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May 23-25, 1979
The Four Seasons Motor Inn
Colorado Springs, Colorado

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WIND ENERGY INNOVATIVE SYSTEMS CONFERENCE PROCEEDINGS

MAY 23-25, 1979
THE FOUR SEASONS MOTOR INN
COLORADO SPRINGS, COLORADO

SPONSORED BY:
U. S. DEPARTMENT OF ENERGY

COORDINATED BY:
SOLAR ENERGY RESEARCH INSTITUTE
JBF SCIENTIFIC CORPORATION — Arlington, VA

EDITED BY:
IRWIN E. VAS

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FOREWORD

Wind energy has the potential of being a substantial contributor to the nation's energy supply by the year 2000. The objective of the Federal Wind Energy Program is to accelerate the development of reliable and economically feasible wind energy systems to encourage the earliest possible commercialization of wind energy. In keeping with the effort to achieve this goal, the U.S. Department of Energy sponsored the Wind Energy Innovative Systems (WEIS) Conference on May 23-25, 1979. Coordinated jointly by the Solar Energy Research Institute (SERI) and JBF Scientific Corporation, the conference was designed to provide a forum for the exchange and dissemination of information related to the current WEIS projects.

The WEIS Conference had three basic objectives: to provide an overview of the advances made in federally funded wind energy innovative systems projects; to encourage interaction and information exchange among people working or interested in the field; and to provide input to the Wind Energy Innovative Systems Program. It was the intention of those who organized the conference to elicit the assistance, direction, and recommendations of the attendees on the current and proposed wind activities to make the WEIS Program an active program in support of the federal program objectives.

Several people made significant contributions of time and effort to the conference. Vicky Curry and Kate Blattenbauer of the Conferences Group at SERI deserve praise for their work as conference coordinators. Special thanks is due to Richard Mitchell, WEIS Project Manager, for his support in coordinating the technical activities of the conference.

Irwin E. Vas
Group Manager, Wind Systems Section

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Overview

THE FEDERAL WIND ENERGY PROGRAM: AN OVERVIEW

George P. Tennyson
Program Manager, Wind Systems Branch
Department of Energy

Innovative, according to Webster, means that which makes new. In this case we are looking anew at wind as a source of energy, attempting to make it more attractive and cost-effective, and to stimulate its widespread commercial use. However, this is a difficult proposition. We have heard from the patent office that there are more patents for wind-operated devices than any other kind. Frankly, there are some days when I think we have seen them all twice. However, we have funded innovative systems in the wind program since the beginning, doing so for as long as these concepts show sufficient promise of superior cost-effectiveness. I think it is useful to note that the Darrieus and the self-twisting blade concepts are graduates of this system. Both are undergoing development in the small systems program after having been selected competitively out of requested proposals. It is also interesting to note which innovative systems are likely to be successful. Usually, these systems are based on the most efficient use of a minimum amount of the given material. This is necessary in order to meet the requirements of cost effectiveness which is the most important determining factor in the application of wind energy technologies. There is no doubt that windmills do work and have for thousands of years, but they must work more cheaply than anything which could replace them in a given situation.

It is this office's policy to solicit proposals for innovative systems. This insures that choices are made competitively by eliminating the "first come, first serve" basis of funding. We compare each proposal against its kind in the allocating of money for innovative systems. I think we are at a watershed of history where cost and scarcity have begun to force mankind to move away from his dependency on fossil fuels to a more integrated and harmonious use of renewable sources of energy. This makes effective innovation, or improvement, of wind systems more important than ever.

If you look at the first viewgraph (a visual representation of how four major issues, Proposition 13, oil price deregulation, OPEC, and Three Mile Island interact with each other and with wind systems), Proposition 13 forms part of what I refer to as the "energy quadrangle." There is no relation to the Bermuda Triangle here. The "energy quadrangle" illustrates the present energy dilemma through the interaction of four forces. The first, Proposition 13, represents the local and national aspirations toward balanced budgets and controlled taxation to avoid rising taxes. The second element of that quadrangle is OPEC, whose rising energy prices continue to affect every nation of the world. The third is the President's program for deregulation of oil prices here in the United States, and the fourth is the recent difficulty at Three Mile Island in Pennsylvania. From our standpoint, I think we could say that wind energy is caught right in the middle, interacting with all of these forces and affected by the interaction between the forces themselves. All of these interactions will affect the future of wind energy. In many respects, three out of four of these forces have the effect of emphasizing the importance of alternative energies - wind energy included. The fourth force represents a constraint on the resources that we can apply to the realization of the promise of any alternative energy source.

The application of the national resources to those alternate energies is, of course, directly affected by the Congressional authorization and appropriation measures. We have considerable interest in that. The House of Representatives held its hearings under the shadow of the spirit of Proposition 13, very much a lead toward fiscal restraint and fiscal responsibility. It is of equal importance to note that the Senate hearings were held in the glare, or perhaps the glow, of the Three Mile Island publicity, which may lead to a different approach to the problems of alternative energy. I think it can be said, without fear of error, that the Joint Committee document prepared between the House and the Senate to resolve the authorization and appropriations bills, ought to be one of the more fascinating documents of this term in Congress.

Also, I think it is important to note that AWEA leadership has been working hard to improve the political climate for wind energy. They have testified before Congress; they have discussed the situation with members of Congress and with the Department of Energy and its members. I think that they would agree with me in saying that the "bloom is off the bush" for alternative energy, and that now we must present well thought out, sound programs that can stand searching inquiry regarding motives, costs, scheduling and eventual output. I believe that these requirements are justified. Anything which does not meet these requirements probably should not survive.

With regard to the situation, I think we should take a look at how we currently view the cost trends in the Wind Systems Branch. These cost trends are based on 1978 dollars and 1978 energy costs. They do not attempt to project energy costs into the future or to reflect future inflation.

Viewgraph #2 (cost trends of large wind systems) illustrates the relationship of the wind speeds to the various costs of energy in terms of kilowatt hours generated. The average or mean wind speed of 12 mph would, in each case, be at the top of the chart, and the highest average wind speed of 16 mph, at the bottom, with the moderate wind speed of 14 mph represented by a bar in the middle. You will notice that there are three classes of production. For preproduction, the single units are virtually the prototype construction. This includes all of the MOD-OA units that we produced, the limited productions runs of about 25 kW or so, and the mature product for the machines of around 100 kW in terms of production run.

I think it is revealing, that for these units in the megawatt classes, the costs show themselves to be well within the useful market for a medium wind speed, even with today's machine, the MOD-2, in sizeable production. In higher wind speed areas they can even achieve wide-scale use. Nevertheless, we believe that for the broader areas of the nation to be able to use wind power, it will be necessary to lower those costs to between 2 and 3 cents per kilowatt hour. I think the figure for the MOD-2 represented there at between 3 and 4 cents per kilowatt hour at its design wind speed of about 14 miles an hour, shows the amount of progress we have made between MOD-1 and MOD-2. I think it also should be emphasized that this is probably a fairly firm data point. We are confident that the MOD-2 entering fabrication now, is a complete design with very careful cost estimation worked out on the unit.

The additional advanced systems show what we feel the next two generations can accomplish. These represent strong challenges, and we look forward to achieving them.

Viewgraph 3 (cost trends of intermediate wind systems) shows the cost trends for the intermediate size wind systems, that is, those of a 200 kW rating at rated speed, or perhaps a million kilowatt hours per year output in a 14 mph wind. I think we can state that the costs for MOD-OA are fairly firm. We know that they are. We have two of the units in operation, a third almost ready to go, and a fourth in planning. However, the second and third generation systems indicate that intermediate-sized wind systems have a good way to go before they enter anything but a fairly restricted market. I think these cost projections are fairly conservative, nevertheless, they indicate our view of the machines at this time.

With the previous charts, we represented the utility case with the large and intermediate systems. The small wind systems, those less than 100 kilowatts, are represented in the next viewgraph, number 4 (effect of cost-of-money on goals for small wind systems). I think the chart for small wind systems illustrates several points. First it demonstrates the effect of cost of money on our goals for small wind systems. The cost of money for the 8 kW systems represents commercial interests, the homeowners, and farmers who can often obtain lower-priced loans. You can see the effect of cost of money there. You can also see that we're getting down into the useful market for wide-scale use if demand charges are not imposed. That applies to some of the 8 kW machines in the current development run, also.

Please note that there are no projections on this chart, as there are on the others, except for the current developmental units. It is interesting to speculate how low the costs will be for the next generation. For the 40 kW size units, you will note that we did not include the homeowner on the basis that there are very few homeowners who would use a 40 kW system. That is probably a realistic view.

I would also like to point out that there is a strong element of doubt, at least by the Wind Systems Branch, in these cost predictions at the present. We have reason to believe that at least one of the 40 kW units is going to be more expensive than what we had projected, not by factors, but by fractions. This was the best projection we had when the chart was made. None of the 8 kW systems have been delivered to us. However, neither has the MOD-2 been delivered. Nevertheless, we are still not quite so confident with these as we are with the figures on large systems. That does not indicate any necessary predilection toward the large systems, just a substantial variance in many of the estimates for these machines, and somewhat less experience with developmental small systems.

At the right, you can see the effect that can be expected if widescale use is required with demand charges imposed by the utilities or requirements of the public utility commissions. This essentially cuts the goal we have to meet in half and makes the problem much more difficult. It is unrealistic to expect no demand charges. Reasonable accounting certainly allows for the inclusion of distribution and backup charges to be allotted against the user who also has alternate energy on the line. That is not a popular point of view with this audience, nevertheless, it is determining the future of the program.

On the positive side, I think you have to say that we have come a long way since the earlier statement that the state-of-the-art for energy from small wind systems costs were about 15½ cents per kilowatt hour. I think we are seeing a much better situation evolve with the development of these new units.

We are proud of our contractors, and Rocky Flats. I would like to add that we did not include the high reliability systems in here, since they were not expected to meet the tight cost goals of the 8 and 40 kW or other machines currently being selected for development. The reason for that is that the machines were designed for an extremely severe environment and would be a specialized application.

With that in mind, let us look at the budget that we see for the future. (Viewgraph 5, Wind Systems Branch budget for FY 79 and FY 80) For fiscal year 1979, the Wind Systems budget is approximately \$60.7 million. For fiscal year 1980, the President's request is for \$67.0 million, over \$2.0 million of which is allocated for the Test Center Building at Rocky Flats. The outlook is for a budget that is essentially level when the effects of inflation are allowed for.

Let us take a look at what this means in terms of the FY 80 work that is to be undertaken. The work, under what was called "program development" in the past, the mission analyses and economic studies - those including the other issues will cover the following items. First, we will continue to identify and assess key United States markets for wind machines. We will work toward a detailed assessment for WECS in selected markets. We will conduct policy analysis for demonstration projects, and we wish to consider the cost and impact of alternative incentives. We will continue to examine the legal aspects of WECS. There will be a continuing assessment of WECS impacts on environmental noise and on aesthetics.

We will study land use constraints on the siting of WECS. We will also study utility modeling for WECS, the economics of WECS tied to the utilities, and technical integration of WECS in utilities. We will conduct value analyses of selected utilities, prepare planning handbooks for the use of WECS, particularly by utilities, conduct applications analyses for small WECS. There will be cost estimations for all classes of WECS. Under the familiar area of Wind Characteristics, we will complete and publish the assessment of wind energy potential for all regions of the U.S. and its territories. This is being conducted now. The assessment for the Pacific Northwest region has recently been completed. This is the pilot region and RFP's have been issued for the various other areas of the United States. Siting methodologies will continue to be studied. We will work on tools for site screening, including calibration and testing of indicators. Just recently, I've seen a very interesting report which might be good for publication on the use of vegetation as a wind indicator prior to the taking of any direct and metric measurements. We will study the effects of wind turbine wakes on siting. We will investigate wind shears in the nocturnal boundary layer. There will be verification and testing of the numerical modeling techniques and updating of siting handbooks. Of greater interest to designers, we will continue to look at wind characteristics for design and performance evaluation. Studies of wind gustiness and directional variability for fatigue and failure analysis will be made. We will publish guidelines for wind characteristics for systems designs that are further refined. We will continue to conduct research concerning wind characteristics for WECS operation. We will complete the forecasts by adapting to WECS user needs. In the area of utility applications, we will study the impact of forecast accuracy on WECS utilization. Also a guidelines document on reliability testing of meteorological instruments will be prepared and the meteorological validation work will be completed on new candidate sites to be selected between now and the first of the year.

The next item down has always been the ever popular small systems. Viewgraph #6 (a chart of Small Systems Development) mentioned the test center activities which will be expanded to accommodate 50 machines including those under current development. The prototypes will be on the lot by that time.

While viewgraph #7 (the Rocky Flats test site) is taken with a telephoto lens, and therefore provides some foreshortening, it also provides another indication of the situation at the test site. The windmills are not that crowded. There is actually a pretty good walk between them. But in the background, one can see the collection of trailers and temporary buildings that house the test center crew. That is one of the indications that we need to build a test center building. The main work is still done in very small quarters behind the cafeteria at Rocky Flats. Additional quarters are maintained in an abandoned cement plant between the cafeteria and the test site.

Assembly is done in one of the warehouse buildings there on the lot and, I understand we are now renting some building space in lovely downtown Boulder for the rest of our crew. Needless to say, coordination of this effort is driving Terry Healy's gasoline bill up, if nothing else, in addition to the telephone bills, due to lack of understanding and lack of coordination. We expect the building to be underway this year and hope you concur that this is a necessary activity.

During the fiscal year 1980, systems development will continue. The 4 and 15 kilowatt machines will have optimized components and subsystems. Prototypes from the earlier system passing the proof-of-concept testing will go into our plan for larger-scale testing. Further developmental projects beyond the 4 and 15 kilowatt units in fiscal year 1980 will depend on funding in addition to that which has been requested by the President's budget. Supporting research and technology in small machines will be primarily the continuation of studies begun in 1979. The aerodynamics analysis and testing, wake measurements, blade coating, yaw control, start-up conditions, utility interconnect, hardware development, etc.

Special studies were instituted during fiscal year 79 that will be completed in FY 80. (Viewgraph #8, the Small Systems Development Program for FY 80) These are certain market studies and application studies, institutional studies, guidelines for users in determining feasibility for using SWECS and selecting and designing systems assessments of the institutional requirements. The field evaluation program will continue. The site selection work will continue. The site selection work will be going on during 1980, also the hardware procurement and installation, data collection and analyses, and assessment of the institutional and technical barriers. The objectives are to determine the procedures for interconnecting SWECS with utilities and to accelerate the establishment of data for arriving at rate structures. Also, we expect the program to have the side effect of supporting the industry, establishing the industry installation and repair sub-element on a larger scale. We have termed the field evaluation type of work as critical to the future of small systems, by facilitating their installation in the field by general users.

Under the discussion of the work on small systems, we will, of course, continue the USDA program. There will be new initiatives in FY 1980. All will involve solicitations. There will be a test of general purpose farmstead power usage in which the 8 kilowatt Rocky Flats development machines will be used. There will be a test of farmstead load management controls concurrence. Development of a variable speed irrigation pump is planned. For second cycle test of high lift hybrid irrigation pumping, they hope to use the 17-meter low-cost Darrieus machine. A second cycle test of low-lift irrigation pumping with the 8 kilowatt Rocky Flats developed machines and a building heating system using the same units are planned. Brooder heating components for chickens and swine, second cycle dairy refrigeration, water heating tests also using the 8 kilowatt machines and economic analysis of dairy refrigeration are also planned.

Sandia will continue actively as our lead center for vertical-axis work. As such, they will continue with the 17-meter VAWT research testing and redesign. Technology development will be continued for structural dynamics. For the machine optimization studies, we will continue the development and procurement of the so-called low-cost units. We will work on technical development of the cambered air foil work, and depending on the availability of funds, the machine development program for medium-scale VAWT using the machine optimization and the structural dynamic codes developed in the program.

Summarizing, the small systems will involve a good amount of work. Looking at viewgraph 9 (Estimated budget for FY80) there will be a continuation of the present programs with MOD-0A at Clayton, which has produced a quarter of million kilowatt hours in its first year. The few problems encountered are related primarily to blades and subsystems. We believe we have that fully corrected now. The Culebra MOD-0A is now operating. Block Island will be ready to turn this month, and the Oahu turbine should be operational by next spring. For the MOD-1 unit, the outlook is good, the tower is up, the technical problems, especially with the blades, have been resolved. This month, blades will be completed, tested to eighty percent of their design limit load and shipped to Boone, North Carolina. We expect the unit to be operational in May and the test program will last two years. MOD-2 is currently in its final phases of detailed design. The current projections of machine costs indicate a production cost of less than two million dollars per machine. As indicated earlier, this is a projected cost of energy of less than four cents a kilowatt hour based on full production run for the one hundredth machine including spare parts, operation and maintenance and installation, in a twenty-five unit cluster of sixty megawatts. This does not include such costs as land.

In addition, there will be new large machine development programs. There is an advanced multi-megawatt wind turbine project in planning. The third generation large machine will approach full commercialization and compete directly with fossil-fueled generating systems in a significant area of the country. The goal is to get system costs twenty to fifty percent below the MOD-2 cost currently being realized. The program will involve extensive conceptual studies and technology development with a contract to be let in 1980. There will be an advanced multi-purpose medium scale wind turbine project, also to be contracted in fiscal year 1980. They will be in the same size ranges as the MOD-0A, but a definite step forward and targeted for small utility applications and possibly certain large farms and industrial applications.

Technology development will continue for these larger units with experimental tests on the MOD-0 in support of the MOD-2 and other advanced machine programs. There is a teetered hub with tip controlled rotor design, evaluating the effects on structural loads and performance. A one-blade rotor will be used to study lower cost of materials and fabrication for blades. The MOD-0A rotor constitutes more than one half the cost of the machine. Other tests are being planned. As you will notice from this Wind Branch funding chart, the Federal

Wind Program has recently been restructured. We found under the old structure we were forced to describe the program in terms of organizations and organizational activities and machines, and that it defied cohesive, specific, and progressive program description. This new structure provides a better fit with the FY 80 program plans and is more in keeping with other DOE research activities.

You may be interested in seeing in the crosswalk charts how the new structure relates to the old one in your specific areas of interest. (Viewgraph #10, a comparison of the old and new Wind System Program structures as they would relate to the President's 1980 budget) The new 1.0 Research & Analysis relates directly to the former 1.0 Program Development except that Wind Characteristics and Technology Development have been removed. Wind characteristics research, performed almost entirely by Pacific Northwest Laboratory, is now a separate program element, which is more appropriate to the specific and prominent role it plays in the program.

The other changes below, rather than reflecting a need for clearer organization, facilitate a requirement for better tracking of wind program progress. Technology Development activities, formerly imbedded as a sub-element of Program Development, now comprise element 3.0 and are being performed by NASA, Rocky Flats, and Sandia. All machine development falls under a single program element now, 4.0. Previously, all program elements had machine development components. The Implementation element, 5.0, will encompass such activities as the Field Evaluation Program.

We are finding this a more workable program structure, and expect that you, too, will be better able to identify program activities and funding levels. (Viewgraph #11, Wind Systems Branch Management organization)

I guess the next question that comes to mind is, "How are you people going to implement this program," referring to Dan Ancona and Lou Divone. That situation is changing somewhat. First of all, we are recruiting two new program managers for headquarters to work with Dan and Lou in that area.

I think, though, that this will not change the Branch policy of conservatism in its basis for energy cost, machine cost, and study result projections. We try to recognize and properly apportion our costs to users, and utilities and we recognize the probability of demand charges, etc. Land costs must be considered. In the Wind Branch, we like to feel you get what you think you paid for. The charges are properly allocated. We are more in line with good accounting practices, using strong sales efforts, than the type of TV commercial that makes claims that are difficult to live up to.

As most of you may have heard, the implementation will be decentralized. Viewgraph #11 shows how that will be handled. The division of activities will be in three areas beneath headquarters. NASA-Lewis will retain the large systems. SERI will conduct the study efforts for use through sub-contracts as well as in-house work, and will include many of the present contractors. They will also conduct innovative programs. Dr. Vas is the coordinator for all these efforts. A field office is being set up with the help of the Albuquerque Operations Office. I will manage that effort for Wind Systems Branch at Albuquerque. For those of you who keep saying, "Yes, we've been hearing that for sometime, too," my reporting date is July 9, 1979.

Recapping, the technical management responsibilities for the various organizations are held by Lewis Research Center which provides technical management for large and intermediate system development program and also provides the supporting research technology effort for these programs. The Rocky Flats Plant manages the test center for the commercially available wind systems, administers the small machine development, and such implementation efforts as the field evaluation program. The U.S. Department of Agriculture will continue to administer research and development projects related to agriculture applications of wind systems. This includes developing requirements for those systems. Sandia Laboratories provides technical management of the vertical-axis wind turbine machine development program and related services such as reporting and research technology projects. The Solar Energy Research Institute administers the research and analysis portions of study elements of the program which include mission analysis, systems analysis, economic, market and application studies. SERI investigates the institutional aspects of WECS usage and investigates innovative wind system concepts. The Pacific Northwest Laboratories, as operated by Battelle Memorial Institute, will continue to conduct both the in-house and contract wind characteristics portion of our effort, with which many of you are already familiar. And now, where to from here? As the price of energy rises, the commercialization prospects for wind energy heighten. In fact, I think we can state with considerable amount of confidence, that we will soon be too competitive to ignore. I think the cost ranges shown on the charts earlier show a strong probability that, with the exception of the strained Federal budgets, things look good for wind. And we expect this to continue unless there is some stunning and unforeseen turn-around. The field evaluation program, administered by the Rocky Flats Plant, will essentially double wind systems sales for this year. Institutional problems should be resolved within a year or two, using the data from that program. And that should be immensely important in determining costs of maintenance, establishing a maintenance network, informing people that the installation throughout the United States is possible in connection with the utilities, and what the procedures are for interconnecting. There will be a very useful handbook, "How to work with your utility to get your wind machine hooked up and turning." Much of the first generation testing will be completed by the end of 1980, and by that time the market study results should be available that would coincide with much of this other work. It is likely that much of the funding will be provided through the Wind Branch for R&D at the present time.

We have seen little provided through other sources for direct commercialization. As I said earlier, I strongly believe that in this timeframe we will be too cost-competitive to ignore. Both the large machines and the small will enter the open market and will succeed because they are cost-competitive. They will do this with the assistance of large demonstration projects if we can provide the proper information and get it properly disseminated to the American public and to its utilities. In the long run, this may be the best way. We must do a much better job of selling our programs, our capabilities, our applicability and our availability. Succeeding without the impetus of large scale Federal buys makes for a healthier market. A market which depends on Congressional appropriations is a market which is subject to the political climate of the day. Demonstration programs have not always had the intended effects. I think it is very important to note that many of the industries which have been under Federal regulation for years are now asking for deregulation, that is, the airlines, and oil industry, who conducted their activities in a very regulated situation, supposedly for their protection. The airlines, at least, appear to be doing very much better with their new measure of independence than they did under the Federal wing. I believe the wind industry is composed of the type of entrepreneur who not only can make it in that market, but may very well be far more successful and far happier in that situation. I do not represent an anti-Federal or anti-bureaucratic turn of mind, but I also know that conducting business is much simpler with fewer Federal forms. It is the aim of the Federal Wind Energy Program to provide the technical capability and tools with which the industry will be working in these coming years. We will go on working toward that end, and if it is the intent of Congress, the people, and the industry that we should assist in providing demonstration programs, we would be more than pleased to work with you. Under the present funding, though, that appears unlikely.

Inventors, innovative engineers and scientists, represent the epitome of the independent activity I was talking about above. It is they who will guide us into this new era of energy. Where does one work more independently than inside his own mind? Ben Franklin once said that no man is so gainfully employed as when he is promoting his own enlightened self-interests, and I think that still holds true.

In summary, innovation in the energy world must lead to better ways, not just change. Certainly, it is not simply a question of changing styles, as with consumer goods, but one of the continued viability of our economic and social systems. This truth of our energy problem is very hard for us to swallow, but it is truth nonetheless, and we must address it with this attitude.

The attractiveness of wind as an alternative energy source makes it imperative that we be especially careful in our assessment of the possibilities this technology can provide us. The devices which will work to provide wind energy are picturesque and intriguing. They represent imaginative and dedicated work. I remember seeing an article in Popular Science some time ago which illustrated a variety of different devices one man had designed to harness wind energy. It was truly fascinating. But unfortunately, economics so often tempers our enthusiasm down to the bone of reality and makes us think less of ideas we believed to be full of such promise. This is the case most of the time, but happily, not always. A handful of the astronomical number of patents for wind energy devices are capable of surviving in the harsh light of reality. As I have said earlier, we want to determine which ideas will survive and we want to do this as early as possible so that funding will be extended to cover the activities that can bring them to fruition. We work hard not to overlook these ideas. There are still many concepts which can make a valuable contribution to the technology. I hope that yours is one of these. Thank you.

