waterbrake nature, and that the industry probably could provide the device off-the-shelf. A research of the companies listed in the Thomas Register as sellers of waterbrakes was very disappointing, however: they are makers, without exception, of high-quality energy measuring systems, and none was the least bit interested in producing a simple machine with no attached instrumentation. At that time, however, All American Engineering of Wilmington, Delaware, stepped forward to offer their "Water Twister," a waterbrake designed to absorb short bursts of energy in such installation as end-of-runway emergency aircraft catching systems.
All American delivered a 12 in. diam. device on loan and it was agreed that the UMass program would then concentrate on testing of Water Twisters for synthesis of such machines into competitive wind power systems.

Three versions of Water Twister type Model Four Systems were then defined for detailed analysis:

(1) **Mod 4, Version A:** the original UMass concept, in which mechanical shaft would be brought down from the Windshaft, into Solar Habitat I, to drive a Water Twister located and immersed in the small (500 gallon) inner concrete tank.

(2) **Mod 4, Version B:** in this version the rotating waterbrake ("Water Twister") is located in the wind machine nacelle, essentially taking the place of the generator, but requiring a less expensive speed-up drive from the windshaft. The heated fluid crosses the wind machine yaw axis via a rotary fluid coupling and flows down and up the pole (supply and return) in insulated concentric plastic pipe, to a heat exchanger immersed in the storage tank. The heat transfer fluid system will be filled with an appropriate glycol-water antifreeze solution. A commercially available double-passage rotary fluid coupling, which with modification can serve this purpose, has been found.

(3) **Mod 4, Version C:** in this version the rotating waterbrake ("Water Twister") is located at the top of the pole, fixed to the pole, so that the windmachine yaws around the input shaft. This obviates the need for the rotary joint but creates a need for yaw drive: the resulting trade-off to be studied is obvious. The rest
of the fluid circuit is essentially the same as that for Version B.

The choice between the thermal losses through the up-down pole fluid circuit and the mechanical losses in a down-pole mechanical drive have been investigated and there is no compelling advantage to either system. It is therefore planned to test each in actual hardware, using a dummy pole erected just outside the laboratory in which the "Water Twister" is being driven by the diesel test rig. Available instrumentation applied to two complete sets of hardware, Version A versus Version B/C, will permit experimental proof of the analytical comparison.

Results to Date: As of the end of July, 1977, the experimental program had reached the point where useful preliminary results were available as follows:

(a) The diesel test rig had been put back into first-rate operating condition, the 12 inch "Water Twister" had been installed in an appropriate test rig, and a complete fluid heat removal system had been built, installed and instrumented. (Photo of Model 4 test arrangement shown on next page.)

(b) The 12 inch "Water Twister" was shown to absorb 42 horsepower at 865 rpm.

(c) The losses between "windshaft" (diesel P.T.O.) and Water Twister input shaft, for this test rig (which simulates very accurately the planned conversion of Wind Furnace One to the Model Four Configuration), were shown to be of the order of 7 horsepower, lost from bearings and gearing.
MOD-4 TEST ARRANGEMENT
(d) The automobile type thermostat installed in the Water Twister outlet did a good job of retaining the heat removal fluid in the Water Twister until it reached a temperature of 185-190°F, at which point the fluid would flow into the heat removal system.

(e) The Power versus RPM curve of the Water Twister is cubic: matching to a windshaft will be simple requiring no controls at all other than those wanted by the windmachine to (a) assist in low-wind start-up and (b) reduce thrust and bending moment on blades in high winds by feathering the blades.

5.4.9 Plans for Continuing Work

The entire Model Four project for the period 1 January 1977 through 31 August 1978 has been set down in detail, a copy of which follows.
MODELS FOUR - PROJECT PLAN

1. The Tasks:

1. Evaluate the Water Twister (25 hp) on the diesel test rig.
2. Evaluate experimentally the thermal losses to be expected from the fluid circuit for an aloft Water Twister.
3. Evaluate experimentally the power losses to be expected from a vertical line shaft capable of driving an on-ground Water Twister.
4. Evaluate the Water Twister (50 hp) on the diesel test rig.
5. Conceptualize a least-cost Model Four Wind Furnace.