RESPONSES TO THE TENNYSON PRESENTATION

James Yen, Grumman Aerospace Corporation: Does cost estimating include land costs? For a single unit, land costs may be insignificant; however, for multiple units, the total land involved might be quite significant. The next point to consider is the life cycle cost of the system, not the initial cost only. Life cycle costs can only be developed after a period of credible testing. There is a vast amount of energy in the air compared to the total oil imports of our country. We will not be able to utilize this energy if we only talk about small units. We must start considering large megawatt units, on the order of 100 MW.

Irwin Vas, SERI: Land costs are not part of the innovative system task itself and, therefore, will not be discussed in any detail. Land costs, however, are included in various studies of the Federal Wind Energy Program.

Tennyson: Land costs are a very important issue and are to be assessed within the Federal Wind Energy Program.

Gerald Leigh, University of New Mexico: The prospects of the future wind energy program appear very exciting. However, I do not see a trend towards large-scale application of the vertical axis machine. The vertical axis machine is an innovative system which will continue to be studied. We should start working on large vertical axis machines, just as we did on large horizontal axis machines many years ago.

Tennyson: A study was completed last December which indicated that the vertical axis machine was cost competitive with the horizontal axis machine. Part of the effort is to define a mid-sized vertical axis unit which was described in the talk. If the analysis indicates that such a unit is cost competitive, we will continue pursuing the idea of a mid-sized machine. Vertical axis machines appear to be competitive now, and small machines are in operation at Rocky Flats. The verticl axis machine may be only half a generation behind the horizontal axis machine. Analysis work will continue for vertical axis machines; in fact, it is branch policy to consider all available options.

Vas: Within the Wind Energy Innovative Systems task we do not assess these two types of machines: the conventional horizontal axis and the conventional vertical axis Darrieus system.

Question: Can you give us any idea what the FY81 budget is for the innovative systems program?

Tennyson: Specific numbers cannot be quoted at this time. We have been requested to make budget plans for FY81. In general, the FY81 budgets are not lower than FY80 budgets, and in most cases they are significantly higher.

Terry Cooper, Nautilus Balloon Works, Inc: There is approximately $900 K for innovative systems in FY79 and $2.2 million in FY80. Are those numbers associated with subcontracted efforts, or do they include administrative costs also?

Tennyson: Those numbers are the total for the program which includes administrative costs. Administration and monitoring of contracts are carried out by the Solar Energy Research Institute; however, those costs are not a major part of the total cost.

Question: NASA is conducting tests with large machines. Has much wind tunnel work been performed for these machines? The aircraft industry in general does significant model tests prior to full-scale tests. What is being done with wind machines in this area?

Tennyson: Extensive tests have been carried out on wind machines. Scale model work has been conducted on the MOD-OA with tip variations and teetered hubs. Basically, there is no major problem of getting the performance characteristics of the machines. Problems are usually associated with costing the system and blade fatigue. It is possible that fatigue tests done on large planes like the 747 or B52 may not have provided conclusive results. However, they were an important step towards the program goal. There are certainly people who feel that we should build mid-scale machines for test and development, but remember that mid-scale machines are not cost effective at the present time. We are evaluating the large machines which may involve some risk; however, there is a good chance of their success.

Lawrence Rowley, Canadair Ltd: Do the utilities in the United States play a large part in the implementation of the program?

Tennyson: We keep in constant touch with the utilities. Different groups within a utility address different issues. The research department will discuss any type of machine; the operating department will only discuss tried and proven machines, and the financial group will only commence discussions if they feel that they can make a profit. In general, they would probably only discuss proven concepts. We are always in close contact with the utilities, and they appear to be forward thinking.

Donald Anderson, Lafayette Engineers: You had said that USDA was testing an 8 kW machine for heating in its farm program. Could you explain this further?

Tennyson: The 8 kW machine would be similar to those used in the Rocky Flats development; for example, the Windworks and the UTRC models. Some machines will be given to USDA for testing and development in the future. However, no further information is available at the present time in this regard. USDA is using a Pinson machine for water heating now. You may wish to contact Mr. Lewis Liljedahl of USDA in Greenbelt, Md., for further information.

Paul Migliore, West Virginia University: I believe that characterizing the Darrieus vertical machines as conventional is a little premature. How does one respond to innovative ideas which deal with quasi-conventional wind turbines? When one moves a concept from an innovative stage to a conventional large-scale system, large amounts of dollars are spent. How do you cope with new ideas in these so-called conventional systems?

Tennyson: The provision is made through the technology development subelement which is handled through the development groups in each of the organizations. For instance, work on tetered hub and tip control is being performed at NASA Lewis.

Session I

OVERVIEW OF THE WIND CHARACTERISTICS PROGRAM

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ABSTRACT

Within the Federal Wind Energy Program, the Wind Characteristics Program Element (WCPE) has been established to assemble and develop wind characteristics information for those involved in 1) designing and evaluating the performance of wind energy conversion systems (WECS), 2) planning energy programs, 3) selecting sites for installing WECS, and 4) operating WECS. The technical portion of the WCPE has been divided into four program areas to expedite the accomplishment of these tasks. Research plans and overall progress to date are presented with emphasis on the Resource Assessment Program area.

OVERVIEW OF THE WIND CHARACTERISTICS PROGRAM[a]

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INTRODUCTION

The overall objective of the Federal Wind Energy Program is "...to accelerate the development, commercialization and utilization of reliable and economically viable wind energy systems" [1]. To achieve this objective the program is organized into several elements. The Wind Characteristics Program Element (WCPE), managed for the Department of Energy by Pacific Northwest Laboratory, has the specific responsibility of providing the appropriate wind characteristics information to those involved in:

- energy program planning
- site selection for installing wind energy conversion systems (WECS)
- design and performance evaluations of WECS
- the operation of WECS [2].

Applied research and development activities within the WCPE are currently addressing four key issues:

- the wind energy resource
- effective siting technology
- economically effective energy conversion
- wind turbine operation in existing electrical networks.

The first of these issues will be discussed in this paper.

Often confused with siting activities, resource assessment, as addressed in the WCPE, refers to the large-scale analysis (i.e., the United States or a collection of several states) of the wind energy resource by producing an estimate of: 1) the wind energy potential of a given area, and 2) the distribution of the wind energy within that area. In siting,

(a) This paper is based on work performed under U.S. Department of Energy Contract No. EY-76-C-06-1830.

however, a small-scale area of about 100 km or less on a side is surveyed for the most favorable locations for wind energy extraction. The smaller area may be selected on the basis of a previous resource assessment. In the WCPE, work in resource assessment and the development of siting techniques are carried out simultaneously in two program areas as depicted in Figure 1.

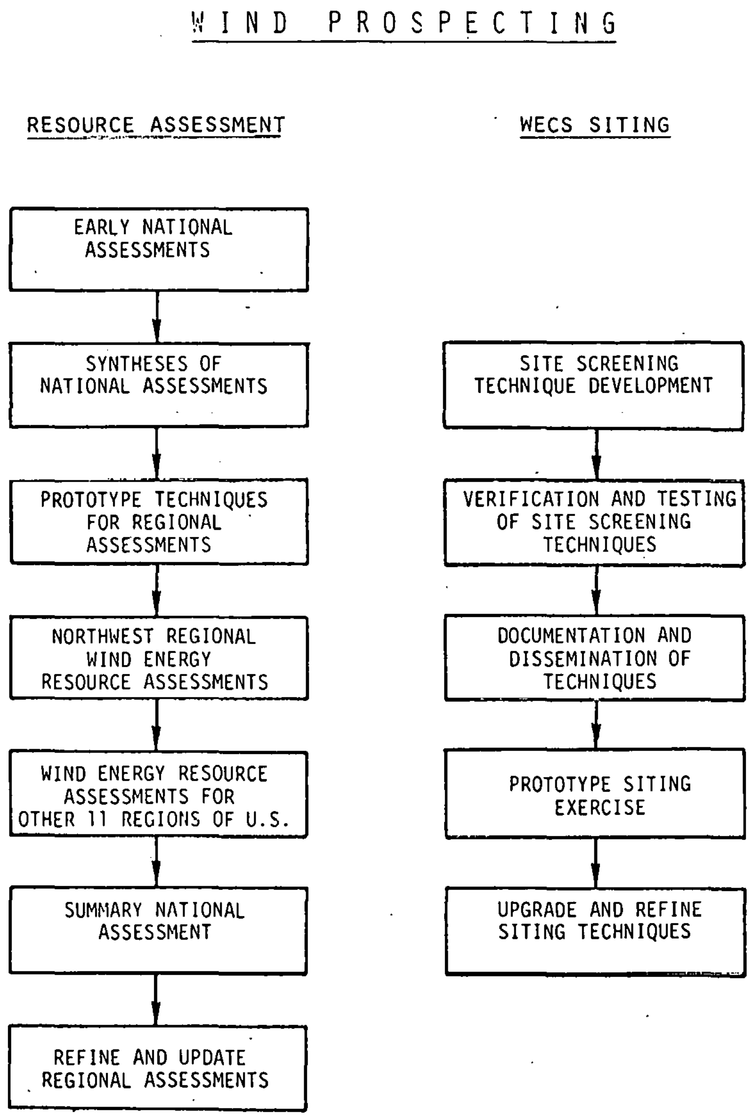

Figure 1. Sequence of Activities for a) Resource Assessment and b) Siting Activities in the Wind Characteristics Program Element of the Federal Wind Energy Program

NATIONAL ASSESSMENTS

Three national wind energy assessments were performed early in the Federal Wind Energy Program. The first assessment was published by Sandia Laboratories in 1975 [3]. The other two assessments were performed as integral parts of separate mission analysis studies and were based on the same National Climatic Center data as the first assessment. Because of discrepancies in the amount and distribution of the wind power density in the three national assessments, a synthesis of these assessments was completed in 1977 [4]. This synthesis was to analyze the causes of the discrepancies and to include the most plausible results in a single assessment (see Figure 2).

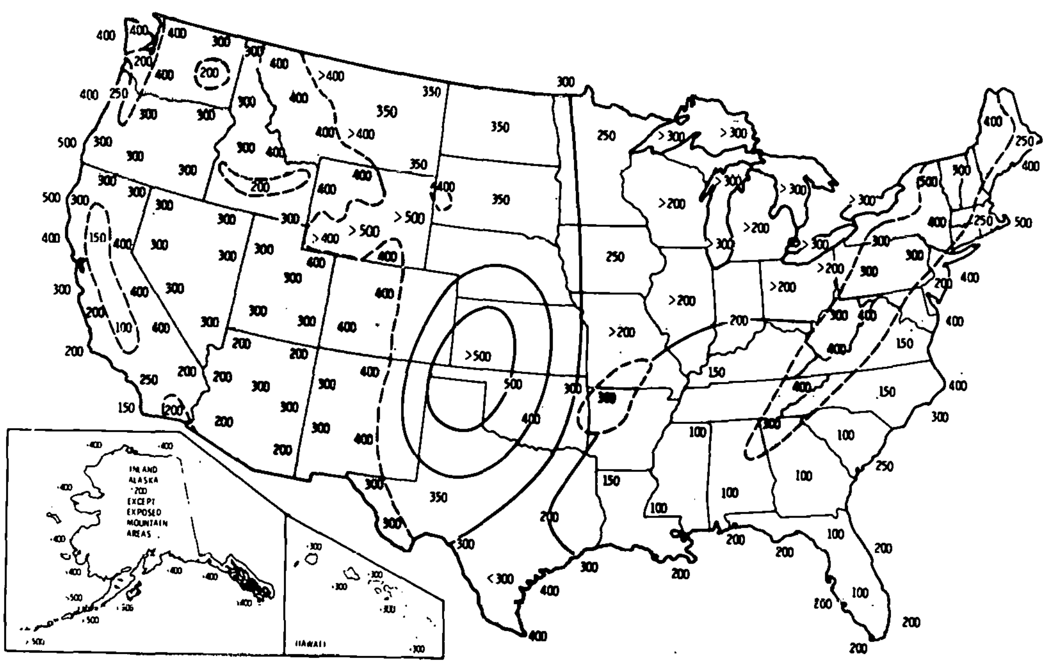

Figure 2. Annual Mean Wind Power (W/m^2) Estimated at 50 m Above Exposed Areas. The shaded areas indicate mountainous terrain in which the wind power estimates represent lower limits for exposed ridges and mountain tops (Elliott, 1977).

These initial assessments contributed to the preliminary wind energy scoping exercises; however, with increased interest in wind energy utilization, more refined and reliable assessments were required on a regional scale. For example, the wind power density values shown in Figure 2 are representative of terrain with good exposure to the wind. The amount of land in a given area with good exposure can vary from about 80% in flat terrain to less than 2% in mountainous terrain. This variation can produce unreliable estimates of wind-power potential in given areas within a region.

TECHNIQUES FOR REGIONAL ASSESSMENTS

The first objective of the WCPE's regional assessment was to develop and test prototype techniques for the analysis of wind-energy potential and distribution over a large area [5]. These techniques involved the utilization of a much larger data set, the application of meteorological and topographic factors in the analysis, and the use of indirect methods of wind-power estimation in areas where no wind measurements existed. Five states in the Pacific Northwest were selected as a test of these techniques.

The wind data stations in the Northwest region that were used in the national assessments are shown in Figure 3a. These stations represent

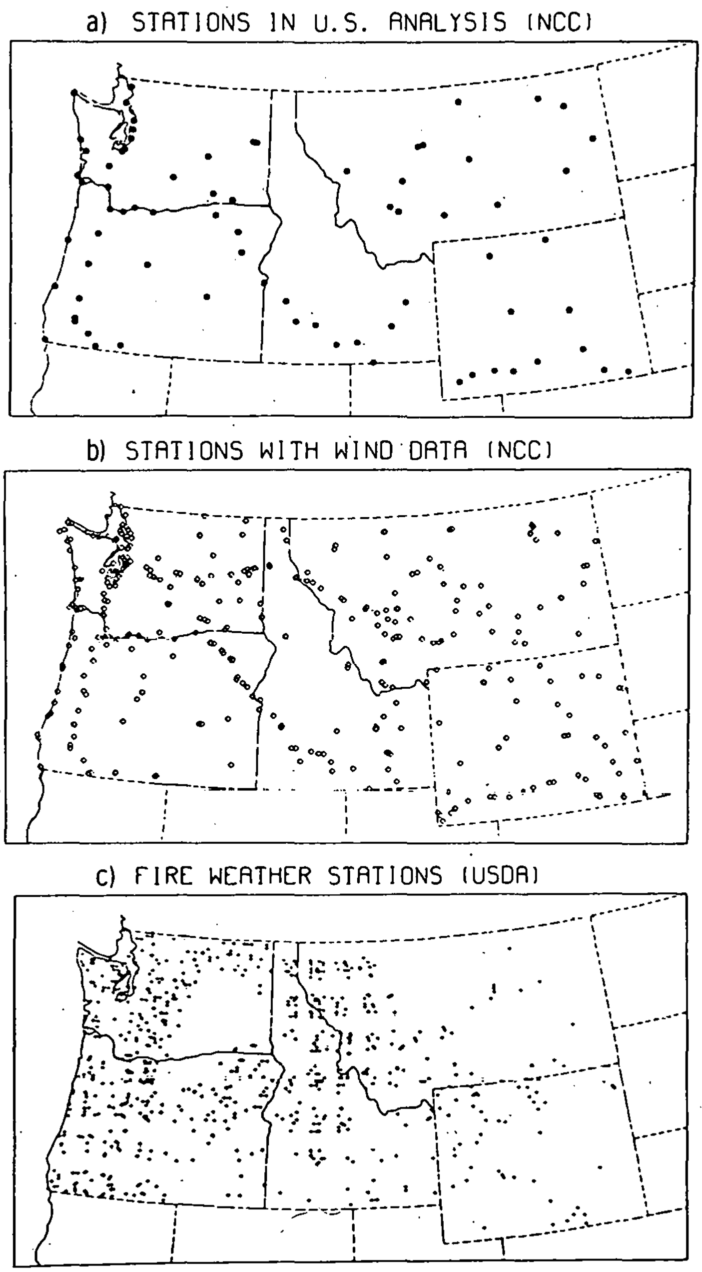

Figure 3. Locations of Wind Data in the Northwest

only half of the stations with summarized data available at the National Climatic Center (NCC). In Figure 3b, all stations with wind data in the Northwest region are shown. For almost 60% of these stations the data is in unsummarized form, but screening techniques may be applied to effectively utilize the information. Data from the Fire Weather Stations of the U.S. Department of Agriculture are shown in Figure 3c. Only a small fraction of this data is useful, but the data that can be used is usually from stations located in areas where there is no other wind data. As a result, the wind data coverage for the Northwest region was increased from about 80 stations to about 350 stations.

The increase in data coverage of more than a factor of four certainly contributes to a more reliable analysis, but there are still many areas of the region without adequate data for wind energy estimates. In many of these areas combinations of meteorological and topographic features can be employed in the analysis to enhance the reliability of the overall assessment. A few features that indicate high wind energy potential are:

- gaps, passes and gorges in areas of frequent strong pressure gradients
- long valleys extending parallel to prevailing wind directions
- high elevation plains and plateaus
- exposed ridges and mountain summits in areas of strong geostrophic winds.

Some features that indicate low wind energy potential are:

- valleys perpendicular to the prevailing wind direction
- sheltered basins
- short and/or narrow valleys and canyons.

The features listed above can be located in a region by careful observation of relief maps and typical surface pressure maps.

Other indirect methods of estimating mean wind speeds involve observations of deformed vegetation [6] and landforms affected by the winds [7]. These techniques were tested to a small degree in the Northwest region. The major portion of the assessment was accomplished with the enhanced data set and the topographic-meteorological analyses.

NORTHWEST REGIONAL ASSESSMENT

The wind power density was analyzed on a seasonal and annual average basis for each state in the region. The results of the analysis of annual average wind power for the Northwest region are shown in Figure 4. The increase in resolution can be seen by comparing this analysis with the analysis for the five Northwest states in Figure 2. The effect of the analysis of meteorological and topographic features is particularly apparent in the long valley in southwestern Montana and the large east-west valley in central Washington.

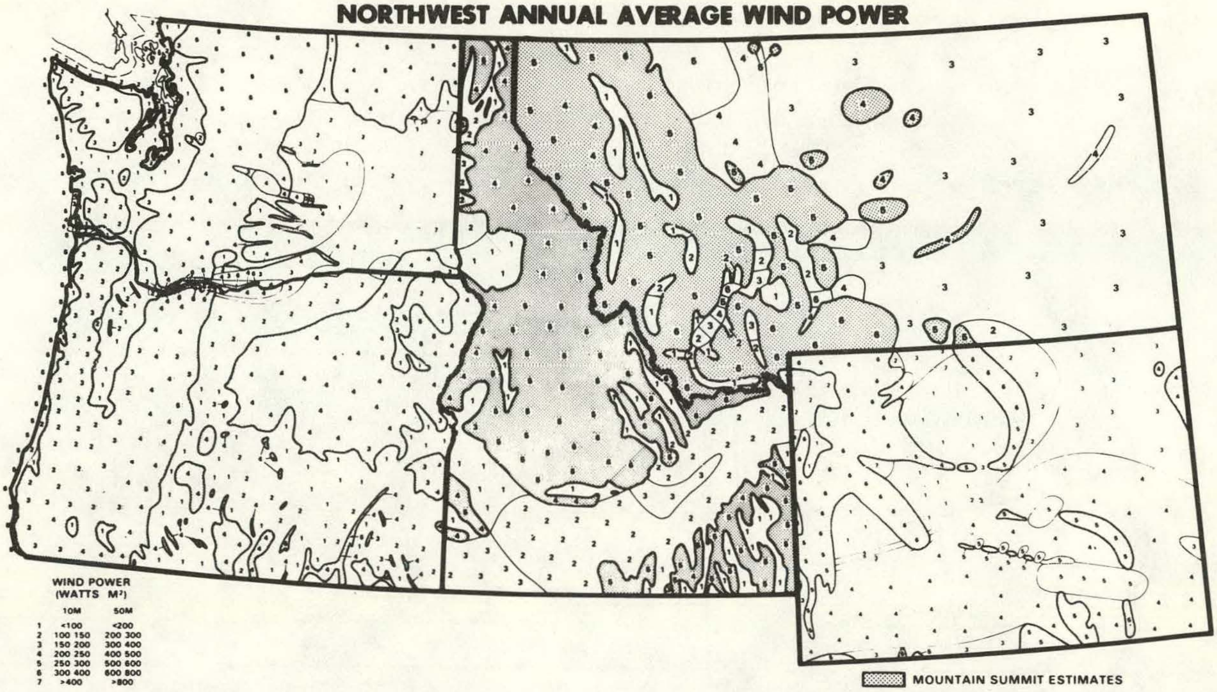

Figure 4. Annual Mean Wind Power at 10 m and 40 m Above Exposed Areas. Shaded areas represent mountainous terrain. (See Fig. 2 for detail.)

As in the national analysis (see Figure 1), the stippled areas indicate that the wind power densities apply only for the well-exposed terrain. However, in the regional analysis there is significantly more definition in the number and distribution of the values shown in the stippled area than was possible to show in the national assessment.

An estimate of the total wind power potential for any portion of the region may be obtained by digitizing the power density values and the landform classifications for the region onto a grid consisting of grid blocks that are one-third degree longitude and one-fourth degree latitude. By assigning selected fractions on the power density to different percentages of the area in the block, according to the landform classification, the wind energy potential for the block can be estimated. The analysis can be performed for any collection of blocks within the region to determine the power available as a function of land area. The grid approach provides a convenient way to assess the effect of existing and proposed wilderness exclusion areas.

Other information provided in the assessment of the Northwest region was a series of graphical data presentations for 12 to 18 stations in each state, depending on the number of stations with time-series data available. These graphs depict such quantities as annual, monthly and diurnal variation of wind speed and power, as well as frequency and duration curves for wind speed and power. The information produced from this analysis is to be compiled into an atlas containing the maps, graphs, tables and descriptions designed to meet the needs of a wide range of wind energy planners.

OTHER REGIONAL ASSESSMENTS

The wind power atlas for the Northwest region will serve as a guide for the analyses of other regions of the country. The Department of Energy has released a request for proposals to conduct wind energy assessments for the eleven other regions, shown in Figure 5, which cover all the

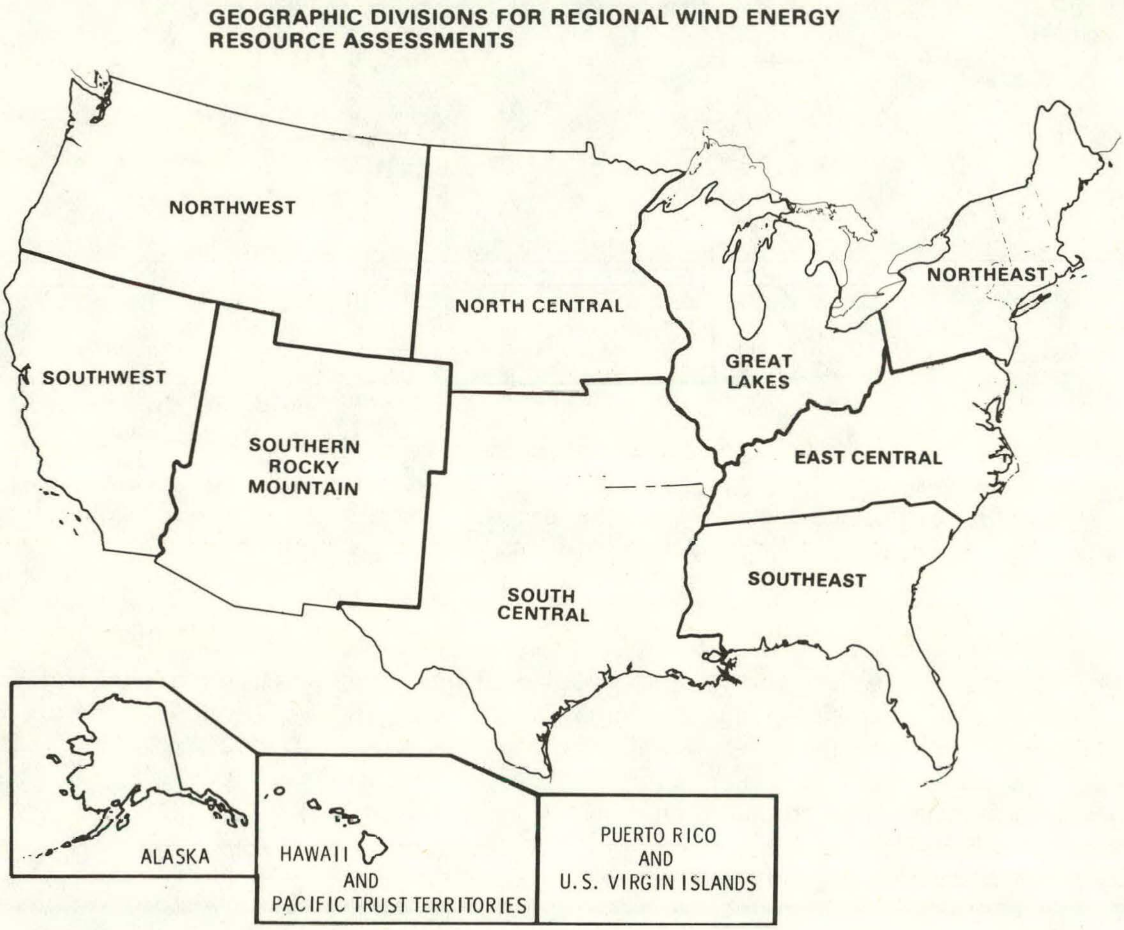

Figure 5. Geographical Divisions for Regional Wind Energy Resource Assessments

other states and territories of the United States. The present goal is to complete all the regional assessments by October 1980. In the process of completing these regional assessments, a wind energy data base will be established in a form for convenient updating as wind data becomes available.

SITING METHODOLOGIES

As indicated in Figure 1, the initial effort in this program area is the development of site-screening techniques. Several techniques have been developed to the point of needing verification and testing before any further developmental work is decided upon. Techniques that are candidates for verification are numerical modeling, physical modeling, and observation of deformed vegetation. A data set that includes wind measurements from a collection of stations in complex terrain has been prepared for testing the screening techniques using numerical models.

One of the most important aspects of the siting program area is appropriate documentation of the techniques for the various kinds of siting needs. In an effort to meet the needs of small WECS users, an interim handbook with a step-by-step description of a siting method has been prepared and distributed [8]. This handbook is under revision on the basis of review comments on the interim handbook. A revised copy of the handbook has been used as a text in a trial presentation of a short course on siting small WECS. Both the handbook and short course are intended primarily for the layman interested in wind power for personal application.

A siting handbook for large WECS is being prepared for review. This document is aimed at a more technically oriented audience and is intended for use by utility companies and other potential users of large machines.

CONCLUSIONS

One of the primary concerns of the utility companies in the utilization of wind power is a reliable assessment of the resource. It has become apparent that the initial national assessments will not meet the needs expressed by the utilities and their representatives. The expressed needs have two conflicting criteria: one is that the assessment be as reliable as possible, and the other is that it be produced as soon as possible. Obviously the approach in the WCPE is to take a middle ground and produce an assessment as soon as possible with the capacity for being updated conveniently. This will mean that planners with urgent needs will have something to work with which has significantly better resolution and reliability than the national assessment. Planners who are more concerned with reliability will have something to work with which they can develop confidence in as they see it verified and upgraded by new data in their region of interest.

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ENERGY TECHNOLOGY AND COMMERCIALIZATION ISSUES

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ABSTRACT

The U.S. Department of Energy has been given the responsibility to conduct programs designed to facilitate the early development and commercialization of alternative sources of energy. Considerable emphasis is being given to technology development for renewable sources. Market demand, price, infrastructure requirements, legal-social-environmental issues, and competing technologies are being studied and assessed with respect to utilizing government incentives and subsidies to accelerate commercialization. Technical issues form one part of the requirements. More importantly, appropriate steps must be taken to secure a commitment from the private sector. The economics of the technology must be clearly understood and adequately demonstrated, along with reliability and performance. This paper reviews the current DOE Wind Energy Program and addresses the above issues in relationship to it. References are made to previous government sponsored development and demonstration projects; where appropriate, analogies and experience are related to the Wind Energy Program. Commercialization requirements, as viewed by the supply and market sectors, are emphasized.

Introduction

Wind Energy Conversion Systems (WECS) appear to be one of the near term technologies that are currently included in the Department of Energy's portfolio of alternative energy sources. The issues to be addressed in this paper, with respect to energy technology and commercialization, are related to WECS. An integral part of most federally funded development projects is the demonstration of technology and processes being developed. There is ample documentation of past projects in which the government has been involved, as well as several independent studies. It is appropriate to review some of the details of these past projects, with an eye towards benefiting and learning from these efforts, and to apply the experience to the WECS program. The current DOE Wind Energy Program plans to spend in excess of $200 million on various demonstration efforts. Thus, any assistance that could be gleaned from what history has shown to be either the "good or bad" points about what should be demonstrated, by whom, and when, could be put to good use in the WECS program, as well as in other DOE programs.

There were six principal sources of data used in completing this research; they are listed in the Bibliography.

The four principal topics to be addressed in this paper are: (1) historical perspective of federally funded demonstration projects; (2) requirements for energy system development and commercialization projects; (3) implications for WECS demonstration projects; and, (4) concluding comments relative to the DOE/WECS Program in general.

Historical Perspective of Federally Funded Demonstration Projects.

The demonstration of a new technology or process is an integral part of the development program, the latter covering everything from the initial concept stage on through to full-scale production and commercialization. The purpose of most demonstrations is to generate new information to aid decision making by potential adopters and other target audiences. New information is directed toward reducing five kinds of uncertainty [1]: technological; cost; demand; institutional; and, uncertainty about externalities.

The first of these, technological uncertainty, has to do with questions related to the feasibility of the technology and its application to the specific situation with which this project is concerned. Hopefully, the demonstration will show that the technology is sound and well understood; that the system performs in a predictable and controllable manner; and that there are no unexpected technical surprises which would require major redesign or system reconfiguration.

Another important factor that is addressed by the demonstration is the economics of the system under development. It is very important that the uncertainty in the cost of manufacturing the product and operating a process be ascertained as early and accurately as possible. The uncertainty can be minimized by scaling the demonstration such that it resembles the anticipated full-scale actual application as closely as possible, and that the conditions of operation are also realistic.

Hard data relative to the other three areas of uncertainty are more difficult to obtain. Demand uncertainty has to do with quantifying the benefits, both private and public, that will accrue from use of the technology. Institutional uncertainty deals with how adoption of the technology will affect the functioning and structure of the adopting organization and, secondly, the adopting organization's relationships with other organizations, such as labor unions or competitors. Uncertainty about externalities — health, safety, environmental and other effects that are not accounted for in the price of either factor inputs or outputs — can be critical to the ultimate success and adoption of the new technology and must be reconciled at the earliest possible time before a commitment can be made to full-scale commercialization.

The means by which information can flow from and to the demonstration project are illustrated diagramically in Figure 1 (taken from reference 1). It is imperative that the target audiences be identified and that their specific needs and concerns influence the planning and execution of the demonstration. Dissemination channels must be provided in order that information about the various uncertainties mentioned can flow freely to the target audiences as the demonstration actually proceeds. Credibility for the

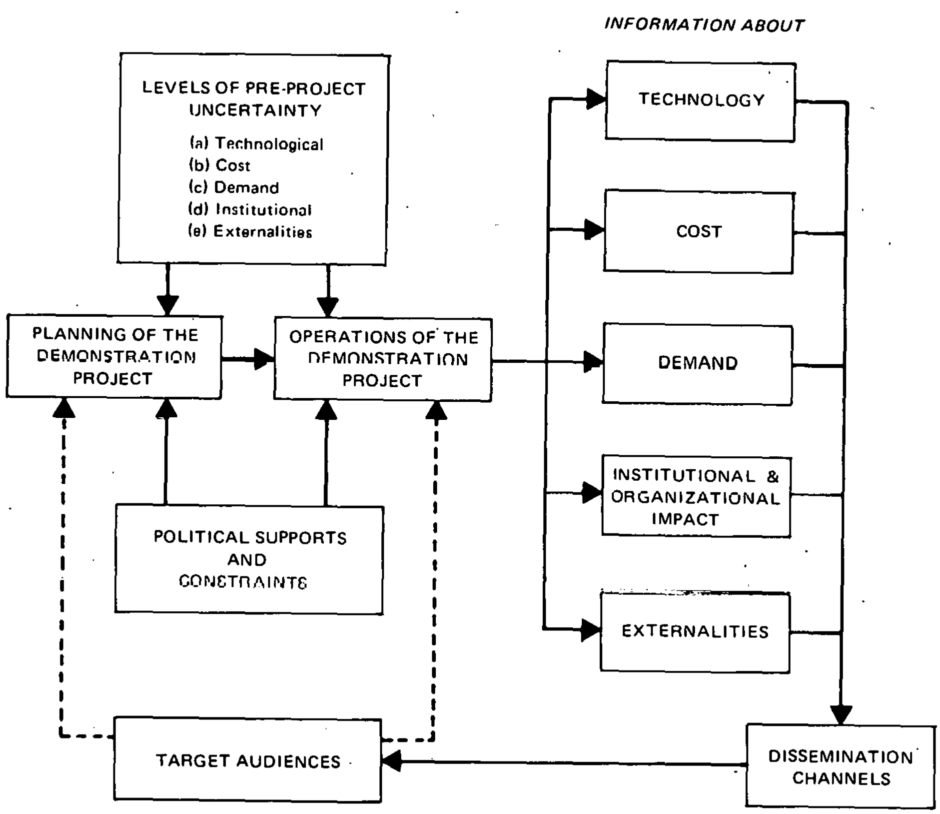


Figure 1. A Model of New Information Flows In Demonstration Projects

results of the project can be expected only if there is relatively free and open access and participation in the demonstration by those who are considering investing in and adopting the new technology or process.

To understand more specifically how energy system development projects can be most effectively organized and carried out, with the maximum amount of benefit being derived from the demonstration phase, it is appropriate to review some past federal projects. In Figure 2 there are thirteen selected case studies of federally funded demonstration projects listed. Data relative to these cases was taken from references 1 and 2.

For each of the listed cases, twelve project characteristics are indicated. A fully shaded circle means that the characteristic is as listed on the bottom of the figure; an unshaded circle is interpreted as meaning the characteristic is the converse of the indicated statement. For example, successful projects are indicated with a shaded circle while unsuccessful ones have an unshaded circle under "project characteristic #1"; a partially shaded circle indicates a partially successful project.

The first five listed projects were found to be successful, the next three partially successful and the last five unsuccessful. Detailed review of the various project characteristics revealed a high degree of commonality within the successful projects. In the group of unsuccessful projects, it was determined that for the most part all of the "preferred" traits identified in the success group were missing. A successful project is defined as one in which the technology or process being developed and demonstrated was eventually commercialized and accepted in the marketplace — a diffusion success.

Analysis of the data given in Figure 2 and the indicated trends points to several conclusions about the appropriateness of demonstration projects and characteristics that contribute to diffusion success [1]. These conclusions are:

1. Demonstration projects have a narrow scope. They are most effective when diffusion is hampered by lack of knowledge in the hands of potential adopters regarding the use of the technology under commercial operating conditions.

2. Diffusion depends on "market pull" rather than "technology push". In the absence of a well-articulated market demand the pursuit of demonstration projects is an especially risky activity.

3. Demonstration projects appear to be weak tools for tackling institutional and organizational barriers to

SELECTED CASE STUDIES OF FEDERALLY
FUNDED DEMONSTRATION PROJECTS

PROJECT NAME	PROJECT CHARACTERISTICS											
	1	2	3	4	5	6	7	8	9	10	11	12
1-SHIPBUILDING R&D AND DEMO	●	●	○	●	●	●	●	●	●	●	●	◑
2-YANKEE NUCLEAR POWER REACTOR	●	◑	○	●	●	●	◑	○	●	●	●	●
3-HYDRAULIC KNEE PROSTHETIC DEVICE	●	●	●	●	●	●	●	○	●	●	●	○
4-POULTRY WASTE PROCESSING	●	●	◑	●	●	●	●	●	●	●	●	◑
5-EXPRESSWAY SURVEILLANCE & CONTROL	●	●	○	●	●	●	●	●	●	●	●	◑
6-MECHANIZED REFUSE COLLECTION	◑	●	◑	●	◑	●	●	●	◑	○	●	◑
7-REFUSE FIRING DEMONSTRATION	◑	●	◑	●	●	●	◑	●	●	●	●	◑
8-SALINE WATER CONVERSION PLANT	◑	○	◑	●	●	◑	◑	○	◑	●	●	◑
9-NUCLEAR SHIP SAVANNAH	○	○	○	○	○	◑	○	○	◑	○	○	○
10-FISH PROTEIN CONCENTRATE PLANT	○	○	○	○	○	○	○	○	○	○	○	○
11-DIAL-A-RIDE TRANSPORTATION SYSTEM	○	○	○	○	○	○	○	○	○	●	●	○
12-INDUSTRIALIZED HOUSING TECHNIQUES	○	○	○	○	○	●	●	○	○	○	○	●
13-PERSONAL RAPID TRANSIT SYSTEM	○	○	○	○	○	◑	○	○	○	○	○	○

CHARACTERISTICS: ● (CONVERSE INDICATED BY ○)

(1) PROJECT SUCCESSFUL
(2) LOW TECHNOLOGICAL PUSH
(3) HIGH MARKET PULL
(4) INFORMATION SUCCESS
(5) DIFFUSION SUCCESS
(6) APPLICATION SUCCESS
(7) LOW TECHNOLOGICAL UNCERTAINTY
(8) NONFEDERAL INITIATIVE FOR DEMO
(9) STRONG TDS
(10) ALL TDS ACTIVE IN DEMO
(11) LOW EXTERNAL TIME CONSTRAINTS
(12) LOW FEDERAL SHARE OF FUNDING

Figure 2. Selected Case Studies of Federally Funded Demonstration Projects

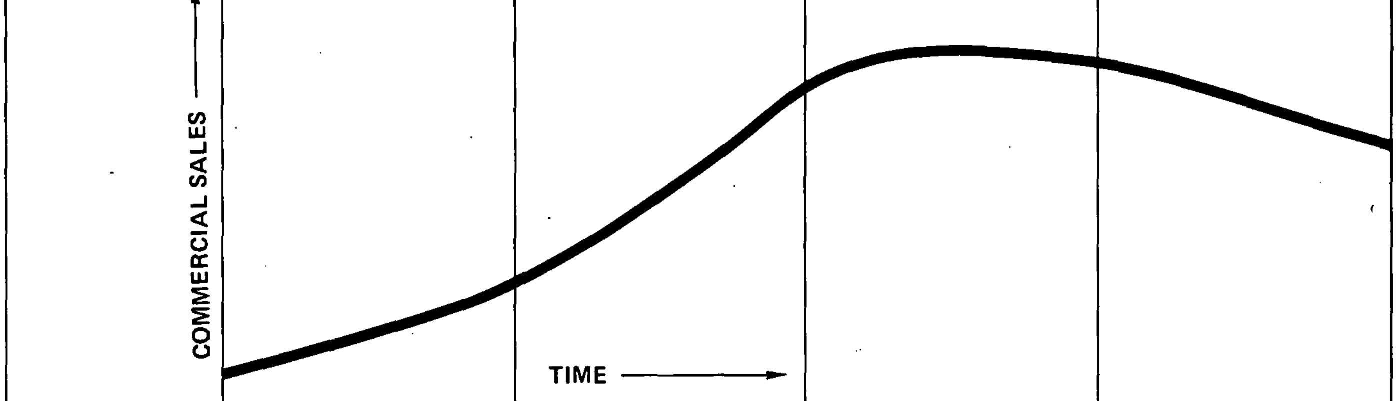
diffusion. Other government interventions, such as changes in regulations or subsidies, may be more effective than demonstrations in stimulating diffusion in such situations.

4. Large demonstration projects with heavy federal funding are particularly prone to difficulty. Heavy federal investment tends to make projects highly visible and vulnerable to political pressures detrimental to success.

5. Dissemination of information from demonstration projects is generally not a serious problem. When projects fail to achieve diffusion success, they generally do so not because of weaknesses in the information network, but for other reasons as noted.

At this point it is appropriate to review what some of the principal characteristics and concerns are for typical energy system development projects. The government has been pursuing the development of various technologies over the years through many of its agencies. The Department of Defense has been an especially large procurer in this respect. Typical concerns in these projects have been' technology development; the cost of the required research, design, development, test, and evaluation; and the extent of the resources required. However, the projects being carried out under the charter of the Department of Energy have at least four additional areas of concern. Unlike the DOD, the DOE is not the customer for the technology being developed; therefore, DOE must be concerned with the commercial feasibility of the technology. Additional concerns are the time to full-scale demonstration, operational economics, and environmental effects.

It is important that, in addition to recognizing the above mentioned concerns, we gain additional insight into how industry views a new product, such as wind energy systems. The process of developing, manufacturing, and marketing a product is illustrated in Figure 3. Termed the product life cycle, there are four distinct stages that characterize a products life: viz., market development, growth, maturity, and decline. Prior to investing in the development of a new product, industry must be reasonably sure of a net positive return on their initial investment. It must be remembered that, in general, industry has a portfolio of product candidates that it could invest its resources in, which includes both energy and nonenergy related products. Industry also has the option of not investing at all, or at least to wait until such time as the visibility into a candidate product's life cycle improves and the chances of successful commercialization improve. The financial exposure that a company encounters with investment in a new product must be adequately



	MARKET DEVELOPMENT	GROWTH	MATURITY	DECLINE
PRODUCT	DEVELOPMENTAL STAGES ONE-OF-A-KIND PRODUCT	PRODUCTION MODEL REFINEMENTS	FULLY DEVELOPED PRODUCT STANDARDIZATION	DEVELOPED, AND OVER CAPACITY EXISTS
PRICE	HIGH	DECLINING	COMPETITIVE	EXTREMELY COMPETITIVE
DISTRIBUTION	BY MANUFACTURERS	CHANNELS OPENING UP	ORDER TAKERS FOR DISTRIBUTORS	OVER-SATURATED
PROMOTION	DEMONSTRATION UNITS TO INTRODUCE THE PRODUCT	BRANDS BEGINNING TO EMERGE	MANUFACTURER DEALS DIRECTLY WITH CUSTOMER	FIERCE STRUGGLE TO RETAIN MARKET SHARE

Figure 3. Product Life Cycle

compensated for by the prospects of a commensurably high return on investment.

Requirements for Energy Systems Development and Commercialization Projects.

It is now appropriate to turn our attention to the details of how a typical energy system development project is structured. In order that there be an efficient and successful outcome of the overall effort there are certain activities that must preceed the accomplishment of other things.

A typical project is composed of five distinct phases, as is illustrated in Figure 4; they are (1) system concept

	PROJECT PHASE				
	-1- SYSTEM CONCEPT STUDIES	-2- SYSTEM DEFINITION STUDIES	-3- SYSTEM DESIGN DEVELOPMENT AND TEST	-4- DEMONSTRATION SYSTEM ACQUISITION AND OPERATION	-5- COMMERCIALIZATION AND DIFFUSION
ACTIVITIES	PROJECT PLANNING - ADMINISTRATIVE IDENTIFICATION OF ENERGY MARKET NEEDS AND CHARACTERISTICS IDENTIFICATION OF TDS REQUIREMENTS DEFINE PROJECT OBJECTIVES AND SPECIFIC GOALS DEFINE SYSTEM OPERATIONAL REQUIREMENTS	SYSTEM FUNCTIONAL ANALYSIS IDENTIFICATION OF ALTERNATIVE SOLUTIONS PERFORM TRADE-OFF ANALYSIS SELECT PREFERRED SOLUTION	DEFINE SUB-SYSTEMS SUBSYSTEM DESIGN COMPONENT SPECIFICATION AND TEST SUBSYSTEM FABRICATION, ASSEMBLY, AND TEST SYSTEM INTEGRATION AND TEST ANALYSIS OF TEST RESULTS (& REDESIGN?)	DESIGN AND CONSTRUCTION INSTALLATION AND TEST FUNCTIONAL OPERATION USER TRAINING	FULL-SCALE SYSTEM PRODUCTION – DESIGN – MANUFACTURE – INSTALLATION & TEST – OPERATION & SERVICE
OUTPUT	DOCUMENT PROJECT OBJECTIVES, PLANS AND GOALS ESTABLISH OPERATIONAL PERFORMANCE BASELINE	ESTABLISH TECHNICAL BASELINE	PROVE TECHNOLOGICAL FEASIBILITY PROVIDE EARLY ESTIMATES OF COST ESTABLISH DEMONSTRATION SYSTEM CONFIGURATION BASELINE	REDUCE ANY UNCERTAINTY IN TECHNOLOGICAL FEASIBILITY, RELIABILITY, AND COST FOCUS IS ON MARKET DEMAND, INSTITUTIONAL IMPACT AND OTHER NON-TECHNOLOGICAL FACTORS GOAL IS TO PROVIDE THE BASIS FOR WELL-INFORMED DECISIONS ON WHETHER TO ADOPT TECHNOLOGY	COMMERCIAL AVAILABILITY OF NEW ENERGY SYSTEM (DIFFUSION SUCCESS)

Figure 4. Structure of Typical Energy System Development Project

studies; (2) system definition studies; (3) system design, development and test; (4) demonstration system acquisition and operation; and, (5) commercialization and diffusion. It is important to note the specific activities and output for each phase. This must be clearly understood by those responsible for planning and carrying out the project, so that the probability for success can be maximized.

The principal output from each phase will be pointed out to emphasize how the sequential output of the project is ordered so as to build confidence in the energy system to be developed. For phase one, the objective is to establish the operational performance baseline for the energy system under consideration. It is important to know at this point in the project just what is to be required of the system when it is operating in its intended application. Until this is clearly defined it is difficult to proceed from this point in developing the system. It is also essential to know just what the eventual user and the specific application require, and that this be included in establishing the system performance requirements.

The second phase of the development project is structured to accomplish the establishment of the technical baseline for the energy system. Various analyses must be carried out, alternative solutions identified, and the appropriate trade-off studies performed so that a preferred solution can be defined. This must be accomplished prior to the specification of the technical baseline. If several options are kept open and the project attempts to move forward from here into the next phase, efforts will be greatly diluted and the project will quickly loose focus of the established objectives. Chances of success will plummet and the project runs the risk of becoming completely disoriented and wasteful of resources.

There are three important outputs of the third phase; they are to: (1) prove technological feasibility; (2) provide early estimates of cost; and, (3) establish the demonstration system configuration baseline. The need to accomplish these things is obvious. The technological and cost questions must logically be addressed at this point so that meaningful progress can be made in the demonstration phase that is to follow. Proceeding to the demonstration without first accomplishing these items can render the whole demonstration effort to be very risky and potentially wasteful of resources.

The fourth phase is concerned with the actual demonstration of a full-scale or near full-scale energy system. This usually requires the expenditure of a considerable amount of resources to design, construct, and operate the required hardware. For large systems this may also take several years to accomplish the full demonstration. It is, therefore, very important that it be success oriented in terms of preplanning and in the actual conducting of the demonstration.

It is also very important that there be participation by all appropriate segments of the infrastructure manufacturers, users, etc. — and that they share a significant portion of the financial risk and expense of the demonstration. Their participation is essential so that a maximum commitment can be obtained from them to adopt the new technology, which will then lead to a diffusion success in the fifth phase of the project.

The historical data available from the previously noted federally funded demonstration projects has assistated in developing four strategies for demonstration [1]. The strategies are stated as follows:

1. Conduct the demonstration on as small a scale and with as little initial visiblity as possible.

2. Do not emphasize large projects at the expense of small ones involving incremental improvements to existing products or processes.

3. Resist political pressure to demonstrate before a technology is well in hand.

4. Allow enough time in the project schedule for slippage, especially when undertaking large projects with significant technological uncertainty.

The foregoing strategies are representative of those that were inherent in the projects that resulted in successful diffusion into the marketplace. Therefore, it is appropriate to give them some consideration when making plans for new energy system demonstrations.

Implications for WECS Demonstration Projects.

It is instructive to review the historical experience of past federally funded demonstration projects to gain some insight into what might be expected in the upcoming WECS demonstrations. As mentioned at the beginning of this paper, it is noted that in excess of $200 million has been planned for WECS demonstrations. It is necessary to ask questions such as whether this is the correct level of federal participation, since industry and potential users are not sharing any real measure of risk in the process.

It was mentioned that all elements of the WECS Technology Delivery System (TDS) must participate in the project to the maximum extent possible, especially in the demonstration phase. The WECS TDS has four major participants and three others that are closely associated. This TDS is illustrated in Figure 5; it is taken from reference 3. The major participants are the equipment industry, distribution and marketing networks, installation and service mechanisms, and the end-use markets. Secondary participants are indicated as industry organizations, affected institutions, and affected government agencies.

Another issue that was brought out, in reviewing the historical demonstration project data, was that project strategies that had a stronger "market pull" focus were more successful than those that emphasized a strong "technology push". The relationship of these two plus a third primary strategy, "supply push", are illustrated in Figure 6. A project can be structured around any of the primary strategies, a combination or blend of then, and, further, this focus can be modified as the project progresses. It is frequently appropriate to emphasize a technology push early in the project and then to gradually shift towards a market pull as the demonstration phase nears. In other projects it might be appropriate to use some other combination of strategies, due to the specifics involved.

To create the best project environment and conditions for maximizing the probability for diffusion success in the WECS Program, the following guidelines should be applied to plans — especially for the demonstration phase.

1. Maintain a sharp focus for the program's objectives and goals. It is essential that there be a minimum number of objectives and goals — preferably singular. WECS can never be "all things for all people".

2. It is essential that the characteristics, needs, and requirements of the marketplace be clearly known and understood. Further, these implications should be reflected in, and form an integral part of, the plans and structure of the demonstration phase.

3. WECS should not be demonstrated prematurely nor on a greater scale and in greater numbers than is absolutely required to accomplish the appropriate objectives of that project phase.

4. It is important not to impose unnecessary time constraints on the achievement of "commercialization", but rather to have a well-planned and articulated program that proceeds in a sequential fashion through the various phases as previously described in this paper.