Note: If the 50 hp Water Twister is received before Task 1 is completed, then Task 4 should be moved up into the second spot (i.e., be renumbered Task 2, and Tasks 2 and 3 should be renumbered as Tasks 3 and 4 respectively.
2. **Task 1:** Evaluate the Water Twister (25 hp) on the diesel test rig.

1.01 Complete the diesel lube-oil pump modification.
1.02 Assemble lube oil system.
1.03 Complete the diesel exhaust system.
1.04 Test operate the diesel.
1.05 Calibrate the torsionmeter.
1.06 Obtain Strobotac.
1.07 Design the Water Twister test frame.
1.08 Build the Water Twister test frame.
1.09 Design the Water Twister thermal insulation cover.
1.10 Obtain materials. Build insulation.
1.11 Complete the Water Twister Test Piping Diagram. Size all pipes, all components. (Both 50 hp and 25 hp devices are to be tested.)
1.12 Prepare Bill of Material for all parts of the Piping System.
1.13 Prepare Piping Arrangement Plan.
1.14 Obtain all parts required for Piping System.
1.15 Prepare Instrumentation Plan.
1.16 Identify, list, all instrumentation required. Identify source for all items, purchased and borrowed.
1.17 Insure that Piping Arrangement Plan and Thermal Cover Plan interface properly with Instrumentation Plan.
1.18 Obtain Instrumentation.
1.20 Prepare Wiring Diagram for electric devices for test rig.
1.21 Verify with Electrical Technician that required electricity
can be provided.

1.22 Prepare list of electric material required. Purchase.
1.23 Build the Piping System.
1.24 Build the Instrumentation System.
1.25 Prepare Instrumentation Calibration concept. Calibrate the test rig instrumentation.
1.26 Set-to-work, groom, test and tune the completed test rig.
1.27 Prepare 25 hp Water Twister Test and Evaluation Plan.
1.28 Conduct 25 hp Water Twister Test Program.
1.29 Obtain at least three high-quality 8x10 glossy b/w photographs of the test rig.
3. **Task 2: Evaluate Experimentally the Thermal Losses to be Expected from the Fluid Circuit of an Aloft Water Twister**

2.01 Review the design of a Version B Model Four appropriate for a 50 hp Water Twister located aloft in a WF-1. Verify pipe sizes, pipe materials, insulation concept, insulation materials and details.

2.02 Using results of Task 1.28 and Task 4., decide the flow rate best suited to Version B, Model Four, and the pumping and the piping appropriate to the concept.

2.03 Conceptualize a test rig that will simulate this version of the Model Four such that thermal losses in the fluid circuit can actually be evaluated. Use the diesel driven 50 hp Water Twister as the fluid heating device, and arrange the fluid circuit to be outdoors, vertical, exposed to weather and wind much the way it will be exposed in service.

2.04 Design the Version B Model Four test rig.

2.05 Detail the support structure required for the Version B Model Four test rig.

2.06 Prepare the Instrumentation Plan for this experiment.

2.07 Prepare the Piping Arrangement Plan, Version B Model Four Experiment. Include a "Working" swivel joint.

2.08 Prepare the Electrical Wiring Plan, Version B Model Four Experiment.

2.09 Prepare the Instrumentation Calibration Concept, Version B Model Four Experiment.

2.10 Prepare the Version B Model Four Evaluation Plan.
2.11 List and identify source, all instrumentation required for Version B Model Four Evaluation.

2.12 Purchase material, build support structure of 2.05.

2.13 Purchase material, complete the wiring of 2.08.

2.14 Purchase material, build the piping system required for 2.07.

2.15 Assemble the entire test rig, set-to-work, test and tune.

2.16 Conduct the Version B Model Four Evaluation.

2.17 Obtain at least three high quality 8x10 glossy b/w photographs of this test rig.
4. Task 3: Evaluate Experimentally the Power Losses to be Expected From a Vertical Line Shaft Capable of Driving an On-Ground Water Twister

3.01 Review the design of a Version A Model Four appropriate for a 50 hp Water Twister located on the ground beneath a WF-1. Verify sizes and details of all mechanical parts.

3.02 Conceptualize a test rig appropriate to the evaluation of line shaft losses in a WF Mod 4 Version A Configuration.

3.03 Prepare the Version A Model Four Evaluation Plan.

3.04 Design the 50 hp Version A Model Four Mechanical Drive, to fit:
   (a) inside a 10 in. diameter standard steel pipe, and
   (b) inside an 11 in. inside diameter hollow wood pole
Select all the mechanical parts. Prepare a complete Bill of Material.

3.05 Purchase the material for one complete mechanical drive per 3.04.

3.06 Design the support structure portion of 3.02.

3.07 Purchase the material for one support structure.

3.08 Build and erect the support structure for the Version A Model Four experiment.

3.09 Assemble the test rig.

3.10 Design the instrumentation appropriate to this Version A Model Four experiment.

3.11 List the source and availability of each instrument required.

3.12 Obtain instrumentation not available on loan.

3.13 Prepare an Instrumentation Calibration Concept for the Version A Model Four experiment.
3.14 Calibrate instrumentation.

3.15 Perform the experiment. Collect and analyze data. Publish results.
5. Task 4: Evaluate the Water Twister (50 hp) on the Diesel Test Rig

4.01 Remove the 25 hp Water Twister from the test rig.
4.02 Design all parts needed to change from 25 hp to 50 hp Water Twister.
4.03 Modify the rig as necessary to carry the 50 hp Water Twister.
4.04 Install the 50 hp Water Twister. Set-to-work test and tune.
4.05 Prepare a 50 hp Water Twister Evaluation Plan.
4.06 Recalibrate Instrumentation.
4.07 Conduct evaluation of 50 hp Water Twister. Collect data, analyze results, publish.
4.08 Prepare concept drawing for optimum 50 hp Water Twister Wind Furnace.
6. **Task 5:** Conceptualize a Least-Cost Model Four Wind Furnace

5.01 Evaluate the results of Tasks 1 through 4. Prepare an evaluation matrix. Decide what the most cost-effective Model Four Wind Furnace Configuration would be based on those results.

5.02 Conceptualize the reinforced concrete center wind furnace support foundation and storage tank combination sketched in 1976. Inject that concept into the above matrix. Again decide the most cost-effective route to follow.

5.03 Prepare a preliminary design and specification for the selected optimal Model Four Wind Furnace.
5.5 **Wind Furnace Drawings and Bills of Material**

A complete set of page size reductions of the working drawings and a complete Bill of Material (Model Four excluded) has been issued as a technical report WF-TR-77-10. The drawings are the ones from which Wind Furnace One was built and assembled. Unfortunately the verbal discussion that accompanied each of the drawings within the shops is missing. A valiant attempt was made to discipline the large group of eager young engineers (and undergraduates) who participated in this program to produce complete and accurate drawings from which journeymen mechanics could work. Enthusiasm and a tight schedule upon occasion over rode that discipline. Considerable quiet pleasure has been taken, however, from the fact that the rudiments of drafting, machine shop, carpenter shop, welding shop and plastic shop practices, and some skills in carrying on a meaningful dialogue with artificers were instilled in those young men. Very few of them had any drawing course; more had a machine design course. Their ability to contribute to the production of an engineering hardware project within a few hours of starting the task is a tribute to their individual competence and willingness.

5.6 **Dynamic Analysis**

At the start of the program the greatest concern about undesirable dynamic characteristics of the wind machine was fear that either wind-wheel frequency or blade frequency would lie too close to support structure natural frequency and that the springiness of the guys might permit unacceptable vibration of the machine atop the tower. It was
possible to assure freedom from that type of problem before structural support material was ordered. It was accepted, however, that the system would pass through one critical speed (about 85 rpm windwheel rotational speed) on the way from stopped to rated speed. Using hindsight, that compromise could have been avoided had the stay attachment point been moved as few as two feet up the pole, or, had solid round bars been used for stays rather than the selected wire rope. It does appear that there is no problem in cross-coupling between windwheel and support system.