5. A maximum level of private sector participation in the project — especially the demonstration phase —

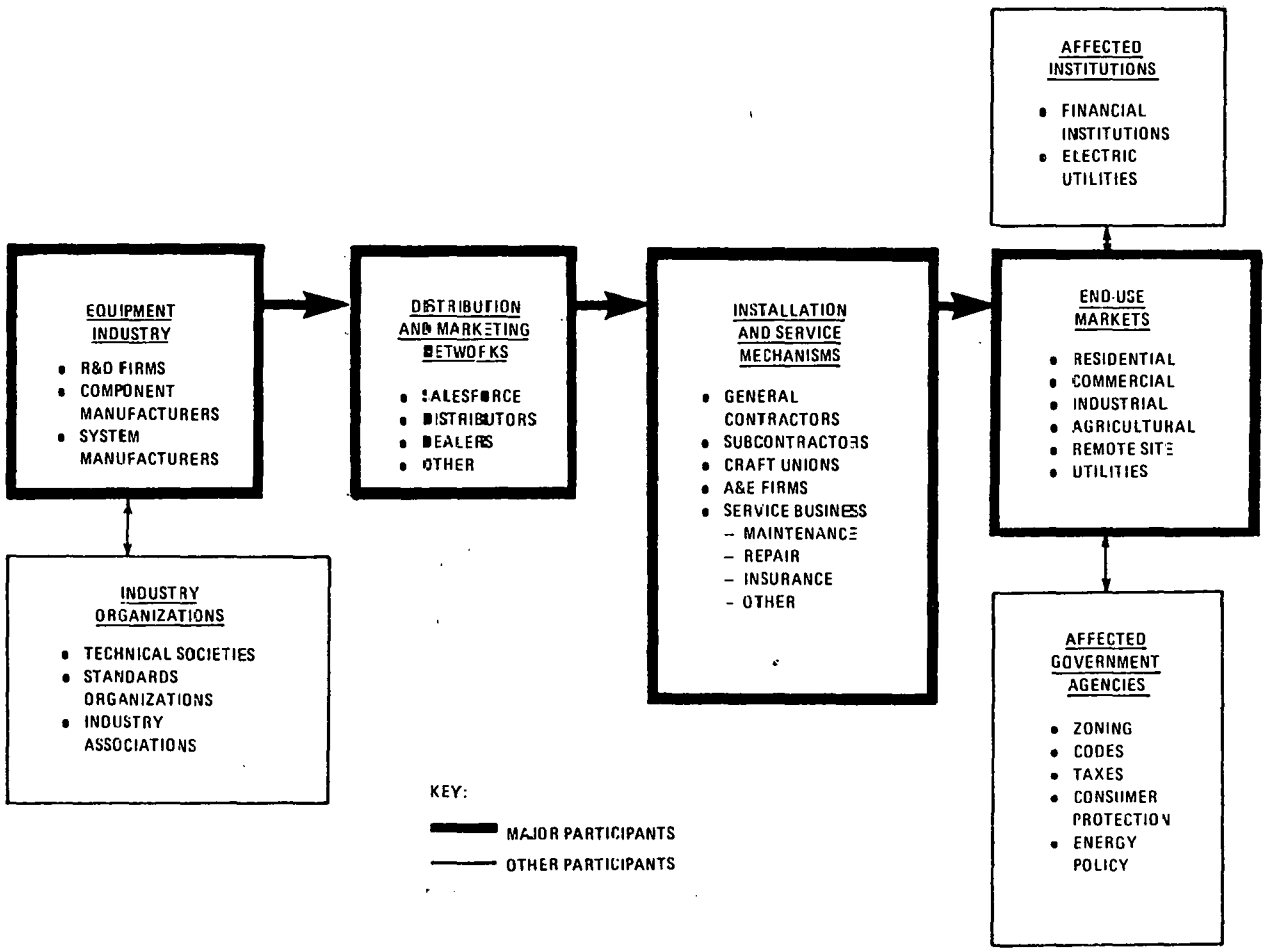


Figure 5. Basic Components of the Generalized WECS Technology Delivery System (TDS)

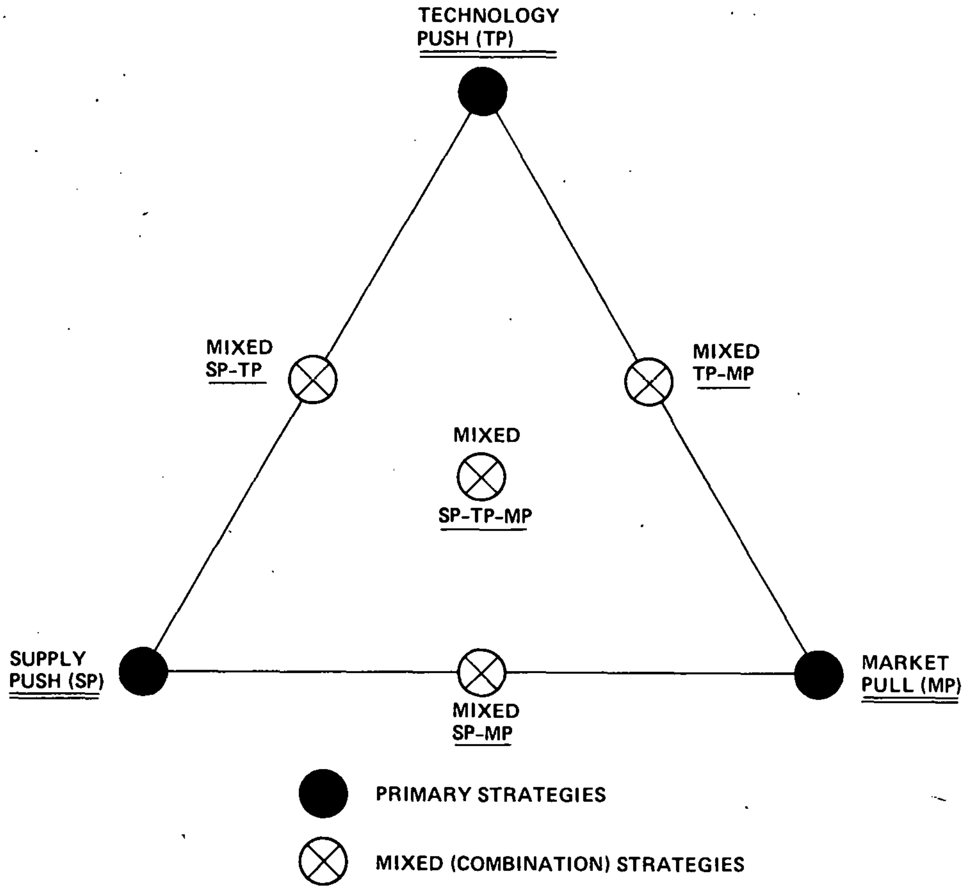


Figure 6. Strategy Definitions

must be engendered so that a firm commitment can be obtained as early as possible.

6. Project personnel must squarely address the possibility that WECS may not achieve a full measure of "diffusion success" and thus they should plan accordingly.

Concluding Comments Relative to DOE/WECS Program in General.

It is appropriate to summarize what has been found to be some of the more important attributes for the successful government demonstration projects in the past. These attributes are as follows [1]:

1. technology was well in hand

2. there was significant cost and risk sharing with local participants (greater than 50% of cost is shared privately)

3. the initiative for the project came from nonfederal sources

4. there existed a strong industrial system for commercialization (TDS)

5. all of the essential elements of the TDS needed for commercialization participated in the demonstration program

6. there was a distinct absence of tight time-constraints on achievement of commercialization.

It is felt that the Department of Energy would benefit significantly from reviewing the foregoing historical evidence and applying it to the many energy system demonstration projects it is contemplating in its portfolio of alternative energy systems and sources. The WECS program is at a stage where it could put these lessons to very good use and capitalize on them, and thus maximize the probability for diffusion success for WECS. Failure can almost be guaranteed if these lessons are ignored and the program structured in a fashion that would run contrary to this experience [4,5,6].

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RESPONSES TO THE PARTHE PRESENTATION

Ernest Rogers, Windworks: I would like to commend you on your excellent talk. Could you explain how you plan for innovation today?

Parthé: You might initially start with the idea of using incentives; however, the final vote will be cast in the marketplace. The consumer can figure out what he wants, and the choice is made on economics. The government may help with incentives, but the marketplace will choose from the alternatives available to it.

Richard Oman, Grumman Aerospace Corporation: Innovative systems are available. How do we get from the innovative system to the market? How do we advise the Department of Energy as to how to go through this process?

Parthé: I am not with industry; however, I can speak about what I have learned from industry. Industry might indicate their needs, which could be reflected back into the program. Industry will choose the different steps in a program which eventually lead to the demonstration phase.

George Tennyson, DOE: I do not believe that the marketplace is aware of all costs involved. For instance, it may be stated that the cost of energy for small machines is 4¢/kWh. But another important issue is the initial cost to the consumer. We might also come up with something good for the consumer that the consumer does not recognize. Many good ideas have failed because they have been approached from the wrong point of view. One must be cautious about innovation, therefore, because it may be inconvenient as far as the marketplace is concerned.

James Yen, Grumman Aerospace Corporation: At present there are three wind projects using utility money; the utility on Cuttyhunk Island off Massachusetts, Southern California Edison, and one other. These systems use three blades with fixed pitch instead of two blades with variable pitch as used by NASA. Should we consider two blades with variable pitch innovative? What guarantee do we have that blades have a 30 year life expectancy? A helicopter blade may only last about 100,000 hours. Experts would claim that anything related to reliability must be tested on a full-scale basis. Experimental testing is necessary rather than paper studies only. Only after tests which confirm the predictions can a technology be considered available.

Parthé: Most of the current studies are probably innovative because they have neither been in the marketplace nor developed extensively. When you state that you plan for a 30 year life, but have only been running the system for one year, you must be aware of all the assumptions involved in the system and in the evaluation of the blade's 30 year lifetime.

Mike Edesess, SERI; Based upon your terminology, a demonstration is different from a test. How do you let the public know you are doing a demonstration and not a test?

Parthé: In a demonstration there would be significant participation from the public, manufacturers, etc.

Session II

ROCKY FLATS SMALL WIND SYSTEMS PROGRAM OVERVIEW

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ABSTRACT

This paper provides an overview of the Rocky Flats Small Wind Systems Program sponsored by the United States Department of Energy (DOE). This program provides technical and management support for the development of small wind systems. The overall objective is to stimulate the manufacture of small wind energy conversion systems (SWECS) by the private sector and utilization of these systems by the public. The information provided in this paper describes the current program in terms of its objectives, activity highlights and future plans for FY1979 as well as projections through 1981.

INTRODUCTION

Operated by Rockwell International, the Rocky Flats Wind Systems Program provides technical and management support to the Department of Energy (DOE) for the development and testing of small wind systems (machines with an output of less than 100kW) designed primarily for farm, home and rural use.

The Federal Wind Energy Program (FWEP), under which the Rocky Flats (RF) program is funded, is designed to support the earliest possible commercialization of wind power to help meet national energy requirements. This goal is being pursued by simultaneously developing advanced small wind systems, addressing the technical, economic and institutional requirements for their use and stimulating their commercial utilization.

Widespread commercialization of small wind energy conversion systems (SWECS) is dependent upon these systems achieving energy costs competitive with the cost of power obtained from conventional sources. But the achievement of competitive costs (by whatever means) will not in itself assure widespread SWECS use if consumer and institutional acceptance has not been achieved. A close coupling of SWECS testing and development activities with research projects oriented toward potential uses for wind power is required to develop the SWECS industry and create an institutional and consumer environment conductive to SWECS commercialization. The RF Program is designed to provide the comprehensive approach necessary to achieve these goals.

BACKGROUND

Wind power has been utilized for centuries for the grinding of grain, transportation, irrigation and drainage. Windmills became an important power source for pumping water in the United States starting in the mid 1800's. At least 75,000 of these pumpers are still in operation. Starting in the 30's, and up to the early 50's, wind generation of electricity was an important rural power source. The widespread use of fossil fuels, however, slowed the development of wind energy conversion systems.

The United States' recent dependence on foreign fossil fuels and increased awareness of the limited reserves of oil and natural gas in the world has resulted in a sharp increase in efforts to develop alternative energy sources. Numerous small manufacturers are offering a variety of wind turbine generators (WTGs) for sale. However, the industry is still developing. Technical data relating to machine output, durability, and behaviour under extreme and varying weather conditions must be made available, together with information on types of power output, the compatibility of various system components, and other questions that might arise when installing a wind turbine generator.

Widespread adoption of small wind energy conversion systems (SWECS) is dependent upon these systems being economically competitive. This means that the cost of power provided by a SWECS must offer definite economic advantages for consumers. Improvements in component and system design are two ways to meet this goal. And while conventional energy costs are expected to escalate in the near future, so too will manufacturing and installation costs associated with SWECS. Furthermore, the advent of competitive costs will in itself not necessarily assure widespread use. A close coupling of SWECS development with programs oriented toward potential uses for wind power is planned to assure maximum stimulation of the SWECS industry.

OBJECTIVES

The primary objectives of the RF program are to stimulate the development and manufacture of SWECS by the private sector and accelerate the acceptance and use of SWECS by the public. To achieve these objectives, Rocky Flats has been assigned a series of specific functions by DOE. These include:

- Establish and operate a national facility where small wind systems are tested, thereby helping to assess the current state-of-the-technology and to identify required technology improvements.
- Subcontract activities in research and advanced systems development designed to reduce the cost and improve the reliability of SWECS.
- Provide appropriate technical support for the formation of standards to be used in the manufacture, product testing, data reporting and installation of small wind systems.
- Disseminate the technical information generated by the program, so that it may be effectively used by potential SWECS users, researchers, manufacturers/distributors and other DOE agencies/programs.

- Perform other required activities to assure that the program provides a basis for the widespread commercialization of SWECS.

A great many technical, economic, environmental, and social issues have to be resolved before significant benefits from wind power can be realized. Non-competitive costs are the greatest barrier to the use of wind systems. While much has been accomplished, the development of rugged, economical small wind systems in partnership with the dedicated, progressive SWECS industry remains the program's primary challenge.

PROGRAM HIGHLIGHTS

Eleven task areas have been identified to meet the RF program objectives. The contribution of each task area to the RF effort is described below.

TASK AREA	CONTRIBUTION
Task I - Program Management	Provides program management functions through a matrix-type organization structure. Interfaces with and reports to DOE/WSB and RFAO.
Task II - Test Center Development	Provides facilities and testing capability required for Test Center Operations (Task III).
Task III - Test Center Operations	Tests commercially available systems and tests prototypes developed under Task IV (Systems Development). Provides machine reports and data for dissemination to consumers, manufacturers and others.
Task IV - Systems Development	Develops advanced SWECS of various sizes. Provides prototypes for testing to Test Center Operations and subsequently to Field Evaluation. Transmits reports to Information Dissemination for peer review, editing and distribution.
Task V - Supporting Research & Technology (SRT)	Performs research in specialized technical areas to increase SWECS reliability and performance per unit cost. Transmits reports to Information Dissemination for peer review and subsequent distribution.
Task VI - Field Evaluation	Installs, instruments and tests commercially available systems and tested RF-developed systems at selected user sites. Provides performance data and information on operational experience.

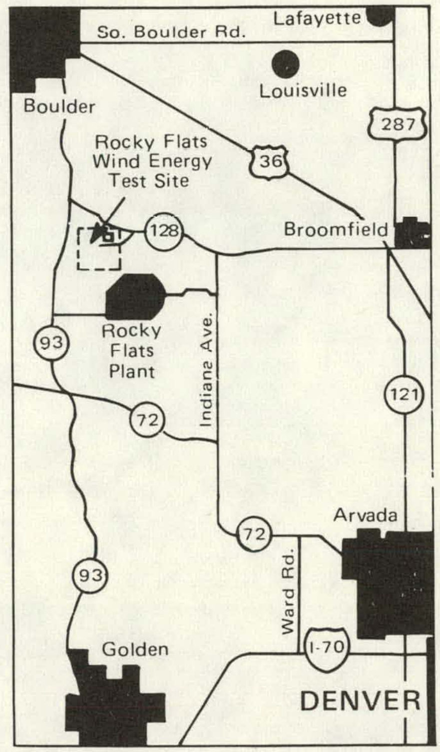
	Transmits reports to Information Dissemination on utility interface requirements, state and local siting requirements and other institutional issues.
Task VII - Special Studies	Performs mission analysis, market studies and institutional studies to determine the potential of and address barriers to SWECS commercialization. Defines SWECS characteristics required for optimum use. Transmits reports to Information Dissemination for peer review and subsequent distribution.
Task VIII - Technical Support	Provides specialized technical support to other task areas.
Task IX - Planning	Provides long-term and operational planning for RF program activities. Prepares planning documents for transmittal to DOE.
Task X - Standards	Assists private industry in the development of consensus standards; obtains technical inputs from Test Center Operations, Systems, Special Studies, and other task areas.
Task XI - Information Dissemination	Processes and distributes all technical and program reports, wind machine data, articles and other materials produced under other task areas. Coordinates workshops, answers correspondence and prepares and disseminates special information packages.

Test Center Development

During FY1976, DOE authorized the establishment of the Small Wind Systems Test Center. Since that time the primary activities have been establishing the site, installing towers and wind turbines and initiating data collection. The testing capacity being developed includes component tests, system tests and environmental tests. Currently, the emphasis is on testing commercially available machines under natural wind conditions.

The test center is located on the northwest corner of the Rocky Flats plant site approximately 15 miles northwest of Denver, Colorado between Golden and Boulder, as shown in Figure 1. Since the test center site is on a large flat plains area facing a mountain pass, the wind regime provides a large variety of conditions, from gentle breezes to hurricane-force wind storms. The high wind conditions predominate from a north-

Figure 1 Rocky Flats Small Wind Systems Test Center Location



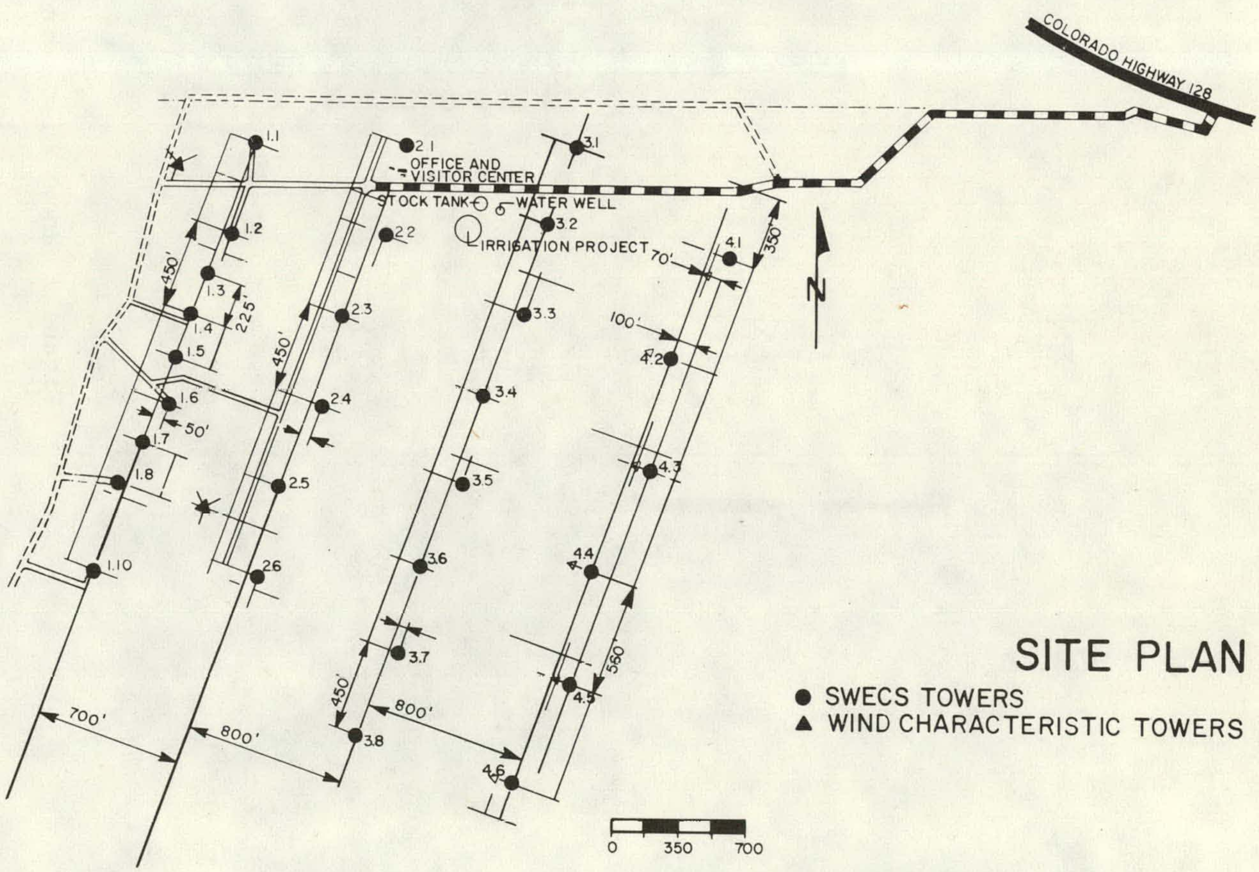


Figure 2 Layout of the Rocky Flats Small Wind Systems Test Center

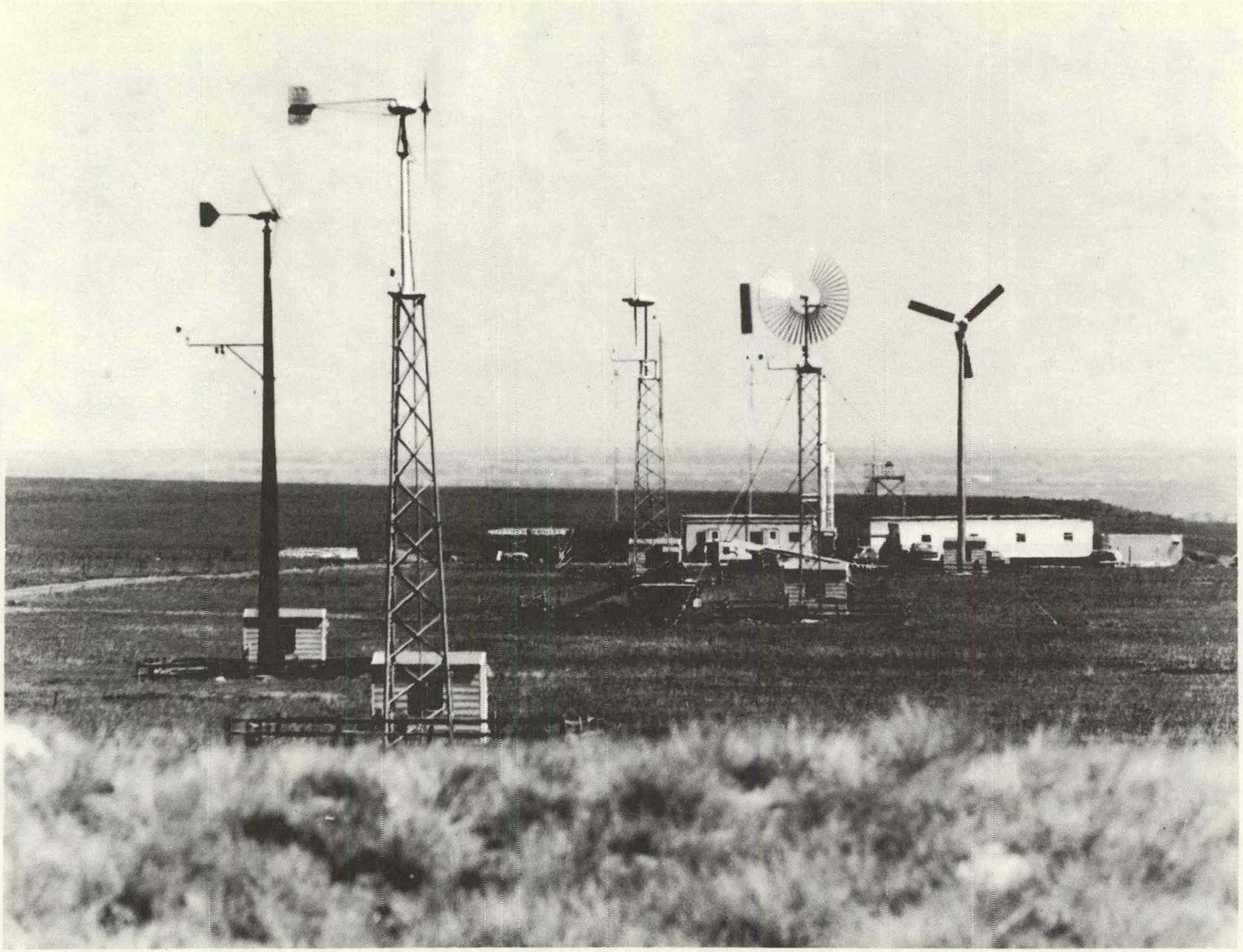


Figure 3 Rocky Flats Wind Systems Test Center

westerly direction, and, therefore, the WTG tower arrangement was laid out as shown in Figure 2, with the rows oriented perpendicular to that direction. Roadways and general construction have been kept to a minimum, in line with a general policy of preserving the natural state of the area as much as possible.