The second area of concern was created by the windshear experiment at Plum Brook. The need for harmony between swept diameter size and machine axis height had been felt almost intuitively when the Wind Furnace 1 principal dimensions were set... but in a sense, the 32.5 ft. dia. had been established long before actual axis height was set. The combination of a 32.5 ft. dia. at a 62 ft. axis height makes windshear dynamic loading insignificant.

The third area of concern with dynamic response of the system or subsystems resulted in a harsh lesson for the research team. A factor of safety of 2.4 on yield strength of the windshaft at rated power and speed (50 hp @ 26.1 mph) had been accepted albeit reluctantly when the decision was made to proceed with the one ton truck rear axle assembly. That axle remained a source of uneasiness to the principal investigator. In late summer 1976 one member of the project team heard a preliminary presentation by a well-qualified aerodynamicist who predicted a torque spike multiplication factor as high as 9.0 in the event of severe gust loading on a windmachine tied electrically in synchronism with a power
grid. What kind of a torque spike might the Wind Furnace-1 experience in a gust when feeding its connected resistance load? It had been planned for some time to include a detailed analysis of this type in the program: indeed, support had been provided for one team member to do a learned doctoral dissertation analyzing all possible aerodynamic excitations and loadings on the system, from moving air particles to the end of any dynamic chain; but that work simply could not be speeded up to give quick, complete answers to the question that had been raised. So three other members of the research team working under the reviewing eyes of faculty undertook a quick analysis. Their ultimate results were excellent but not quick. The critical heating season, October to mid January was lost, the windmill sitting idle, waiting for results. Finally in late January, 1977 the principal investigator directed that the machine operate, that the 2.4 factor of safety appeared to be adequate.

It may still be shown that gust loading could break the main drive of Wind Furnace-1 when the definitive analyses of the situation has been completed. In the meantime at least some members of the project team may have learned that engineering analysis in real life is only a means to an end, not an end in itself, and that a good engineering manager can count himself lucky if he is able to muster only 80 to 90 percent of the facts that he really wants before he has to make a decision.

Two major technical reports on the dynamic characteristics of Wind Furnace-1 and on propeller type windmills in general are still in preparation: they can not yet be referenced here in the project's
final report.

5.7 Wind Data Collection and Productivity Analysis

The 1971-1973 studies of windpower systems by Heronemus had led to the conviction that computer aided analysis and design would be only as valuable as the quality and extent of wind data applicable to that site and height. Without reliable, pertinent data crude approximations of productivity were just as accurate as results of sophisticated computer analyses. The Orchard Hill site for Wind Furnace One was selected without prior analysis of either good wind data or insolation data: it was hoped that interested parties, prospective customers, might be given much more credible cost predictions for other sites in the region. A number of a.c. and d.c. powered recording anemometers were set up at stations ranging from Mount Equinox and Grassy Brook Village in Vermont to Barnstable Harbor on Cape Cod. Some of the instruments were provided by others, with a UMass commitment to read and analyze the tapes. Arrangements were made for students to read some tapes and visually assign hourly averages while other tapes were sent to an outside company for digitizing (the UMass Computer Center did not have such equipment).

Some useful results were obtained from those instruments. Other data of value were obtained from the data banks at Brookhaven National Laboratory and from two different sets of instruments located on Mount Tom, Holyoke, Mass. Those data were in aggregate useful enough to provide experimental verifications of some productivity analysis models, and also have provided guidance as to wind system feasibility in
the region. It has been determined, for example, that:

(a) Wind systems on Mount Equinox would be very productive, very economic, particularly in the heating mode during the heating season, whereas wind systems at Grassy Brook Village would have to be placed quite high up in the air to be reasonably productive.

(b) Wind energy available over Mount Tom, in the hills on the West Bank of the Connecticut River in Leyden and on the shoreline at Cape Cod would be very productive. The winds atop Mount Tom at an elevation of about 700 ft. above the adjacent broad valley floor are particularly energetic. On the other hand, winds at Northfield on the East Bank of the Connecticut and at Montague and at Amherst are not very energetic.

This part of the project was in a sense unique in the USERDA Wind Energy Program because it was conducted as an integral part of a mission oriented system project. It will not be continued as part of the Wind Furnace project but may be continued as part of a much larger national wind resource assessment program. The usefulness of productivity predictions for a region, a neighborhood and for a specific site to aid commercialization of the Wind Furnace should not be forgotten. It is hoped that this small UMASS effort might be integrated into the much larger ERDA program but that the results from all of the larger programs be as useful as possible to prospective system purchasers.
5.8 Interface Management

Interfaces between the windmachine system, the flat plate collector system, the thermal storage subsystem, the Habitat and its basement laboratory and the Orchard Hill site were identified carefully near the beginning of the project and partially documented. That incomplete attempt at interface management seems to have been adequate, though not complete, because all interfaces have been matched rather gracefully as the project progressed. This technique served as an excellent secondary purpose: four faculty members, who were somewhat suspicious of the scholarly competence of each other, were brought together often enough and required to speak to the same agenda often enough that they were able to discover some common ground and mutual respect. A common schedule of events, a master test program and sequence, and a combined and sharing approach toward instrumentation needs and problems were also by-products of interface management efforts.

5.9 Project Coordination and Management

This project was started as an academic research effort funded by gifts. All of the basics of the academic environment were incorporated from the beginning - the continuing search for truth and learning in the process were placed far ahead of completion of a hardware system by a certain date. Indeed there was little prospect during the first two years that a system would ever be completed if only for lack of resources. When completion of the project was proposed to USERDA, it was proposed as the completion of an academic project, and the principal investigator had to propose a schedule and specific tasks to be accomplished within that schedule. That was done knowing
full well that the principal investigator would never, personally, be able to compensate for slow performance on the part of any member of the team. So, in a very real sense, the proposed schedule was not found in truth.

USERDA, through Dr. Lilljidal of the Agricultural Research Service, had no mandate to support academic research when they awarded the first and the second year's contract to UMass. They took the risk and accepted the fact that the preponderance of their money was going to support graduate education, first, and to create a Wind Furnace System, second. The participants in this work will be forever grateful to USERDA and to ARS for stretching a point and using their funds to support education.

The participants in the project did try to meet the schedule. The budget was met simply because there is no way within the academic research system to incur an overrun, and hardly any chance that money available will not be spent.

Management practices were those possible in the academic research mode. The work to be accomplished was divided, indeed in some cases 'created', to match the expertise of the participating faculty and students. The essential goals of each part were described in terms of the layer or group goal of designing, building, erecting and testing a complete system. Weekly progress meetings were held - something quite foreign to the academic mode. The argument and haggling that characterize a healthy educational system had to be tolerated but decisions had to be made fairly early on by the principal investigator and then enforced to the best of his ability.
The major burden of coordinating fiscal contributions from different schools, inputs from the Physical Plant Department, the work of the outside contractors with the core design and fabrication work fell on the shoulders of the Project Manager, Dr. Duane Cromack. It was a full-time effort to create that complete laboratory at Orchard Hill, an effort absolutely essential to any possible success of this project, and accomplished with skill and perseverance.

Fortunately there was some real talent available within the School of Engineering shops, in the persons of seven other departmental technicians, and residing in the Secretary of the principal investigator's department. And that talent was given willingly. It is proper to say that the design of every piece of that windmachine was finally determined and settled by Professor Costa, manager of the School of Engineering Shops, always tuned precisely to what could be done with available materials and tools, and always done with precision results.

The schedule was not met. The Wind Furnace started operating six months after it was to have operated: six months in 24 is not a record of which to be too proud. All that can be said to seek comfort is that when it did work, it worked beautifully, and it continues to work beautifully.

Much could be said about the details of management, or lack thereof. Perhaps a few comments are pertinent in case anyone ever reads this bit of history seeking guidance as to whether or not similar projects should be attempted in the academic research mode.