Wind turbine generator towers, associated data acquisition systems and WTG power output control equipment for positions 1.1 through 2.6 have been installed, and are operational. Additional towers and control sheds are now being installed in Rows 3 and 4. Additional towers are also being added to Row 1.

Weather data is being taken at 10 and 40 meter heights on two meteorological towers located at positions WCT 1 and WCT 2 in Figure 2. In addition, two 15-meter high portable towers are positioned near position 2.1 and a third 15-meter tower is located opposite position 2.2. All these locations provide wind speed and direction data. Temperature data are collected at both the 10 meter and 40 meter heights on meteorological tower WCT 1.

Wind speed and direction data are also taken at each WTG tower. The anemometers are located on booms approximately 1-1/2 to 2 rotor diameters below the WTG hub height, and provide input to the data collection system.

The data acquisition system consists of a generation and signal conditioning subsystem, an analog to digital conversion subsystem and a central computer used for system control and permanent data storage. The electrical analog signals generated from sensors mounted on each WTG are routed to microprocessors housed in an instrumentation and power control shed located at the base of each WTG tower. This microprocessor converts the analog signal to a digital signal, performs preliminary calculations and temporarily stores the digitalized information. The Central Control and Storage computer integrates each microprocessor at the test site on a scheduled basis, acquires the data, and permanently stores it on digital tape for subsequent analysis.

The WTG power control and storage subsystem consists of a microprocessor control unit and a resistor bank located in the shed at the base of each tower. In addition, there is a 120 volt central power storage bank located in a shed near the computer trailer. The power storage bank consists of 60 deep discharge 2-volt batteries with a capacity of 1760 ampere hours.

Test Center Operations

A major objective of the activities at Rocky Flats is to test small wind energy systems over a wide range of actual environmental conditions (See Figure 3). The data collected from this testing will:

- Provide consumer information for potential buyers of small wind systems.

- o Provide detailed engineering data for use by developers, manufacturers, and researchers of small wind systems.

Quantitative as well as qualitative data are being collected. The qualitative data includes information on the condition in which a machine is received from the manufacturer, usefulness of operating manuals, installation difficulties which were encountered, and operational experience. During the testing process, Rocky Flats personnel interface directly with the manufacturers of machines under test to discuss problems encountered and provide them with current operational data.

The collection of quantitative technical data is being implemented by gathering both long term and intensive testing data. Some of the machines and towers thus far installed and operated are listed in Table I.

Long Term Data - Long Term Data results from continuous testing 365 days a year. The data collected is restricted to two areas of interest: 1) basic machine performance (rotor RPM, generator voltage and amperage, etc.); and 2) the general wind characteristics (velocity, direction) in which the machine operated during the test period.

Intensive Testing Data - Detailed information is also obtained relative to structural and/or performance characteristics of wind system components during periods of high winds and/or unusual environmental conditions. The high volume of data collected during intensive testing periods is obtained from such sensors as strain gages, accelerometers, and thermocouples. Measurements are made in such critical components as blades, rotor shafts, gearboxes, and towers.

Actual test experience with these systems has varied from machine to machine. Problems have ranged from cracks in tail vane assemblies to loss of blades. As a direct result of test center experience at Rocky Flats, two manufacturers have redesigned portions of their WTG systems. One other manufacturer has made modifications to its machine based on input from Rocky Flats as well as from other owners. Thus, it can be seen that test center experiences have already had a positive effect on the industry, with the result being improved hardware.

Systems Development

Under the Systems Development task element of the RF Program, outside organizations are funded to develop advanced SWECS to achieve reduced wind-generated energy costs. Three projects are currently underway to design and build prototype 1-2kW, 8kW and 40kW WTGs for test at Rocky Flats (see Figures 4 & 5).

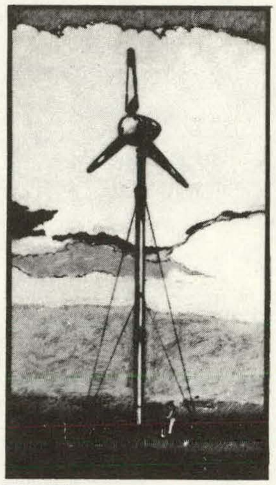
Needs have been identified for low cost SWECS of approximately 8kW output for home or farm use. Also, numerous applications exist in deep well irrigation, general farm/ranch applications, and for small isolated communities and industries for a machine of 40kW output. Low system cost is particularly vital in each of these cases. The third major need was for a high-reliability system, developing approximately 1-2kW, for remote locations where the cost of installing and maintaining

TABLE I

COMMERCIAL SWECS BEING TESTED AT ROCKY FLATS

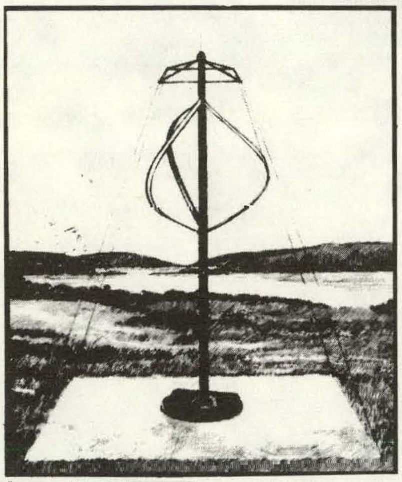
Position	Tower	WTG
(See Figure 2)		
1.1	Dunlite 12m (40 foot)	Dunlite 2kW
1.2	Aermotor 12m (40 foot)	Altos 1.5kW
1.3	Octahedral 12m (40 foot)	North Wind (Jacobs) 3kW
1.4	Concrete pole 12m (40 foot)	Kedco 1.2kW
1.5	Rohn 25g, 12m (40 foot)	Sencenbaugh 1kW
1.6	Wood pole 12m (40 foot)	---------------
2.1	Swing tower 17m (55 foot)	---------------
2.2	Concrete pole 17m (55 foot)	Grumman 15kW
2.3	Rohn SSv 17m (55 foot)	Zephyr 15kW
2.4	Rohn 80g, 17m (55 foot)	American Wind Turbine 2kW
2.5	Steel post 17m (55 foot)	Elektro 6kW
2.6	Rohn SSv 17m (55 foot)	---------------
Stock Tank	Sparco	Sparco
	Scheduled for Installation In Early FY1979	Millville 10kW
		Aeropower 1kW
		Pinson Cyclo-turbine 2kW

Figure 4 Advanced SWECS Under Development
(1-2kW and 8kW)

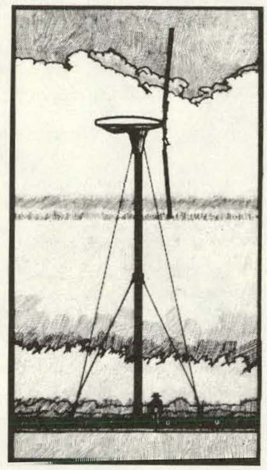


Windworks 8kW

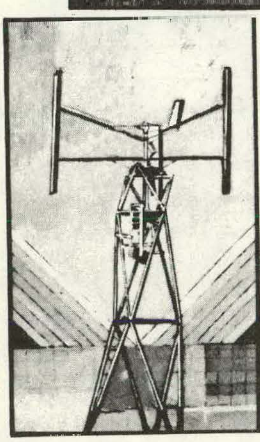
Grumman 8kW



Alcoa 8kW

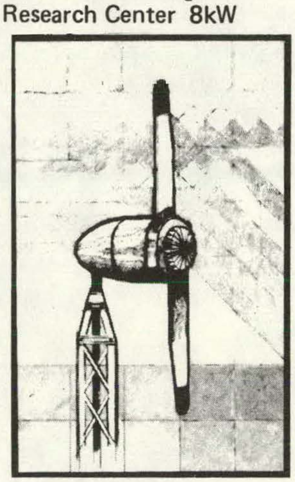


United Technologies
Research Center 8kW



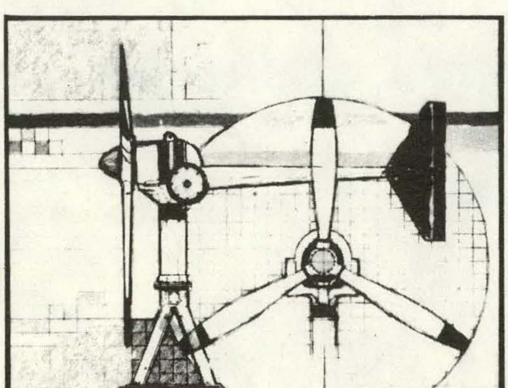
Aerospace Systems Inc.

1kW High Reliability



Enertech

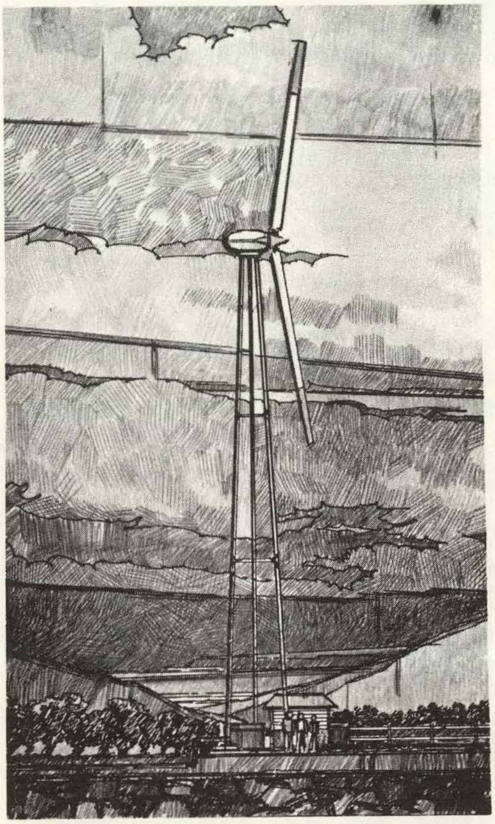
1kW High Reliability



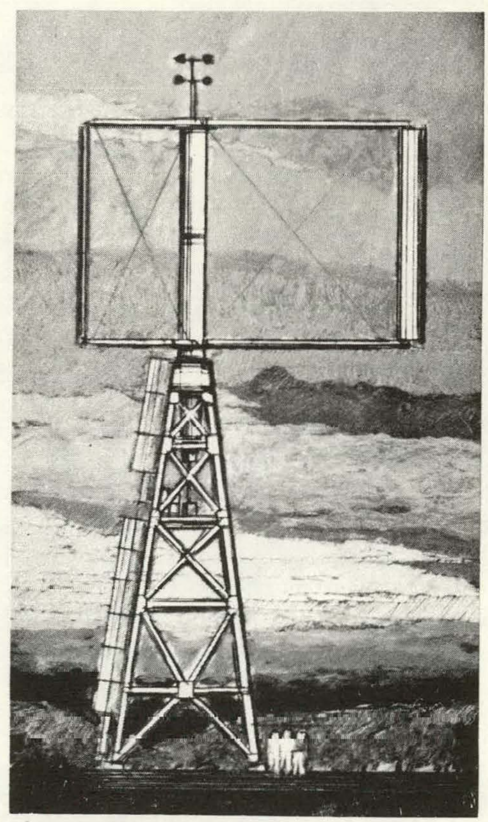
North Wind

1kW High Reliability

Figure 5 Advanced SWECS Under Development (40kW)



Kaman



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conventional power systems is high. Possible applications in this category are communications repeater stations, pipeline galvanic protection, remote seismic monitoring stations, and off-shore navigational aids.

Contracts were awarded in 1977 for the 1-2kW and the 8kW projects. Two 40kW contracts were awarded in late 1978. Details of the system specifications are listed in Table II. Multiple awards were made, with small business participation in both the 8kW and High Reliability programs. Summaries of these projects are provided in the Appendices. The prototypes developed under the projects will be tested at Rocky Flats. Towers will be installed in Rows 3 and 4 of the test site during the next year to accommodate the new systems.

Supporting Research and Technology (SRT)

During FY1978, work progressed on the testing of a wind system in a residential heating application by the University of Massachusetts. This project, a continuation of an effort started in 1975 at the university's "Solar Habitat", will provide design and economic tools for use by researchers and consumers in determining the feasibility of wind powered heating at any site in the U.S.

Late in FY1978, planning was initiated for a series of SRT projects to provide designers with technical data and analytical techniques which can be used in increasing SWECS performance per unit cost. Inputs for these efforts were obtained from the wind energy community at a planning workshop.

Field Evaluation

During FY1978, RF instituted planning for a Field Evaluation Program for SWECS. This program involves the field testing of commercially available SWECS and SWECS developed under contract to Rocky Flats. Each system will be instrumented and interconnected with a utility system to provide supplemental power at a user site. Data provided by the SWECS and experience obtained in installing and operating the systems in cooperation with utilities would be made available to the public.

Special Studies

Planning for Special Studies designed to provide mission analysis, market information, applications studies and institutional studies used input from an RF/industry workshop held in September, 1978. Projects already underway include a SWECS component cost analysis and the measurement of SWECS-produced noise for comparison with existing regulations. Projects for FY1979 have been identified and defined, including market and institutional studies and a study of dispersed SWECS interconnected with a utility.

Technical Support

This task has provided support to Test Center Operations and Systems Development activities on an "as required" basis. This has included

TABLE II

Specifications of Advanced SWECS Under Development

Contractor	kW @ 20 mph	Configuration	Rotor Size	WTG Weight (lbs)	Tower Weight (lbs)
1-2kW (High Reliability) Systems					
Enertech	2.3	2-blade horizontal axis downwind	16.4 ft dia.	350	300
North Wind	2.0	3-blade horizontal axis upwind	16.4 ft dia.	325	300
Aerospace Systems Inc.	1.0	3-blade vertical axis cycloturbine	15 ft dia. x 8 ft high	508	N/A
8kW Systems					
Windworks	8.0	3-blade horizontal axis downwind	31 ft dia.	1600	2362
United Technologies Research Center	9.0	2-blade horizontal axis downwind	31 ft dia.	1855	2619
Alcoa	11.0	3-blade vertical axis Darrieus	33 x 34 ft	10,480	-
Grumman	11.0	3-blade horizontal axis downwind	33.25 ft dia.	2540	N/A
40 kW Systems					
Kaman Aerospace Corp.	40.0	2-blade horizontal axis downwind	64 ft dia.	4900	4000
McDonnell Aircraft Corp.	40.0	3-blade vertical-axis giromill	32.5 ft x 65 ft	N/A	N/A

support to the establishment of data collection procedures at the test site, the performance of data analyses, and support to the review of Systems Development subcontract activities. The current areas of technical expertise include aerodynamics, aeroelasticity, wind characteristics/meteorology, mechanical and electrical engineering.

Planning

The expansion of the RF program has involved the preparation of comprehensive long range and operational plans for achieving program objectives. A workshop was conducted in late FY1978 to obtain planning inputs from the wind energy community for development of the Supporting Research and Technology (SRT) and Special Studies sections of this program plan.

Standards Development

The objective of this task is to provide technical support for the formation of consensus standards by private industry and their acceptance in the manufacture, product testing, and reporting of data on small wind systems. The development of data on these standards will aid in the acceptance of small wind systems by consumers, by the financial and insurance industries and by utilities with which SWECS will be interconnected.

RF developed a comprehensive plan for providing technical support to standards development. Under the plan, the American Wind Energy Association (AWEA) would be private industry's focal point for establishing voluntary consensus of institutional/consumer needs and the conduct of workshops attended by representatives from industry, utilities, financial institutions, consumer organizations and other groups affected by standards.

Information Dissemination

This task involves the effective dissemination of technical and consumer information produced by the entire Rocky Flats Wind Systems Program to potential users, manufacturers/suppliers and other DOE agencies and programs. The results of this effort will increase awareness of the potential uses of small wind systems. A general objective of this task is to develop at Rocky Flats a contact point and information center for all available small wind systems data. Some of the reports issued under this task include:

Massachusetts, University of, Amherst. Investigation of the Feasibility of Using Windpower for Space Heating in Colder Climates. (Third quarterly progress report covering the final design and mfg. phase of the project, September-December, 1975). W. E. Heronemus, December, 1975, 165 pp. Contract No. NSF-WER-75-00603. (ERDA/NSF/00603-75/T1)

Nielsen Engineering and Research, Inc. Wind Power for Farms, Homes and Small Industry. J. Park and D. Schwind, September 1977. 230 pp. Contract No. E(04-3)-1270. (RFP-2841/1270/78/4) Available in late 1978.

Rocky Flats Plant Technical and Management Support for the Development of Wind Systems for Farm, Remote and Rural Use, Annual Report for the Period October 1976-September 1977, October 1977. 125 pp. Contract No. E(20-2)-3533. (RFP-2721/3533/78/2) Available in late 1978.

Rocky Flats Plant. An Index of Manufacturers, Researchers and Distributors Currently Involved in the Development of Wind Energy Conversion Systems. American Wind Energy Association. February, 1978. 72 pp. Contract No. EY-76-6-04-3533 (DOE/RF/3533-78/1).

Rocky Flats Plant. A Guide to Commercially Available Wind Machines, prepared with the assistance of the American Wind Energy Association, April 3, 1978. 121 pp. Contract E(29-2)-3533. (RFP-2836/3533/78/3). Available in late 1978.

RESPONSES TO THE HEALY PRESENTATION

James Yen, Grumman Aerospace Corporation: What is the value of the power coefficients for the machine?

Healy: The power coefficient varies between 0.3 and 0.4. Sandia has recently indicated that on the vertical axis machine the power coefficient may be as high as 0.53. Some of these machines are not standardized; therefore, the power coefficient cannot be identified. Blades may be handmade, many of them from wood. We even find variations between sets of airfoils for the same machine.

Peter Moretti, Oklahoma State University: How is your information disseminated?

Healy: Information developed during the program is made public through standard DOE channels such as the Technical Information Center (TIC) and the National Technical Information Service (NTIS), Department of Commerce. While in this area you might wish to visit our test site. Our machine program is divided into two phases; the first phase is the design and development of a new machine; the second phase is the fabrication of the prototype. Most of the machines will be up during the summer and will be evaluated during the next winter. Phase I reports should be available in about four months from now. Phase II reports should be available by the end of the next calendar year. We also try to get the information to the public by means of workshops similar to the last one held recently in Boulder.

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DARRIEUS WIND TURBINE PROGRAM AT SANDIA LABORATORIES

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Abstract

The objective of the Darrieus Wind Turbine Program at Sandia Laboratories is to develop and transfer the necessary information associated with vertical axis wind turbines (VAWTs) to allow commercial companies the opportunity to develop, manufacture and sell VAWTs. First-level aerodynamic, structural, testing and systems analyses capabilities have evolved to support and evaluate complete systems designs, and contracts have been let which are planned to result in the completed installation of a low-cost 17m VAWT by February 1981. A number of potential improvements have been identified during this first level design cycle which may substantially lower future system costs.

INTRODUCTION

The Darrieus Wind Turbine Program at Sandia Laboratories began in its present form in 1975. The program objective was and is the development and transfer of necessary information associated with vertical axis wind turbines (VAWTs) to allow commercial companies the opportunity to develop, manufacture and market VAWTs. This paper outlines the approaches taken to meet this objective and describes the results of the first-level complete design cycle as well as potential system improvements uncovered during this cycle.

TOOL DEVELOPMENT

Aerodynamics

A workable knowledge of VAWT aerodynamics is needed for two aspects of turbine design, performance evaluation and as input to structural codes. Aerodynamic calculations at present are based primarily on conservation of momentum models. These range in complexity from single streamtube models (SIMOS, [1]) accessing blade airfoil section data for one value of chord Reynolds number (Re) to multiple streamtube versions (DARTER, [2]) which utilize section data for an arbitrary set of Re's. When only performance information is of interest an extremely fast working algorithm (PAREP, [3]) is available. PAREP references curve fits of various results taken from both analysis and experiment. Gross performance characteristics can be reliably predicted by all of the above codes. Accurate local blade load predictions are not so accurately made. The streamtube models are substantially deficient in this regard. This shortcoming has motivated the development of a vortex filament based representation of the turbine and its wake. This concept also allows for the important effects of blade interference to be considered. Two- and three dimensional versions (VDART2, VDART3, [4]) of this Texas Tech University scheme are available. At this time they are undergoing evaluation, and efforts are being made to reduce their relatively long computer run times.

Necessary as input to all of the above aerodynamic codes are blade airfoil section characteristics. Only a small amount of section data appropriate for VAWT applications is available in the open literature. This is because most non-VAWT applications require only pre-stall and relatively high Re behavior to be known. VAWT operations involve a significant amount of post-stall running, and large portions of the blades operate at Re's in the 10^4-10^5 range. Blade section information (lift, drag and pitching moment coefficients) at Sandia now comes in largest part from two sources. Pre- and early stall behavior is calculated using the code PROFILE [5], one of the many airfoil characteristic synthesizers to become available in recent years. Post-stall aerodynamics are taken from a series of wind tunnel tests [6] on NACA symmetrical sections. The results of these tests showed that at post-stall angles of attack lift and drag are largely independent of which section is being considered. PROFILE is also used to evaluate samples of sections taken from actual blades used on Sandia test turbines.

Structures

Structural analysis needs to address system static and dynamic loads as well as blade flutter. Current practice is to design first to static requirements and then to examine and redesign if necessary to avoid the undesirable effects of dynamic loads or blade flutter. The MARC static, non-linear finite element code is the basic tool used in the first portion of this procedure. It treats quasi-static centrifugal and aerodynamic operating loads, gravity loads and parked turbine loadings which occur in high winds. In order for the quasi-static results to be acceptable system natural frequencies need to substantially exceed typical load excitation frequencies. The finite element code SAPIV is the primary vehicle for examining frequencies of the blade/tower/tiedown system. Present conservative design philosophies (high static requirements, two-ended blade support, basic stiffness of the tiedown system) produce resonant frequencies which are well above the typical driving frequency and so allow confidence to be placed in the MARC predictions. This may not be the case in future designs. Here cost considerations are suggesting reductions of conservatism in static requirements, alternate blade manufacturing schemes, and higher rotor height-to-diameter ratios (H/D's); changes which may lower system natural frequencies. In anticipation of this possibility efforts are now underway to formulate a comprehensive forced-response dynamic model for use in future structural design efforts. These potential changes may also have a negative influence on the character of blade aeroelastic flutter instability. This is not now a problem with extruded aluminum blades built to current static requirements. However approximate analyses [7] and experiments [8] with scale models have indicated that the ratios of aerodynamic forces to blade mass and elastic stiffness, blade bending to twisting stiffness, and blade to tower torsional stiffness may require additional attention to the flutter issue. Quantitative information on the influence of these parameters on flutter speed is being obtained analytically and experimentally at this time.

Turbine Testing

Available Machines

The purpose of the Sandia VAWT test facility is to (1) evaluate aerodynamic and structural performance, (2) develop testing techniques, and (3) demonstrate the practicality of and solve problems associated with operation of VAWTs in a synchronous mode with the power grid. There are three basic turbines serving as test beds. The 2m machine had its origin as a wind tunnel model and is presently being used to correlate free-air and wind tunnel performance. The 5m turbine first appeared as a prototype device in 1975 and, due to its convenient size, serves as a vehicle for experimentally evaluating potentially improved blade designs. These possible improvements lie in the areas of new manufacturing techniques, section camber and thickness, planform incidence and twist, etc. The third machine is the 17m. It is this turbine which forms the basis for the first-cycle design total system and which is tied to the utility grid. It not only provides information on full-scale rotor manufacturing processes but also on the various other components comprising the entire power generation system.

Instrumentation and Data Collection

The 17m's instrumentation is the most extensive of the three, and the bulk of the following remarks will apply to this turbine. Windspeed is measured by two anemometers placed on a tower 22 feet above the top of the rotor. The windspeeds measured here can be correlated by similar measurements made at each of four heights on a nearby meteorological tower. The anemometers used are high accuracy ($\pm$ 1%), highly responsive units which are unfortunately subject to frequent ice, hail and high wind damage. They are retained and repaired/replaced as necessary because of the accuracies needed in this measurement. Windspeed is corrected via a 0.1 experimentally determined site shear factor. Power train instrumentation consists of a torque sensor on the low speed shaft (for rotor aerodynamic power), another torque sensor on the high speed shaft (for transmission power losses), and RPM, output voltage, current and power monitoring devices. System stress levels are taken by various strain gages on the tower and blades. This information is pulse code modulated and transmitted to magnetic disc through a slip ring. In addition measurements of brake and transmission temperature are made.

The above data are treated via the "method of bins" [9], a scheme whereby average values of power, torque, etc. are obtained as functions of ambient windspeed.

System Design

The goal of the efforts at Sandia is to bring about delivery of commercial wind energy conversion systems. System design is the ultimate tool used in this process. System design takes the knowledge gained from the aerodynamic and structural investigations, turbine testing and many other areas and integrates it to synthesize an economically viable wind energy conversion system. The nature of this integration is obviously crucial to the success of the design and rests upon many factors. The economic optimization model developed at Sandia for this integration incorporates a large number of inputs from many sources and is constantly being updated as new information becomes available. The model is frequently used and heavily relied upon. Its uses include (1) providing economically optimum and structurally adequate system configurations for the point design task, (2) identifying cost trends (to serve as a design tool for making technical decisions on an economic basis), and (3) providing a capability to rapidly estimate the absolute cost of VAWT electrical energy for a wide variety of operating and configurational conditions.

CURRENT DESIGN

Aerodynamics

Current aerodynamic designs emphasize simplicity in order to both minimize cost and technical risk. The blade section is the symmetrical NACA 0015. Constant chord untwisted planforms are bent to the straight line-circular arc-straight line troposkein approximation [10]. Solidities fall between 10 and 15 percent, a range dictated by economics. Efficiencies in excess of 40% (occurring at a TSR between 5 and 6) have been demonstrated with this combination of parameters. The combination also allows for self-regulation. Aerodynamic stall causes maximum power to be produced at a TSR of approximately 3.

Structures

Minimization of technical risk and cost also drives the structural design. The blades have constant wall thicknesses both chordwise and spanwise. This allows the sections to be manufactured by extrusion. For chords of 0.61m (24") or less the extrusion is single. With larger chords multiple sections are used with the sections being joined by spanwise welds whose chordwise locations are chosen to avoid compromising strength. Tower designs are large diameter, thin walled tubes. Conservative design factors are used throughout. A factor of 2 is used for blade fatigue stress where these stresses are calculated for the highest operational wind speed of 26.8 m/s (60 mph). Blade buckling is calculated for 67 m/s (150 mph). The tower buckling factor is 10.

Tiedown cable natural frequencies are set above all excitation frequencies anticipated during machine operation.

Economics

Systems possessing the basic aerodynamic and structural characteristics noted above and operating in a utility grid application have been analyzed via the Sandia economic optimization model. Additional assumptions were (1) wind shear exponent of 0.17 from a reference height of 10m (30'), (2) production quantity of 100 units, (3) owner annual operating cost of 15% of the delivered price, and (4) optimization based on minimizing annual operating cost per unit of energy supplied. Primary qualitative results include (1) turbine H/D's should fall between 1.0 and 1.5 with an advantage toward the 1.5 value, (2) the two-bladed configuration is more cost-effective than the three-bladed, although both are competitive, (3) very large turbines (> 61m (200')) are less cost effective due to large raw material costs relative to energy collection capacity, and (4) very small turbines (< 10m (30')D) are less cost effective due to large fixed costs relative to system energy collection capacity.

The costs predicted here agreed reasonably well with actual cost estimates for several point designs given independently by A. T. Kearney, Inc., and Alcoa Laboratories. Results of these two studies are shown in Fig. 1. It may be seen that energy costs between 4 and 5¢/kW/hr @ 6.7 m/s (15 mph) are possible, the optimum size is in excess of 46m (150') and that there are small but significant economies of scale for systems from 15m(50')-46m(150')D (~ 100-1600kW). Also, small systems (< 30kW) need further development to be cost effective in the utility grid application.

First Cycle Design

Following from the efforts described above a design and fabrication contract has been let to Alcoa. The end product represents the first full cycle of development of an economically feasible, industry produced, commercially marketable Darrieus VAWT. The machine parts layout of this H/D = 1.5 turbine are shown in Fig. 2 and its design characteristics are given in Fig. 3. Installation for the first of four copies is due to be completed at DOE/Rocky Flats by February 1981. System weight breakdown is shown in Fig. 4, and the electrical characteristics are summarized in Fig. 5. The siting and intended environments of the last three machines are outlined in Fig. 6.

FUTURE VAWT DESIGN

Aerodynamics

One version of the economic optimization code allows the user to assess the effects on cost-of-energy (COE) brought about by changes in aerodynamic performance characteristics. Named CPTAILR, the code is obviously of great assistance to the aerodynamicist as it identifies which of the many possible alterations to the aerodynamic design may be fruitful and those which may have a negative bearing on COE. Three changes identified by CPTAILR as decreasing COE are (1) increase maximum power coefficient ($C_p$max), (2) move the TSR at stall regulation (TSR @ $K_p$max)

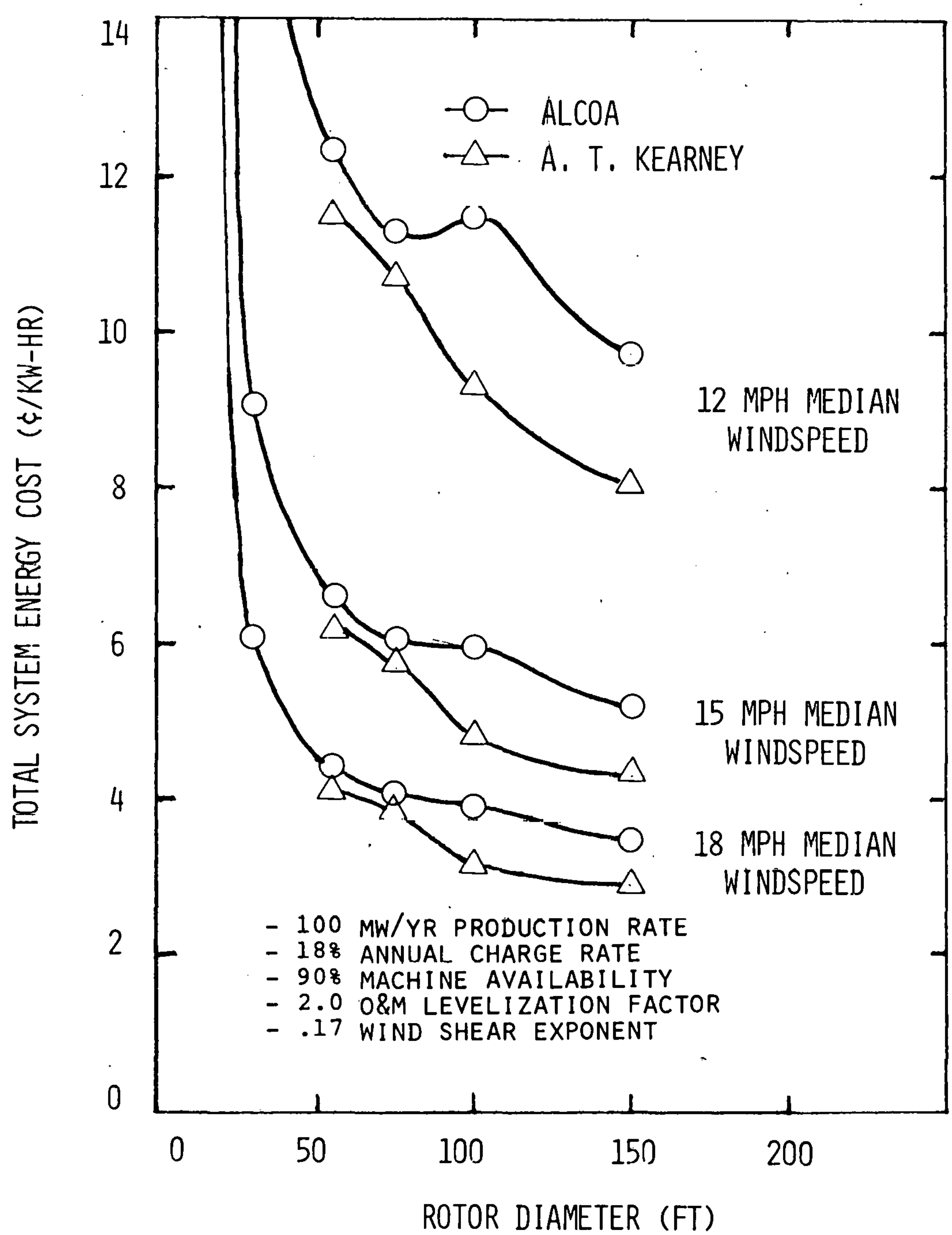

FIGURE 1. INDEPENDENT COST ESTIMATES, POINT DESIGNS

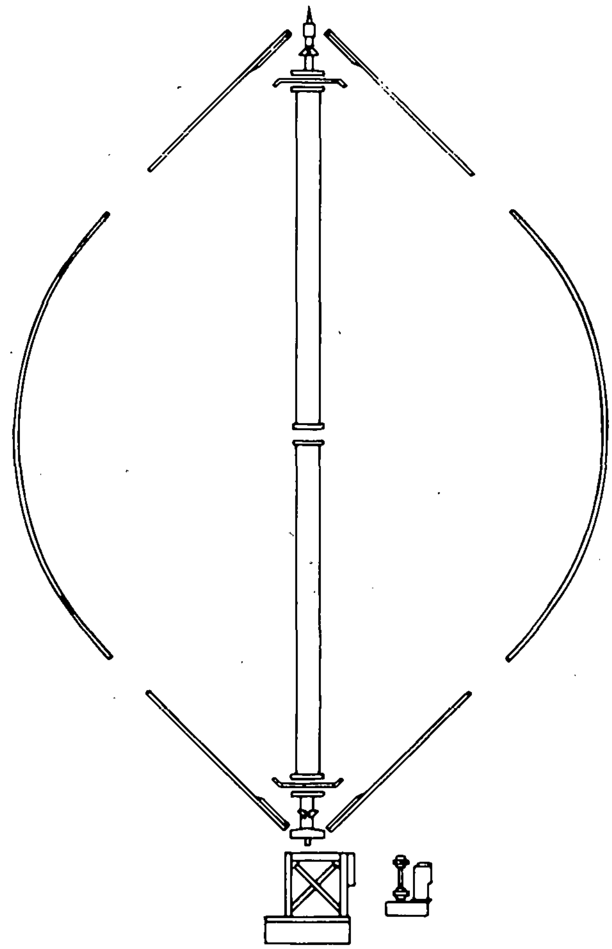

FIGURE 2. ALCOA 17m, H/D = 1.5 TURBINE MACHINE PARTS LAYOUT.

Rated Electric Power	100 kW, 3-Phase, 60 Hz, 460 V
Rated Windspeed at 30′ Ref.	13.8 m/s (31 mph)
Cut-In Windspeed at 30′ Ref.	5.4 m/s (12 mph)
Shutdown Windspeed	26.8 m/s (60 mph)
Turbine rpm	51.5
Rotor Height	25.15 m (82.5 ft)
Number, Type of Blade	2, NACA 0015
Blade Chord	0.61 m (24 in.)
kWh/yr at 15-mph site	235,000
Capacity Factor	0.27
System Weight, Less Concrete	24,600 lb
kWh/lb at 15-mph Site	9.6
$/lb FOB Factory, 100 Units/yr	2.12

FIGURE 3. ALCOA 17m, H/D = 1.5 TURBINE CHARACTERISTICS.

System Weight

Total Weight (Factory Hardware)	24,600 lbs
Weight Distribution (Percent)	
Tower	53
Blades	15
Tie-Down	6
Drive Train	21
Electrical	5
Specific Output (15 MPH Ave. Sea Level) $\frac{KWHR}{LB}$	9.6

FIGURE 4. ALCOA 17m, H/D = 1.5 TURBINE WEIGHT BREAKDOWN.

Electrical System

Generator/Motor	150 HP, 480 V, 3 ϕ 1800 RPM Lincoln Motor
Grid Connection	400 AMP 3 Pole Safety Switch with Dual Element Fuses
Control	Microprocessor Based - INTEL 8748 Normal Operation Emergency Operation Ground Fault Vibration Overspeed

FIGURE 5. ALCOA 17m, H/D = 1.5 ELECTRICAL CHARACTERISTICS.

closer to the TSR @ $C_p$max, and (3) increase the TSR's of all points on the C_p curve. The Alcoa 17m turbine may be used to illustrate the effects of these changes. The reference condition will be taken as operation at sea level in a 6.7 m/s (15 mph) median windspeed. Figure 7 gives the predicted decreases in COE associated with each individual performance modification and the combined effect of simultaneously making all three.

It is anticipated that changes of this type may be brought about by using cambered airfoils and/or nonuniform planforms on blades which may be produced for approximately the same cost as conventional blades. Analytical and experimental investigations are underway on the feasibility of these changes.

Structures

Substantial COE improvements are anticipated through revised structural design. These will probably come from reduced requirements (consistent with large horizontal machines), more sophisticated analysis capabilities and the knowledge acquired through extensive testing.

Anticipated changes in requirements would lower (1) parked blade buckling criterion from 67 m/s (150 mph) to 54 m/s (120 mph), (2) design/operational windspeed from 27 m/s (60 mph) to 18 m/s (40 mph), (3) tiedown cable tension, (4) tower buckling safety factor from 10 to 5, and (5) blade weight through tailoring blade wall thicknesses. Figure 8 lists the component weight and cost reductions which are predicted to follow in going to the less stringent structural requirements. The reduced generator/electrical and transmission costs follow from the fact that the lighter system optimizes at lower rated power and windspeed. The lower weights also lead to lower shipping costs and, when the new tiedown tensions are considered, lower foundation costs. The combined effect on COE is a substantial 25% reduction.

Transmission Investigation

Transmission (or speed increaser) costs represent 25% of that of the total lightweight system. This large fraction suggests that this item is a worthwhile one for potential cost reductions. The prospects here are bright as current transmissions are standard hardware items used in conventional ways in an application for which they were not specifically designed. One would suspect that the existing designs are not optimized to wind turbines.

Alternate Blade Fabrication Methods

Improvements in the \$1.4-1.8/kg (\$3-4/lb) cost for blades deriving from aluminum extrusions would obviously be desirable. Their specific cost is approximately twice the average cost per unit weight of the total machine. Target areas for these improvements include uses of composites and/or cheap materials along with more efficient joining/extrusion methods. Candidates include the pultrusion process using a glass/resin composite and a roll/stretch formed steel blade.

Low-Cost 17 Meter Siting

Unit	Environment	Site Selection
1	Structural and Performance Confirmation Testing	DOE/Rocky Flats
2	Demonstration in Agricultural Application	Undetermined (USDA Program is Candidate)
3	Demonstration in Utility Application	Selection by Battelle/PNL
4	Severe Environment Utility Application (Wind, Ice, Lightning)	Selection by Battelle/PNL (Candidates include Sandia Crest; Cold Bay, Alaska)

FIGURE 6. ALCOA 17m, H/D = 1.5 TURBINE INTENDED SITING.

Cost of Energy Reductions Through Aerodynamics

	Change	Reference	New	COE Decrease (%)
1.	$C_p max$	0.39	0.41	5.0
2.	$\frac{TSR@K_p max}{TSR@C_p max}$	0.55	0.70	8.0
3.	TSR	range	1.25 x range	2.5
4.	1,2,3 above simultaneously			14.0

FIGURE 7. ANTICIPATED REDUCTIONS IN COST OF ENERGY TO ALCOA 17m SYSTEM THROUGH AERODYNAMICS.

Item	Weight Reduction (%)	Cost Reduction (%)
Blade Weight	50	35
Spirally Welded Tubular Tower Weight	55	55
Generator/Electrical System		8
Transmission		10
Foundation and Tiedown		45
Shipping and Assembly		30
Total Net Reduction in Cost of Energy		25

FIGURE 8. ANTICIPATED REDUCTIONS IN COST OF ENERGY DUE TO LOWER STRUCTURAL REQUIREMENTS.

SUMMARY

Efforts at Sandia Laboratories towards development of aerodynamic, structural, testing and systems tools and data bases for design and construction of VAWTs have been outlined. A complete first cycle design has been described in detail. Potential improvements uncovered during this cycle have been noted along with the anticipated means to both assess and effect these improvements.

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RESPONSE TO THE KLIMAS PRESENTATION

Question: Can you comment on the blade life and its effect on economic projections?

Klimas: We are considering a blade life of approximately 10^7 cycles. This is long compared to operating conditions imposed on helicopter blades.

Paul Migliore, West Virginia University: What is the largest value of cord to radius ratio that you have tested experimentally?

Klimas: We have tested a 24-in. cord with the 17-m high Darrieus or approximate .0642 radius ratio.

Migliore: Have you satisfied yourself that the 0015 airfoil is the best choice?

Klimas: It has not been determined that it is the best choice.

Migliore: Do you have any long-term plans for straight bladed vertical axis turbines?

Klimas: No, we do not.

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UTILITY-SIZED WIND-POWERED ELECTRIC PLANTS
BASED ON THE MADARAS ROTOR CONCEPT

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Dayton, Ohio

ABSTRACT

The Madaras Rotor Power Plant concept was analyzed and updated to determine its capability to compete technically and economically with conventional horizontal axis wind turbines (HA-WTG). This concept, developed in the 1930's, utilizes rotating cylinders, vertically mounted on flat cars, to react with the wind (Magnus effect) and propel an endless train of cars around a closed track at constant speed. Alternators geared to the wheels of each car generated electrical power, which was transmitted to a power station by a trolley system.

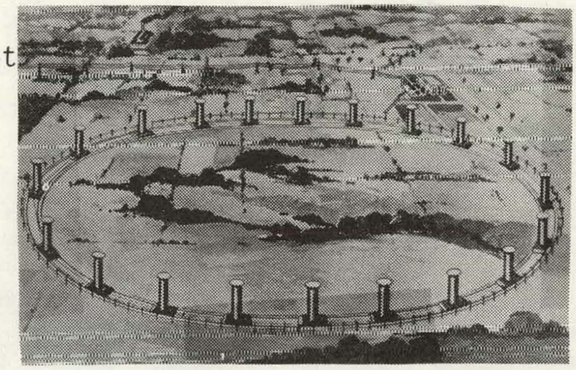

FIGURE 1. MADARAS ROTOR POWER PLANT

The study consisted of a wind tunnel test series, an electromechanical design, a performance analysis, and a cost analysis.

Results indicate that the most efficient Madaras plants should have racetrack planforms and that utility-sized plants can be constructed (>228 MW and >975 x 10^6 kW-hr/year). Further, Madaras plants are less land intensive than HA-WTG plants, and energy costs of Madaras plants varied from 12 percent higher to 22 percent lower relative to comparably-sized HA-WTG plants.

BACKGROUND

Analytical studies, wind tunnel experiments, and full-scale aerodynamic tests of the wind-powered, Madaras Rotor Power Plant were conducted in the 1929 to 1934 time period. This system, invented by Julius D. Madaras, consisted of 27-m high by 6.8-m diameter cylinders which were vertically mounted on flat cars and rotated by electric motors to convert wind energy to Magnus-effect forces. The forces propelled an endless train of 18 cars around a 457.3-m diameter, closed track (Figure 1). Alternators geared to the car axles were calculated to produce up to 18 MW of electric power at a 8.9 m/s track speed in a 13 m/s wind. Twice

*Senior Research Engineers, Aerospace Mechanics Division, UDRI.

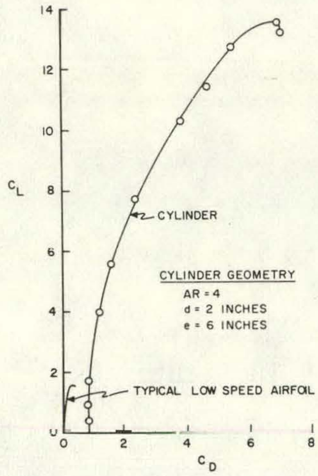

FIGURE 2. COMPARISON OF LIFT-DRAG POLARS OF A ROTATING CYLINDER AND AN AIRFOIL.

during each orbit of a rotor car around the track (at points ± 90° from the wind), each spinning rotor in turn must be de-spun to a stop, and then spun-up in the opposite direction. This cycle is necessary in order to assure that the propulsive force changes direction so that all rotors are propelling the train in the same angular direction. Force measurements obtained from a full-size rotating cylinder mounted on a stationary platform proved that the concept was technically feasible, but the project was discontinued prior to pilot plant demonstration because of the Depression. The reason for using a rotating cylinder instead of an airfoil to propel the train is that a rotating cylinder generates a lift force about ten times larger than that of an airfoil. (Fig. 2 shows lift-coefficient, C_L versus drag coefficient C_D.)

A Unique feature of this program was that it was sponsored and monitored by a consortium of seven electric utility companies, with the Director of Research of the Detroit Edison Company serving as project monitor.

The University of Dayton Research Institute has conducted studies of the Madaras system to verify the initial computations made by Madaras and his co-workers. These studies have included a thorough review of the literature of the Madaras program (contained in a set of 14 unpublished technical reports obtained from Detroit Edison) as well as discussions with two key men who had worked with the original Madaras project: Mr. Russell F. Hardy who was the Chief Engineer of the Madaras Rotor Power Corporation, and Mr. Walker Cisler, who recently retired from the position of Chairman of the Board of the Detroit Edison Company. Our studies also have included a review of all wind tunnel tests on rotating cylinders conducted since the mid 1920's, performance simulation studies, and economic analysis.

Cost estimates in 1934,done by an outside consulting engineering firm, indicated that 18,000 kW plants would cost $38.50/kW and the cost of power at the busbar would vary from 1.23 to 2.30 mills/kWh, depending upon annual wind conditions; only one-third the cost of steam power plants in 1934.

The primary objective of this program was to demonstrate the degree in which Madaras power plants having capacities in the 10 MW to 200 MW range are competitive with horizontal axis wind turbines.

Design criteria selected for this system are based on those used for the General Electric study of large horizontal axis wind machines to facilitate direct comparison of results. The primary ground rules for this study were:

- This was a conceptual design trade study of the basic system proposed by Madaras. Only off-the-shelf hardware and available technology were to be used. Thus a system design optimization analysis was beyond the scope of the program.

- Design wind conditions included:
  - Wind duration curves having 8.1 m/s mean wind speed at 9 m height above ground.
  - Structure must withstand winds of 53.6 m/s with the rotor train standing still on the track.
  - Structure must be able to operate in wind gusts to 26.8 m/s while operating at the rated wind speed of 13.4 m/s.
- Design life of 30 years for rotating parts and 50 years for static parts.
- System must withstand hail up to 2.5 cm diameter, operate in a temperature range of -51°C to +49°C, and operate in snow, rain, lightning, salt vapor, and windblown sand and dust.

WIND TUNNEL TESTS

The wind tunnel tests, conducted in the University of Michigan's 2.1m x 1.5m (7 ft x 5 ft) subsonic wind tunnel were run to:

- Validate existing wind tunnel data on rotating cylinders.
- Develop aerodynamic characteristics of rotating cylinders with end plates as a function of cylinder and end plate geometry.
- Obtain data on power required to rotate the cylinder.
- Evaluate rotating cylinder performance in an atmospheric boundary layer.

In all tests, flow conditions were designed to represent adequately those of a full-sized Madaras rotor.

Both 50 mm diameter and 152 mm diameter wind tunnel test models were tested, with the smaller model being used primarily to develop background, isolate problem areas, and to obtain design information for the larger cylinder. All cylinders were equipped with internally-housed motors capable of rotating the cylinder at speeds from 0 to 20,000 rpm. High speeds are required on models as small as these to obtain proper surface speed to wind speed ratios (U/V) and to provide sufficiently accurate resolution of loads on the wind tunnel 6-component balance system. (The full-sized cylinder will be designed to rotate at speeds of about 186 rpm.)

Over 200 test runs were conducted in the overall test series. A unique aspect of the test series was the series of tests conducted in a simulated atmospheric boundary layer. For these tests, a boundary layer similar to that of wind blowing over grassy plains was simulated by wooden quarter-round strips placed traverse to the wind flow along the floor of the tunnel. These strips which were placed at 0.3 m intervals from the entrance of the 6.1-m-long test section up to the model, simulated the boundary layer profile quite well across the width of the tunnel.

The free stream tests were conducted with either a bottom fairing or both a bottom and top fairing. Actually, the bottom fairing was used to isolate the model support sting (which was mounted to the balance system) from the air flow. The top fairing was merely a mirror-image strut that was not fastened to the model, but which cleared the top of

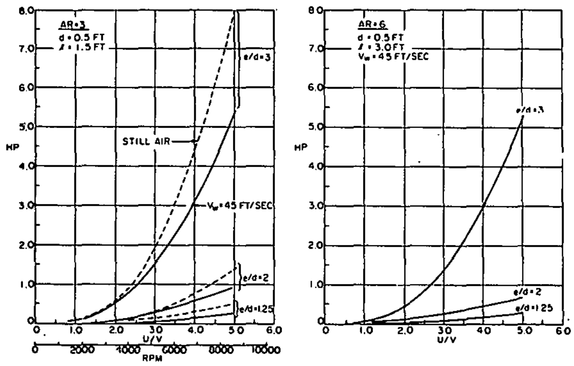

FIGURE 3. POWER REQUIRED TO ROTATE CYLINDER FOR VARIOUS END CAP DIAMETER RATIOS AND TWO ASPECT RATIOS.

the model by about 0.8 mm (.032 in). By comparing data obtained with the single and double fairings, the effect of the fairing on the aerodynamic coefficients was ascertained, and then the data were corrected accordingly. No correction of this sort was required for the boundary layer tests.