(a) The tasks required detailed subdivision of effort and agreement on nature of work and amount of support before
anything was started. It was in reality a whole package of "best-efforts subcontracts" with a large number of individuals. There was no opportunity to redirect resources once a year's effort had begun.

(b) The principal performers were newly graduated engineers without practicing experience (the graduate research assistants). GRA's are capable of accomplishing incredible amounts of work and producing outstanding results. At times they are literally slaves to the desires of their major professors. This situation exists right up to the point where the next day's homework problems, in someone else's course, must be started. Then the major professor becomes the slave, because academic excellence, scholarly performance on the part of all participants must be paramount. Some task master professor whose course is being taken by a number of the GRA's working on a project can literally wipe out the project with homework assignments (this happened twice during the course of this project, and the professor responsible neither knew or cared). GRA's are atheletic types: one skiing accident can set back a project 2 to 3 months.

(c) Professors sometime tend toward an individualist's outlook on life; bringing ten faculty from five different departments together in a mission-oriented research project and expecting them all to treat the planned path without some wide excursions takes a little doing. It is the opinion of the principal investigator that this team exhibited an unusual
loyalty to the common cause. Unfortunately their efforts were not hailed by their more independent colleagues, in some instances. Future joint effort may well be impossible unless such joint efforts are given formal recognition as worthy scholarly efforts.

(d) The administrative aim of the university, purchasing, accounting, etc., gave excellent service to the project. The mechanism which exists is well structured to serve many large projects like this one.

(e) It is questionable that this principal investigator would be willing to undertake another similar hardware-producing project within the academic environment. When all the pluses and minuses are balanced out, the drain-down in physical and emotional stamina required of one, perhaps two, individuals, is too great.
6. **Listing of Participating Personnel**

(a) W.E. Heronemus - P.I., Management, overall responsibility for the design, assisted by Brian Kuhn (receiving no support from the grant) candidate for B.D.I.C. in business and energy.

(b) D.E. Cromack - Deputy P.I., Chief Administrative Officer, and head of the Aerodynamics, Analysis & Tunnel Working Group, and responsible for Interface Control and Construction Liaison for Working Group 07, the Solar Habitat. Assisted by: Fred Perkins and Paul Lefebvre candidates for M.S. in Mechanical Engineering.

(c) A. Chajes - Head of Working Group 01, Support Structures. Assisted by Wen-Sen Chen and Steven Bailey, candidates for M.S. in Civil Engineering

(d) R.V. Monopoli - (receiving no support from the grant) supervising B. Caccamo, candidate for B.S. in Electrical & Computer Engineering, who has designed and built the Pitch Controller.

(e) R.M. Glorioso - Provided consultaion to both the Load Controller and the Pitch Controller working groups.

(f) M. Eds - Candidate for M.S. in Ocean Engineering - in charge of the necessary laboratory work and analysis and the design of the Load Controller. Assisted by: D. Handman, undergraduate research assistant and W. Clark, Electronics Technician, and G.D. Sheckels, (receiving no support from this grant) consultant to the Load Controller Group.
(g) A.J. Costa - Responsible for the design and manufacture of the Mechanical Assembly, Hub, and all required shop work. Assisted by: C. Butterfield, candidate for M.S. in Mechanical Engineering, who is the design engineer for the hub; F. Antoon, candidate for M.S. in Mechanical Engineering, who is the design engineer for the main frame, main drive, pole matcher, slip ring assembly, nacelles, general arrangement, and weights and moments record and control.

(h) F.J. Dzialo - Responsible for structural analysis of competitive blade concepts.

(i) J.G. McGowan - Responsible for Total System simulation, subsystem sizing, all thermal components, the design of the experiment and instrumentation. Assisted by G. Darkazalli, candidate for Ph.D. in Mechanical Engineering, who is the simulation engineer and system analyst; W. Wells, candidate for the M.S. in Mechanical Engineering who is the design engineer for all thermal systems and all thermal components, and Lou Socha, candidate for M.S. in Mechanical Engineering, responsible for solar insolation data collection.