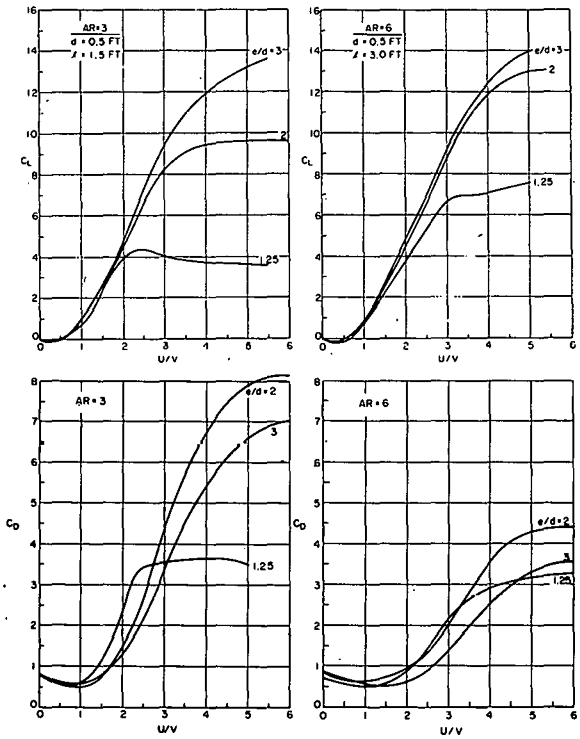

FIGURE 4. FREESTREAM C_L AND C_D VERSUS U/V, AR OF 3 AND 6, and e/d RATIOS OF 1.25, 2, and 3.

The power required to rotate the cylinder is presented in Figure 3. Two observations are of particular importance:

- There is a significant increase in power absorbed by the rotor for e/d > 2.
- There is little difference in power absorbed as a function of AR.

Typical free stream test results for the shortest aspect ratio (AR=3) and longest (AR=6) cylinder for all of the three end plate sizes (e/d ratio) are presented in Figure 4. Here, the lift and drag coefficients are plotted as a function of U/V, the surface speed of the rotor divided by the wind speed. This parameter is analogous to the angle of attack of an airfoil. Results conformed with our expectations, and curve shapes and magnitudes correlated well with previously-published data for comparable geometries. Primary observations of importance are:

- C_L increases dramatically with increased end plate size, especially between e/d = 1.25 and e/d = 2.
- For large values of AR, the benefit of increasing e/d beyond 2 is questionable. Thus, it appeared that an optimum design point may occur near e/d = 2.
- Up until stall occurs, end plate size increases tend to decrease drag coefficient. This is a result of reduced induced drag resulting from an apparent increase in aspect ratio caused by the end plate.

Thus, by combining the observations from Figures 3 and 4 it appeared that a good design would be achieved for a rotor having AR=6 and e/d=2. This combination would provide high lift, low drag, and reasonable power

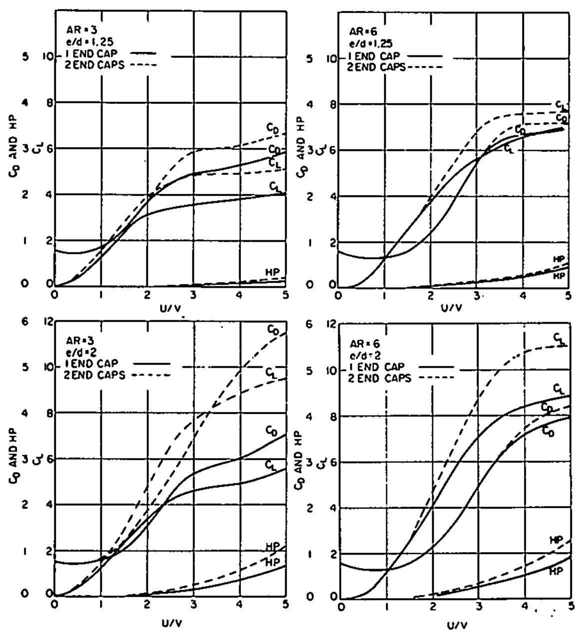

FIGURE 5. C_L,C_D POWER VERSUS U/V FOR BOUNDARY LAYER TESTS FOR e/d RATIOS OF 1.25 and 2; ONE AND TWO END CAPS; AND ASPECT RATIOS OF 3 and 6.

levels for spinning the rotor. We also concluded that aspect ratios greater than 6 might be even more attractive; however, since wind tunnel size prevented testing a larger cylinder, data for larger aspect ratios would have to be obtained by extrapolation and use of the conventional induced drag equation which is a function of C_L^2 and AR.

Although not presented in the interest of brevity, measurements of lift moment and drag moment also were obtained for use in computing the centroid position of these forces as a function of U/V. These measurements were of particular interest when we conducted the boundary layer test series, because the primary reason for this test series was to obtain aerodynamic data for use as an independent check of our model for predicting the combined effect of the two airload distributions that are imposed on the rotor: (1) a uniform air load versus rotor height caused by motion along the track; and (2) the non-uniform atmospheric boundary flow distribution with height caused by the wind. The combination of these two flows to obtain the resultant velocity yields a spiral air load distribution with height. Since this combination of air flows cannot be obtained in a wind tunnel it was necessary to develop an empirical model based on our tests.

Typical boundary layer data are presented in Figure 5. As with the free-stream results, the data trends and accuracy are satisfactory, and the data verified well our predicted centroid positions by our model.

Most of the observations from the boundary layer data were similar to those for the free stream data. In addition, it was concluded that the use of top and bottom end plates (instead of one top plate as Madaras planned) would be beneficial to performance.

ELECTROMECHANICAL DESIGN

Design loads on the rotor, rotor support, tower car, and track were developed from inputting the design criteria into our Madaras performance simulation program, which predicts the forces on the various components as a function of angular position on the track. Typical aerodynamic loads normal and tangential to the track for an operational wind condition were calculated.

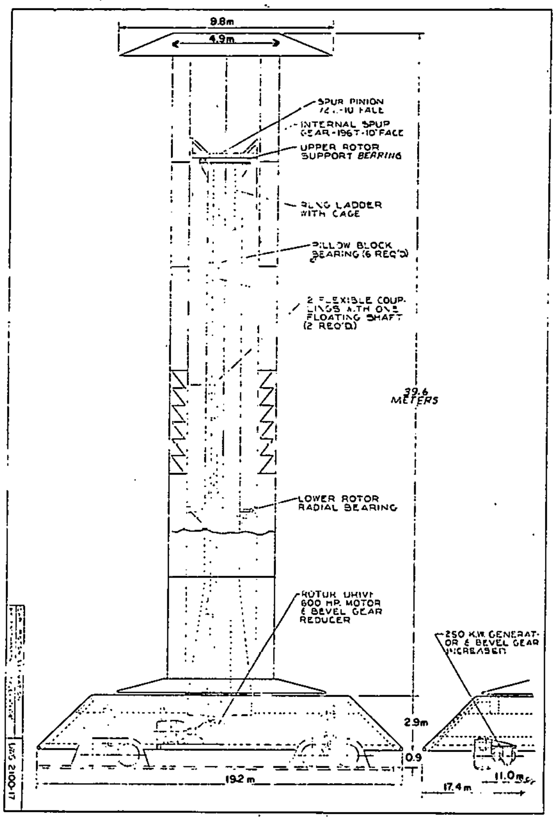

FIGURE 6. REVISED ROTOR CAR CONFIGURATION.

Results of the load analysis for the three wind conditions (i.e., operational, operational + gust, and static operations at hurricane conditions indicated that the operational gust load was the most severe. Other load conditions analyzed were:

- Aerodynamic loading on the end cap
- Acceleration loads caused by:
  - Rotor travel around the curved track
  - Centrifugal body force caused by rotor rotation at 186 rpm
  - Angular acceleration during rotor spin-up from 0 to 186 rpm
  - Snow and ice loads
  - Car weight
  - Wheel and lateral restraint loads (idler wheels bearing on the side of the track were used to react lateral loads instead of a flanged wheel)
- Cyclic fatigue loading.

Structural, Mechanical, Site Design

The rotor car design concept which evolved from our studies is depicted in Figure 6. A summary of the overall design follows.

- Dimensions
  - AR = 8 and e/d = 2
  - Cylinder length = 38.1m (125 ft)
  - Cylinder diameter=4.9m(16ft)
  - End cap diameter=9.8m (32 ft)
  - Track gage = 11.0m (36ft)
  - Car length = 19.2m (63 ft)
  - Car height = 3.8m (12.5ft)
  - Car width = 17.4m (57 ft)
  - Gross car weight = 328,000 (723,000 lb)
- Structural Configuration and Materials
  - Rotor - Semimonicoque, longeron trusses, circumferential truss stiffeners, and circumferentially corrugated skin. All 2024-74 Alclad aluminum alloy.
  - Cap - Semimonicoque, radial trusses at 45° increments, stressed skin. All 2024-T4 Alclad aluminum alloy.
  - Support Tower - Monocoque cylinder on top of truncated cone, skin thickness variable from 9.5 mm to 12.7 mm, all of ASTM A-242 corrosion-resistant steel.
  - Rotor Car - Semimonicoque, frame of built-up longitudinal and lateral box beams 0.9 m to 1.22 m deep, pipe skirt support, rectangular tube intercostals, and 3 mm-thick stressed skin. Structural steel frame with ASTM A-242 corrosion-resistant steel skin. Floor steel-reinforced concrete for ballast and environmental protection for electrical equipment.
  - Suspension system - Four, two-wheel trucks, one at each corner of the car. Wheels are 1.2 m diameter with a 279 mm tread, forged AISC

1045 steel hardened to depth of 25 mm. Each truck was coupled through a speed increaser to a 250 kW, 4160 V induction generator. Thus, 1000 kW of generating capacity is provided for each rotor car.

Power transfer from the rotor car will be accomplished by a three-slipper, spring-loaded trolley arm attached to the car. Power will be collected by an overhead, triple-tracked, rigid trolley rail on the inside of the track. The trolley will be supported by commercial light posts spaced about 12.2 m apart.

The rotor cars will be coupled together in an endless train by two wire ropes (70 mm diameter) attached to the main frame structure mid-point of the front and rear of each car. The point of attachment will be 3-m above the track; sufficient to allow for the catenary deflection between cars.

Dynamic balancing of the rotor in the field after assembly was proven to be simple and effective in 1930: the rotor was rotated by its motor, and lead weights were fastened to structural members along the length of the rotor until smooth operation was observed on vibration measuring instrumentation. Similar methods would be used for balancing the rotors described herein.

A typical site layout, road bed, and rail configuration will have a racetrack configuration and is envisioned to include: • Service road around the outside of the track. • A spur track leading to an assembly-maintenance, and a control building. • Drains, utilities, roadbed, and track. • Trolleys, power distribution, and telemetered control system. • Two viaducts under the track to facilitate access to the "in-field" portion of the track in order that the land can be used for agriculture.

The roadbed will consist of two parallel independent rails or tracks. Each track will be built as follows:
• An evacuated, well-compacted soil base. • A 1.6-m high ballast foundation of crushed coarse and fine aggregate. • A 36-cm-thick by 2.4-m-wide pavement of steel reinforced concrete. • A flat rail made of 51-cm wide by 10-cm thick steel bolted to the concrete pavement every 1.2-m of track length.

Electrical Design

The electrical design considered four components.
• Rotor Spin System • Generator System • Control and Instrumentation System • Electrical Interface System

The rotor spin system selected consists of a 450 kW, 500 volt dc motor on each car with a silicon-controlled-rectifier dc motor control system. Dynamic braking of the rotor can be either by regenerative braking or by allowing viscous drag to decelerate the rotor. Direction reversal will be achieved by reversing polarity of power leads to the armature, and speed control will be achieved by balancing the input power level to the armature against the demand of the control function signal. A motor voltage, current, power, or speed profile time history can be used as a motor control function; or an external signal from the central computer can be used for control. This concept was selected over other methods because of the need for continually variable speed control as a function of wind speed and rotor position on the track; and the need for rotor spin direction reversal twice each orbit of the track.

One of the major results of the spin motor study was the discovery that there were three sources of spin motor losses, that these losses were highly significant, and that Madaras considered only one of these loss mechanisms. These loss sources are: • Power required to overcome the viscous friction of the rotor caused by spinning (the only one considered by Madaras). • Power required to overcome rotor inertia while accelerating the rotor from 0 to 186 rpm, and the loss in energy during rotor deceleration (Madaras assumed complete recovery of the inertial energy of the spinning rotor by regenerative braking). • Power lost in heating motor windings during the low speed, acceleration stage during which time the motor is operating at very low efficiency (i.e., from 0 to 45 percent efficiency as the motor speed increases slowly from 0 to 70 percent of no-load speed).

Of these three mechanisms, the latter is by far the most severe: only 44 percent of the power input to the motor is delivered to the shaft during each start-up cycle. Of course, losses decrease to only about 10 percent when the rotor reaches full speed.

Madaras also erred when he assumed full capture of the spinning rotors inertial energy by regenerative braking. However, even during braking, viscous friction absorbs considerable amounts of energy which is unavailable for regenerative braking, and then the "motor-turned-generator" heating losses (like the third type of motor heating loss above) absorb so much power, that only about 3 percent of the energy originally input to the spin motor can be recovered during regenerative braking. Thus, we elected to use natural viscous forces to de-spin the rotor in order to save wear on the spin motor and to reduce the cost of power transfer equipment.

The selection of the 450 kW size for the spin motor was governed by a trade study utilizing our Madaras plant performance simulation program. From these studies we decided that a good design point occurred at a 450 kW motor size and a 1372 m (4500 ft) track diameter. The study was for a circular track; however, as will be described later, a racetrack pattern improves performance considerably.

The generators selected for the Madaras system was sized for 1 MW rated output from each rotor car at a rated wind speed of 13.4 m/s. For each car, four 250 kW (because of wheel drive torque limitations) three-phase, 60 Hz alternating current induction generators were considered to be the best for a Madaras plant. Although a synchronous generator is more efficient, the problems of aligning and maintaining precisely in phase all the generators on all rotor cars in a large plant seemed to overweigh the added efficiency one would gain from a synchronous generator.

It is believed that the efficiency of the induction generators would be in the 80 to 85 percent range, with a leading power factor of from 0.8

to 0.9. This power factor would be corrected by a synchronous reactor system at the control building distribution station.

The control system will include the following components:
- A minicomputer-based primary controller in the control house.
- A microcomputer-based controller on each car.
- A two-way radio telemetry system to link all the car units to the primary controller
- A wind sensor network dispersed around the track and hard wired underground to the primary controller.
- Monitoring instruments and control actuator circuits on each car and on system network components.
- An operators station in the control house consisting of monitoring instruments and manual over-rides of the primary controller.

Standard equipment would be used for these items and power plant control would be automatic; however, CRT, panel displays, and hard copy readouts would be available for monitoring and manual control modes also would be provided.

System network elements required to interface with the various electrical subsystems include:
- Car trolley and feeder bus (4160V, 3 phase, 500 ampere capacity).
- Distribution circuit to the trolley feeder bus (power pick-off from the trolley every three-and-one-half rotor car spacings to limit trolley amperage to 500 amperes).
- Synchronous reactors for power factor correction.
- Utility feeder circuits.
- Substation.

The substation would be located adjacent to the control house to simplify and shorten all feeder circuits.

PERFORMANCE ANALYSIS

The objectives of this study were: (1) to conduct a design trade study of the various plant operational parameters; (2) to determine the effect of mutual interference between rotors on power plant output as a function of inter rotor spacing; and (3) to determine the net power output in the form of power duration curves corrected for mutual interference effects.

Objectives of the major investigations in the design trade study were to select for final cost analysis:
- A relatively efficient rotor geometry and size.
- Spin motor size and track diameter.
- Track speed and rotor rpm.
- Spin motor schedule.

These results then were merged to define the plant configuration and operating conditions that appeared most attractive from a performance standpoint and in view of certain cost and efficiency considerations.

Our Madaras plant performance simulation program was used for this study. This program has provisions for inputting all data, geometrical and operational parameters, and all losses developed in the earlier studies,

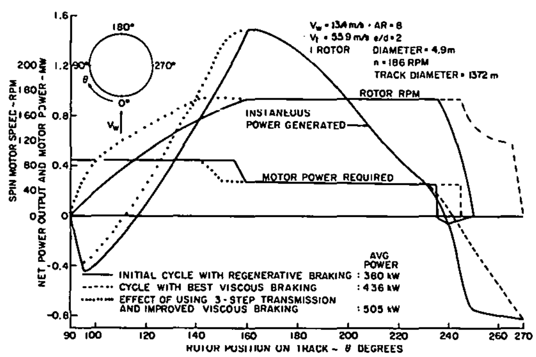

FIGURE 7. NET POWER OUTPUT FOR ONE ROTOR. SPIN MOTOR POWER, AND MOTOR RPM VERSUS ROTOR POSITION ON TRACK AS AFFECTED BY USE OF VISCOUS BRAKING, REGENERATIVE BRAKING, AND A THREE-STEP TRANSMISSION TO VARY THE SPIN SCHEDULE.

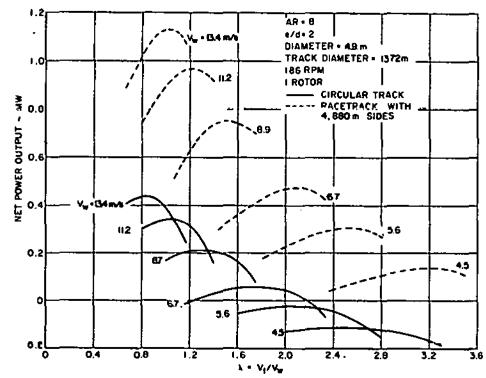

FIGURE 8. NET POWER OUTPUT FOR ONE ROTOR VERSUS λ AS A FUNCTION OF WIND SPEED. PERFORMANCE IS PRESENTED FOR BOTH A 1370 m (4500 ft) DIAMETER CIRCULAR TRACK AND A RACETRACK HAVING 1370 m (4500 ft) DIAMETER ENDS AND 4880 m (16,000 ft) STRAIGHT SECTIONS.

and simulates plant performance for any set of these conditions for any wind speed. Output in the terms of power output/rotor for a circular track of diameter D, and for a racetrack having straight section S of any length is provided.

As a result of these studies, the following plant configurations and operational conditions were selected for the performance and cost analysis.

- Rotor Geometry
  - AR = 8 • e/d = 2 • height = 38 m (125 ft) • diameter = 4.9 m (16 ft) • end plate diameter = 9.8 m (32 ft) • two end plates • area = 186 m^2 (2000 ft^2)
- Spin Motor Schedule (see Figure 7 for one-half of cycle)
  - Maximum angular acceleration at 450 kW to 186 rpm
  - Constant 186 rpm until track position of 245°
  - Viscous drag braking to stop
  - Reverse rotation direction and repeat cycle
- Track Speed
  - Circular Track = 8.9 m/s (20 mph) • Race Track = 13.4 m/s (30mph)
- Track Size
  - Circular Track = 1372 m (4500 ft)
  - Racetrack = 1372 m end diameter with 3050 m (10,000 ft) to 19,210 m (63,000 ft) straight sections.
- Wind Speeds
  - 13.4 m/s (30 mph) max • 3.0 m/s (10 mph) min
- Air Density

A plot showing typical performance of a circular and a racetrack plant is presented in Figure 8. It is interesting to note that the loci of optimum performance of the racetrack and circular plants occur at all wind speeds at track speeds of 13.4 m/s and 11.2 m/s, respectively. (The parameter λ represents the track speed (V_t) to windspeed (V_w) ratio.)

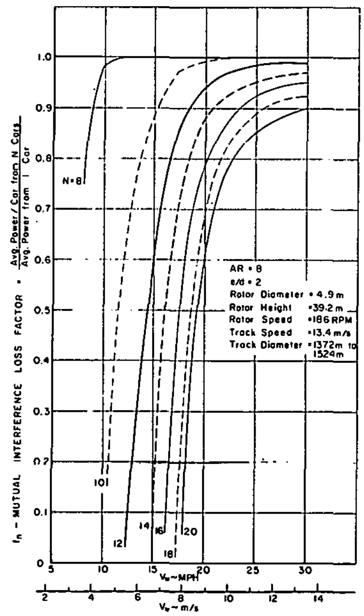

FIGURE 9. MUTUAL INTERFERENCE LOSS FACTOR VERSUS WIND SPEED FOR VARIOUS NUMBERS OF ROTORS ON A 1524-m DIAMETER TRACK. CONSTANT ROTOR SPEED AND TRACK SPEED OF 186RPM AND 13.4 M/S, RESPECTIVELY.

A lower than optimum track speed for the circular plants was selected to improve annual energy yield by reducing inter-rotor, mutual interferences, losses.

The mutual interference study, conducted by Professor H.C. Larsen of the Air Force Institute of Technology made use of the vortex analysis which he developed for analyzing the Giromill, now under development by the McDonnell Air-Craft Company [1]. Since the Giromill and the Madaras system are essentially comparable in concept, and since the analysis has been validated by wind tunnel studies, the method was considered appropriate for the Madaras rotor mutual interference study.

Professor Larsen's analysis essentially determines the effect of all vortices shed from each rotor in the plant on the vortices shed by all other rotors in a power plant, and then determines the effect of this vortex field on the wind velocity vector at all points around the track orbit. The net effect is that the vortex field causes changes in the wind velocity vector which reduces the magnitude of the rotor's propulsive force along the track. As rotor spacing decreases, mutual interference losses increase until a point is reached where it is counterproductive to add more rotors.

As shown on Figure 9, the effect of interference is intensified as the number of rotors, N, increases and wind speed decreases. The wind speed at which a curve starts represents the cut-in wind speed. The data from Figure 9 were used in conjunction with data from Figure 8 to develop the net output from a total Madaras plant taking into account all electromechanical, aerodynamic, and mutual interference losses.

The last aspect of this study was to develop power duration curves for various sized Madaras plants. These power duration curves were obtained from the standard wind duration curve having a mean wind speed of 8.1 m/s at a height of 9 meters in accordance with our design specifications. This curve was uprated to a height of 25 m (the center height of the Madaras rotor) by the usual 0.167 power law. An additional wind duration curve for Medicine Bow, Wyoming, also was used to provide a means for comparing Madaras plant performance with that of a large array of MOD-1 wind turbine generators at Medicine Bow. These wind duration curves and the resulting power duration curves from two Madaras plants are presented in Figures 10 and 11, respectively.

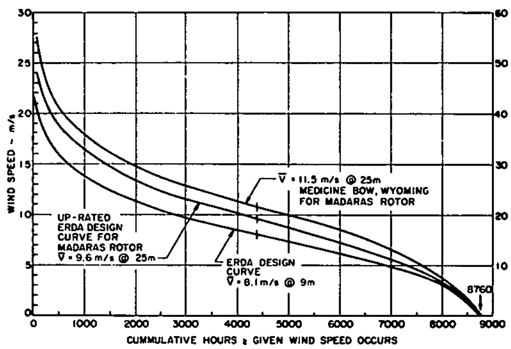

FIGURE 10. MODIFIED WIND DURATION CURVE TO REPRESENT WIND CONDITIONS AT A ROTOR MID-HEIGHT OF 25m (82 ft) ABOVE MEAN TERRAIN LEVEL.

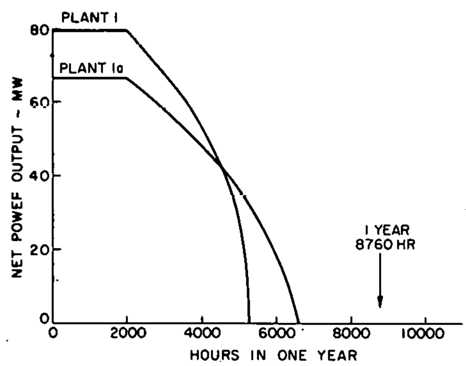

FIGURE 11. POWER DURATION FOR TWO PLANTS BASED ON THE $\overline{V}$=9.6 M/S DESIGN WIND DURATION CURVE AT 25-m HEIGHT.

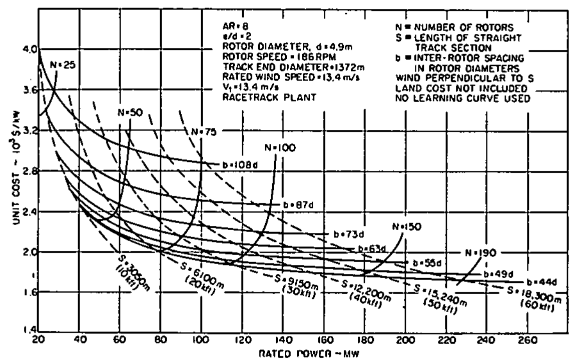

FIGURE 12. UNIT PLANT COST VERSUS RATED POWER FOR RACETRACK CONFIGURATION AS A FUNCTION OF INTER-ROTOR SPACING, LENGTH OF STRAIGHT SECTION OF TRACK, AND NUMBER OF ROTORS. DOE DESIGN WIND DURATION CURVE: $\overline{V}$=8.1 m/s at 9 m.