(j) C.A. Johnson - (Receiving no support from the Grant.) Responsible for the concept, design and engineering and construction supervision for the Solar Habitat. Assisted by: W. Clark and Allan Milkewicz, Technicians, Civil Engineering Department.
(k) R. Kirchhoff - Responsible for analysis and tunnel investigations of the interference between adjacent wind wheels.

7. Publications

7.1 Progress and Administrative Reports to Date

PR 75/1 First Quarterly Progress Report Covering The Initial Organization of the Project, March to June, 1975.

PR 75/2 Second Quarterly Progress Report Covering the Design Phase of the Project, July to September, 1975.

PR 75/3 Third Quarterly Progress Report Covering the Final Design and Manufacturing Phase of the Project, September to December, 1975.


AR 76/1 Administrative Report for the Period Ending August 31, 1976.


7.2 Papers and Published Reports


8. The Educational Component

Four doctoral candidates received significant support from this project. One has completed his degree requirements and the other three are expected to finish by January, 1978. A fifth doctoral candidate has been supported by private funds meant to parallel this project.

Fifteen masters candidates have received all or part of the support provided them while they obtained their degrees. Mechanical, Civil, Ocean, Industrial and Electrical engineering advanced degrees are included in those fifteen.

Eight undergraduates have experienced a significant involvement in this research project: each has received financial support varying from very small stipends to nearly full support of education. Engineering, physics, forestry and wood technology disciplines are included in those eight. Three of them received support from NSF Undergraduate Research Participation Grants, allowing them to associate with this project.

Ten faculty have received support from this project. Two other faculty have participated without support. One other received support from related project funds and, one other has received research initiation funding for work related directly to wind turbine blades.

One graduate level course in Windpower Engineering has been created as a direct result of this project. Many individual undergraduate and graduate level special projects have been undertaken for academic credit as a direct result of this project. At least three formal non-technical undergraduate courses, three freshmen engineering modules and campus-wide interest in energy and energy alternatives have been
created as a result of this activity. Many of the involved faculty
have lectured all over the country (and in a number of foreign
countries) as a result of external interest in this project at UMass.

This University is truly grateful for the support which has
created such a significant addition to its educational program.
9. **Recommendations for Future Work**

This is a Final Report summarizing the last two years of effort of a continuing research project. This project has created a significant laboratory and operating alternative energy system. For awhile this laboratory was also used as a demonstration site visited by thousands of citizens interested in alternative energy systems.

As a minimum, the laboratory and system should be operated as a teaching laboratory, data collection site, and public demonstration facility. Several thousand citizens had visited the facility before it was closed to the public for lack of funds to support demonstration. It is safe to say that more grade-school, high school and college students have received their first introduction to solar energy hardware in Solar Habitat I than at any other place in New England. This educational process should be expanded.

The system should be run continuously to establish a track record, a real demonstration of the wind furnace process. Indeed, a second and perhaps a third machine, improved models of WF-1 and/or perhaps a vertical axis windmachine should be designed, built and installed at the same Orchard Hill site. Then one machine can be used to obtain specific aerodynamic data in support of future designs while the others simply prove how much heating energy can be extracted from the winds.

The Wind Furnace experiment should be replicated as soon as possible at a number of other sites to show experimentally how the concept fares in different wind regimes. There is an excellent location at the University's marine station near Gloucester, MA, to show how a
Wind Furnace will produce in an Atlantic coastal wind. There is an excellent location at the University's marine biology station on Nantucket which would show how the Wind Furnace will produce in an islandic wind. Then one should consider some partners in other regions: (a) an installation in Canton, New York, (b) an installation in Iowa, (c) an installation on an Indian reservation in North Dakota, etc. That purchase of at least ten identical machines and their installation in diversified locations, should be next on the list. And that is not a project for an academic research team, but an industrial extension of their past work.

One day soon the first offshore urban Wind Furnace system should be built and installed, perhaps off Hull, MA. Two designs for that first installation have been prepared by students and faculty in the University of Massachusetts.

In summary, can anyone else identify any equally simple and ecologically sound program, capable of early and quick commercialization, that has the potential for saving 270 million barrels of petroleum imports per year?