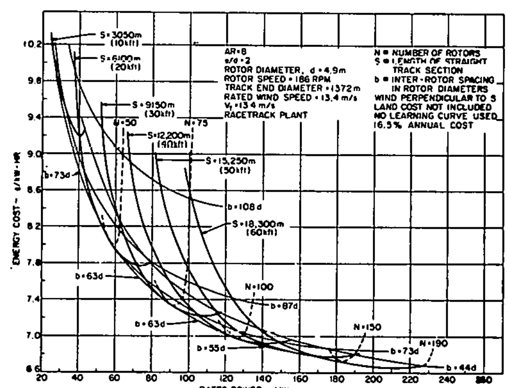

FIGURE 13. ENERGY COST VERSUS RATED POWER FOR RACETRACK CONFIGURATION AS A FUNCTION OF INTER-ROTOR SPACING, LENGTH OF STRAIN SECTION OF TRACK, AND NUMBER OF ROTORS. DOE DESIGN WIND DURATION CURVE: $\overline{V}$=8.1 m/s at 9 m.

COST/PERFORMANCE ANALYSIS

Cost estimates in a modular form suitable for scaling Madaras plants to a wide range of sizes were developed by a professional engineering firm which specializes in cost estimating. In addition, generalized equations describing plant geometry were developed in terms corresponding to the modular cost variables.

Our analysis indicated that even the most efficient circular plant was not sufficiently economical for further consideration. Even when accounting for the effects of an 85 percent learning curve on the rotor and track, the manufacture of 500 plants comprised of 20 rotors on a 1372-m diameter track and a 16.5 percent annual cost and a 30 year life; the minimum installed cost of a 7.85 MW circular plant would be \$1539/kW in a region where mean wind speed is 8.1 m/s at a 9-m height. For this same plant, the expected energy cost would be 6.2¢/kW-hr, based on annual energy output of 37.76 x 10^6 kW-hr, and land cost of \$1500/acre.

TABLE 1

EFFECT OF LAND COST, LEARNING CURVES, AND MEAN WIND SPEED ($\overline{V}$) ON PLANT AND ENERGY COST - SEA LEVEL DENSITY

Plant No.	$\overline{V}$ 9-m Height	P_R	Annual Output	A_n	No. Plts.	No. Rotors	Rotors-85%L.C.; Track 90%L.C. Plant Cost(1)	Energy Cost ∿ ¢/kW-hr(2) Land Cost ∿ $/Acre 0	500	1000	1500	3000
-	m/s	MW	10^6kW-hr	Acre	-	-	$/kW					
49-60	8.1	211	931	745	1	170	722	2.69	2.70	2.71	2.72	2.73
					10	1700	492	1.84	1.84	1.85	1.86	1.88
					100	17000	342	1.28	1.28	1.29	1.30	1.32
44-60	8.1	228	975	748	1	190	681	2.62	2.63	2.64	2.64	2.66
					10	1900	463	1.78	1.79	1.79	1.80	1.82
					100	19000	321	1.24	1.24	1.25	1.25	1.27
49-60M	9.7	211	1103	745	1	170	722	2.27	2.28	2.28	2.29	2.31
					10	1700	492	1.55	1.56	1.56	1.57	1.58
					100	17000	342	1.08	1.08	1.09	1.09	1.11
44-60M	9.7	228	1170	748	1	190	681	2.19	2.19	2.20	2.20	2.22
					10	1900	463	1.49	1.49	1.50	1.50	1.50
					100	19000	321	1.03	1.03	1.04	1.05	1.06

(1) Does not include land cost. (2) Based on annual cost = 16.5% of plant cost.

On the other hand, large racetrack plants appear to be quite attractive. Figures 12 and 13 contain parametric plots, respectively, of cost/kW and cost kW-hr versus rated power. These plots indicate the relationship of various parameters on cost and rated power input: inter-rotor spacing, b, in number of rotor diameter, d, where d = 4.9 m (16 ft); length of the straight section, S, of the racetrack, and number of rotors. These curves do not reflect the effects of learning curves or land cost, and Figure 13 is based on annual costs equal to 16.5 percent of total plant cost.

It should be remembered that the racetrack plant is dependent upon a unidirectional wind (including reciprocal directions) for proper operation. Such areas as those near large bodies of water or near the Great Plains area, such as Medicine Bow, Wyoming, would be ideal sites for such a plant.

Table 1 presents cost and performance data for the two largest Madaras plants studied. Plant numbers indicate size; e.g.: Plant 49-60, the inter-rotor spacing is 49 rotor diameters and the length of the straight track section is 60,000 ft (18,300m). The suffix M indicates a Medicine Bow, Wyoming, wind duration curve. Sea level air density was used for Table 1 configurations.

The separate and combined effect of learning curves, land cost, and mean wind speed on Madaras plant and energy cost are shown in Table 1. Costs are in 1978 dollars. These data indicate that land cost has an insignificant effect on energy cost because plant cost is high relative to land cost, and also because we elected to purchase only that land required for the track and road, the power station, and the area enclosed by a fence line offset 100 ft from all plant tracks and buildings (A_n in Table 1). The "infield" area inside the track would be retained by the owner for agricultural purposes. Viaducts under the track at each end would provide access to the property, and the property would be a large, open, unbroken expanse that would be attractive for large scale farming (about 6460 acres for Plant 44-60).

The learning curve effect on energy cost for a given plant can be seen by comparing one column of figures under a given land cost or by comparing Plant 49-60 with Plant 44-60. These data indicate that energy from Madaras plants is sensitive to learning curves. Madaras plants also are more economical as they are built larger, as shown dramatically in Figure 13, and to a much smaller extent on Table 1 (compare energy costs for Plant 49-60 with 44-60).

Comparisons of the Madaras system with horizontal axis wind turbine generators (HA-WTG) were made to determine whether or not Madaras plants showed promise of producing electrical energy at a lower cost than HA-WTG's (the basic objective of this study). Comparisons were made with HA-WTG plants proposed by Mr. S.J. Hightower [2] of the Bureau of Reclamation, Department of Interior for installation at Medicine Bow, Wyoming. These two plants consisted of 49 and 98 MOD-1 WTG's, respectively, designed by the General Electric Company. These plants were selected for the comparison because they utilized large, modern HA-WTG's, and because the study included all costs required to connect the HA-WTG array into a complete plant, just as this Madaras plant study has done.

Equitable bases for the comparison were developed and coordinated with Hightower. The more important ground rules for the comparison were: 1978 dollars; 5-year construction period; construction interest at 7 percent; plant life of 30 years; Financing—Federal Annual Fixed Rate = 15%; Operation and Maintenance annual cost 2% of base plant cost; land purchased—net area (A_n) in Table 1 for Madaras plant,1500 ft diameter per HA-WTG (specified by Hightower); same learning curve equations and 85 percent learning curve for WTG and Madaras rotor, and a 90% learning curve was used for the track.

Cost elements in the estimate for both plants included all direct costs for equipment, electrical connection, and land; management, engineering, and overhead; contingencies; and interest.

The comparison was made for the following two sets of conditions:

- Medicine Bow—2134 m elevation, air density ratio = .81.
  - Two plant sizes, each type: ≈ 98MW, 196 MW • Mean wind speed = 9.7 m/s @ 9-m height • Federal Financing • Land cost = \$200/acre
- Other Site—sea level, air density ratio = 1.0
  - Same two plant sizes • Mean wind speed = 8.1 m/s @ 9-m height
    - Private financing • Land Cost = \$3000/acre

The results of this comparison are shown in Table 2, which describes the geometry, performance, installed cost, and annual cost and energy of each plant. Plant ID numbers assist in the comparison: e.g., Madaras Plant 1 is compared with HA-WTG Plant 1a. Plant 3 (also 6) was added for completeness since it was the largest Madaras plant analyzed. The cost results for Plants 3 and 6 in Table 2 do not agree with those in Table 1 because costs in Table 1 were altered to conform to the comparison ground rules upon which the data in Table 2 are based.

The major observations drawn from this data in Table 2 are:

- Plant cost is about equal for both systems.
- Annual energy output and hence plant factor is higher for the Madaras

TABLE 2

OVERALL COMPARISON OF SEVERAL MADARAS AND HA-WTG PLANTS AT TWO WIND REGIONS

	PLANT ID NO.	PLANT DESIGNATION	PLANT GEOMETRY: PLANT LENGTH	PLANT WIDTH	PLANT AREA	NET AREA PURCHASED	TRACK PERIMETER	NUMBER ROTORS/ WTG	ROTOR/ WTG (1) SPACING	PERFORMANCE: $\bar{V}$ @ 9 m	RATED CAPACITY	(7) ANNUAL OUTPUT	PLANT FACTOR	V_R @ 9 m
	-	-	m	m	Acre	Acre	m	-	m	m/s	MW	10^6kW-hr	-	m/s
MEDICINE BOW PLANTS	1	44-25M (4) 99.18MW	9213	1468	3341	437	19,610	91	215	9.7	99.18	412.0	0.47	13.4
	1a	HA-WTGM 98 MW	14,700	1590	5772	1988	N/A	49	920	9.7	98.0	409.6	0.48	11.2
	2	44-50M 191.43 MW	16,863	1468	6115	660	34,910	162	215	9.7	191.43	797.9	0.48	13.4
	2a	HA-WGTM 196 MW	14,700	3975	14,432	3976	N/A	98	920	9.7	196.0	819.2	0.49	11.2
	3	44-60M 227.77 MW	19,880	1468	7209	748	40,940	190	215	9.7	227.77	947.9	0.48	13.4
PLANTS WHERE $\bar{V}$ = 8.1 m/s	4	44-25 99.18 MW	9213	1468	3341	437	19,610	91	215	8.1	99.18	423.9	0.49	13.4
	4a	HA-WTG 98 MW	14,700	1590	5783	1988	N/A	49	920	8.1	98.0	362.6	0.42	11.2
	5	44-50 191.43 MW	16,863	1468	6115	660	34,910	162	215	8.1	191.43	819.5	0.49	13.4
	5a	HA-WTG 196 MW	14,700	3975	14,457	3976	N/A	98	920	8.1	196.0	725.2	0.42	11.2
	6	44-60 227.77	19,880	1468	7209	748	40,960	190	215	8.1	227.77	975.4	0.49	13.4
$\bar{V}$ = 8.1 m/s No Land Cost	7	44-50 191.43 No Land Cost	16,863	1468	6115	660	34,910	162	215	8.1	191.43	819.5	0.49	13.4
	7a	HA-WTG 196.0 MW No Land Cost	14,700	3975	14,457	3976	N/A	98	920	8.1	196.0	725.2	0.42	11.2

	PLANT ID NO.	INSTALLED COST: ROTOR OR WTG	TRACK	ELEC. CONN.	SITE AND FACILITIES	CONTINGENCIES (2)	MGMT. ENGR. OVERHEAD	LAND COST (3)	CONST. INTEREST	TOTAL PLANT COST	COST kW	ANNUAL AND ENERGY COST: FIXED CHARGE (6)	O&M	TOTAL ANNUAL	ENERGY COST
					10^6 Dollars (1978)						$/kW	10^6 Dollars (1978)			Mills/kW-hr
MEDICINE BOW PLANTS	1	21.27	26.48	7.61	9.99	6.73	14.87	0.12	14.67	101.74	1026	8.56	1.74	10.30	25.0
	1a	55.52	N/A	6.85	9.35	(5)	10.70	0.56	14.42	97.40	994	8.19	0.99	9.18	22.4
	2	33.08	43.18	12.37	14.61	10.50	23.56	0.18	24.03	161.51	844	13.58	2.75	16.33	20.5
	2a	94.38	N/A	13.70	15.54	(5)	18.89	1.12	24.94	168.57	860	14.17	1.98	16.15	19.7
	3	37.38	49.44	14.15	16.35	11.90	26.76	0.21	27.29	183.48	806	15.43	3.17	18.55	19.6
PLANTS WHERE $\bar{V}$ = 8.1 m/s	4			SAME AS 1				1.84	Same as 1	103.45	1043	15.52	Same as 1	17.26	40.7
	4a			SAME AS 1a		(5)		8.37	Same as 1a	100.21	1074	15.78	Same as 1a	16.77	46.2
	5			SAME AS 2				2.78	Same as 2	164.10	857	24.62	Same as 2	27.37	33.4
	5a			SAME AS 2a				16.73	Same as 2a	184.18	940	27.63	Same as 2a	29.61	40.8
	6			SAME AS 3				3.15	Same as 3	186.42	818	27.96	Same as 3	31.08	31.9

(1) WTG spaced in three rows, staggered, equilateral triangular array at 15 rotor diameter (d = 61 m)
(2) Contingencies in HA-WTG plant inched in site and facilities figure.
(3) Includes allowance for funds used during construction, due to outright purchase of land.
(4) The suffix letter M refers to Medicine Bow plants; all others for wind duration curve $\bar{V}$ = 8.1 m/s.
(5) Contingencies for HA-WTG plants are included in the electrical connection cost.
(6) Fixed charges for Medicine Bow plants based on Federal financing at fixed charge of 8.41 percent. All others, fixed charge = 15 percent.
(7) Based on air density ratio of 0.81 — 7000 ft(2134m) above msl.

plants than for the HA-WTG plants at the 8.1 m/s mean wind region. MOD-1 performance data for this other site were obtained from General Electric [2].

- Madaras plants use considerably less gross land area than HA-WTG units spaced 15 rotor diameters apart (915 m); less net area needs to be purchased for Madaras plants; and the remaining land area in the "infield" of a Madaras plant can be used more efficiently for agriculture or industry than the broken up tracts of land scattered among arrays of HA-WTG plants.
- Annual operation and maintenance costs of Madaras plants are greater because of their added complexity.
- Energy cost of Madaras plants at Medicine Bow varies from 4 percent to 12 percent higher than that for comparable HA-WTG plants; and at the sea level site, Madaras plant energy cost is from 13.5 percent to 22.2 percent less than HA-WTG cost.
- Madaras plant energy cost relative to HA-WTG energy cost is unaffected by the magnitude of the annual fixed cost rate, but land affects the

relative cost position of HA-WTG plants because HA-WTG plants use considerably more land area than Madaras plants. Further land use of an HA-WTG farm is less efficient.

CONCLUSIONS

This conceptual design study of the Madaras Rotor Power Plant included an analysis of all major components of the Madaras system. It is believed that a reasonably efficient conceptual design for the Madaras system has been developed, and that this design fulfills all criteria initially established.

The more significant conclusions drawn from this study are itemized below.

(1) Madaras plants having capacities from 7.9 MW to 228 MW with annual energy output varying from 32 x 10^6 kW-hr to 1170 x 10^6 kW-hr are feasible. No limitations were noted that would restrict maximum plant capacity to 228 MW. Thus, Madaras plants are capable of providing plant capacities of interest to electric utility companies.

(2) Madaras plants having circular track configurations probably are not economically competitive with HA-WTG plants because of the large electric losses of the spin motor and the mutual interference losses which limit the number of rotor cars to about 20 per plant. The minimum track diameter appears to be 1372 m (4500 ft).

(3) Losses in a Madaras plant are significantly larger than those of a HA-WTG plant. The aerodynamic and mechanical losses are tolerable, but there is need to reduce the electrical losses significantly. Until electrical and interference losses are substantially reduced, racetrack plant configurations must be used for Madaras plants.

(4) For the range of track end diameters studied for both circular and racetrack plant configurations, minimum energy cost is obtained where minimum inter-rotor spacing is about 44 rotor diameters (d = 4.9 m) and the minimum track diameter (end diameter of a racetrack) is about 1372m.

(5) The free stream and boundary layer wind tunnel data obtained during this study are the most complete set of data on rotating cylinder versus geometry and wind speed profile available in the literature. This set of data can be used directly to predict full-sized rotating cylinder performance.

(6) It is believed that the 125-ft high (38 m) Madaras rotor offers a superior structural alternative to 200-ft to 300-ft (61 m to 91 m) diameter, flexible wind turbine blades when subjected to wind, gust, and tower loads.

(7) The potential problem areas and disadvantages of Madaras plants relative to HA-WTG plants are: • The Madaras system is more complex, has higher losses, and will require higher operation and maintenance costs than a horizontal axis wind turbine system. • The use of a racetrack plant configuration is necessary for optimum Madaras plant performance (at this time). Thus, Madaras plants will be limited to regions having nearly unidirectional winds or to those regions in which off-axis winds have an angular variation of less than ± 45° and which occur only a small portion of a total year.

(8) The advantages of the Madaras plant over a comparably-sized HA-WTG plant are: • A rotating cylinder rotor structure is simpler and can

be built to have greater structural strength, durability, and reliability as compared to large, flexible rotor blades exposed in a wind and gust environment. • Madaras plants show higher sensitivity to economy of scale. • Madaras plants use land more efficiently and use less land than HA-WTG plants.

(9) The Madaras Rotor Power Plant concept using a racetrack plant configuration appears at least to be economically competitive with horizontal axis wind turbine generators, and more probably the concept shows promise of out-performing horizontal axis systems from a number of standpoints: structural durability, economy of scale, energy yield, and efficient use of land. The results of this study indicate that, although the Madaras concept does not represent a major breakthrough in wind energy conversion technology, Madaras racetrack plant energy cost varied from 12 percent higher to 22 percent lower than the energy cost of MOD-1 plants. This advantage, although attractive, is diminished by the Madaras system's limited application arising from a possible scarcity of large, flat, land areas having sufficiently unidirectional wind velocities, if further studies indicate only racetrack plant configurations are feasible.

(10) Although more efficient HA-WTG systems (MOD-2) are being developed, it is believed that more efficient Madaras systems also can be developed given the opportunity to conduct the necessary design studies. Thus, the Madaras system should be analyzed further in order to determine more accurately how well it fulfills the promise indicated in this present study. In particular, it is believed that improved performance will be realized from a more in-depth study of rotor spin schedule, the electrical and structural systems, and the mutual interference losses.

Acknowledgments

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1. R.V. Brulle, "Feasibility Investigation of the Giromill for Generation of Electric Power, Midterm Report," April-November 1975, Energy Research and Development Administration, November 1975.

2. T.R. Korneich, Proceedings of the Third Biennial Conference and Workshop on Wind Energy Conversion Systems, Volume I, September 19-21, 1977, Sponsored by the United States Department of Energy.

RESPONSES TO THE WHITFORD PRESENTATION

Question: How do you justify having 1500 ft around each wind turbine?

Whitford: That was not my criteria, but was stated by Stanley Hightower. It relates to the problem of blade throw and safety. The Madaras system does not have this type of a problem.

Gerald Leigh, University of New Mexico: I wonder about lateral stability. What happens to the rotor when it is struck by a gust?

Whitford: The system was designed to accept a gust hitting the tower.

Edward Uhlig, Tuskegee University: Could the spacing of the cylinders be varied?

Whitford: A vortex analysis was carried out by Professor Larson to answer this point. He indicated that the distance between the rotors should be approximately 700 ft. The vortices shed off the cylinders are large, probably greater than those shed from a 747. The vortex analysis has also been applied to racetrack configurations.

ELECTROFLUID (EFD) WIND DRIVEN GENERATOR

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ABSTRACT

The Electrofluid Dynamic (EFD) wind driven generator directly converts wind energy to electrical energy without moving parts. Conventional wind turbines are currently limited in size, with the greatest diameter presently envisaged being 300 to 400 feet. For the EFD wind driven generator there are no fundamental reasons to restrict the size; therefore, economics of scale and far larger powers than from conventional systems can be realized. Analyses predict favorable performance characteristics for EFD wind generators; however, specific experimental data have been lacking. Research areas presently being emphasized are discussed and performance of experimental arrays under test in an Eiffel-type wind tunnel are also discussed.

INTRODUCTION

Recently much research has been conducted on wind driven generators. All of these devices except the EFD wind driven generator employ rotating machiner and moving parts.

The EFD wind driven generator directly converts wind energy to electrical energy without moving parts except possibly for diverting it into the wind. In an EFD generator, charges of one polarity are seeded into a flowing neutral gas. Viscous interactions drive the charged particles against an electrical potential and produce dc power. Typically, the EFD generator uses high voltages and low current densities. A schematic diagram of a simple EFD wind generator is shown in Figure 1. The generator consists of the following parts:

1. A mechanism for producing charged colloids.
2. An inlet electrode which also serves as an attractor electrode.
3. A collector electrode.
4. A high voltage power supply.
5. A feedback control system.

The high voltage power supply places the attractor electrode at a high voltage relative to the colloid producing mechanism. Charged colloid particles of one sign produced by the charging system are swept past

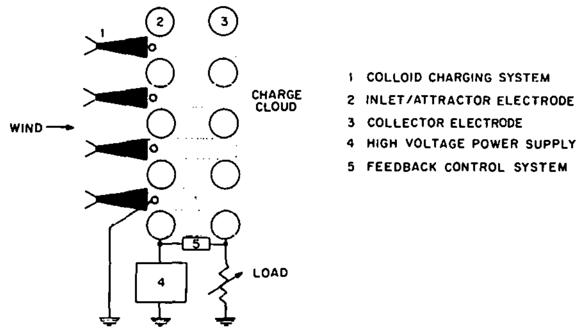

FIGURE 1. SCHEMATIC OF AN EFD WIND DRIVEN GENERATOR.

the attractor electrode by the moving air towards the collector electrode. The collector voltage depends on the load and current, but the charged particles must be driven up a potential hill by the neutral particles of the moving air. Thus, electrical power is generated directly by the moving air with no moving parts required. The feedback control system senses the voltage on the collector and adjusts the attractor voltage, thereby controlling the output current in order to hold the output voltage constant.

A substantial theory has been developed for predicting the performance of EFD wind driven generators and is available in References 1, 2, 3, 4, and 5.

EFD WIND GENERATOR PERFORMANCE

The theory of EFD devices is well developed and scaling laws are understood. Experimental evidence compares favorably with available theory and the feasibility of the EFD generator has been well established (References 6 and 7). Because high power and high power densities were desired, the main thrust of the previous research was directed toward high velocities and high pressures in the conversion section. Due to electric breakdown, the maximum drop that can be achieved in a one-dimensional EFD generator at one atm is about 40 N/m^2 whereas, at 30 atm the pressure drop could be 900 times as high, or 36,000 N/m^2 (Reference 7). Now, the pressure drop of 40 N/m^2 is not too interesting in most applications, but it is quite suitable for wind driven generator applications. The ideal wind driven generator extracts 8/9 of the dynamic pressure of the wind, thus the 40 N/m^2 corresponds to a velocity of 8.57 m/s or 19.2 mph. Consequently, below 19.2 mph the performance of an EFD wind driven generator is not limited by electrical breakdown: pressure drops in the conversion section will be less than the 40 N/m^2. Above 19.2 mph the EFD wind driven generator is limited by electric breakdown and the pressure drop in the conversion section would remain constant. The power, therefore, would go up linearly with the velocity through the conversion section. The ratio of the velocity at the face of the generator to the wind velocity is two-thirds for ideal performance and would be held at this value for wind velocities less than 19.2 mph. In the conventional wind driven generator this could be achieved by varying the pitch of the rotor blades while in the EFD wind driven generator this is accomplished by varying the current and, therefore, the charge density in the conversion section.

Above the velocity of 19.2 mph, the ratio of velocities varies from the value of two-thirds and asymptotically approaches one (the freestream wind velocity) as the pressure drop in the conversion section becomes small compared to the dynamic pressure. The results of our analysis are shown on Figure 2 where the curve labeled "ideal one-dimensional EFD wind generator" is for colloids without slip. Also shown is the effect of slip for a particle mobility of 1 x 10^{-6} (m/s)/(V/m) which probably could be actually achieved in practice.

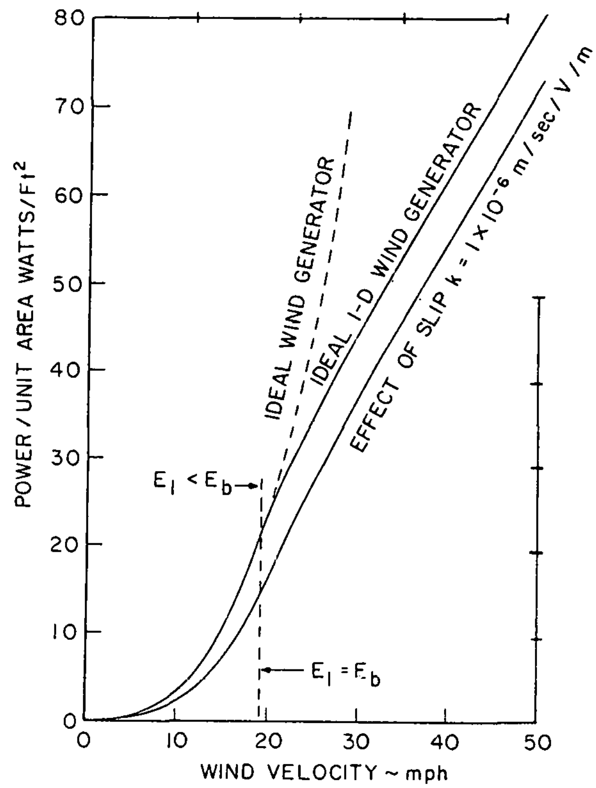

FIGURE 2. PERFORMANCE OF AN EFD WIND DRIVEN GENERATOR.

If two-dimensional effects are included, then higher pressure drops can be obtained before breakdown limits performance: hence, higher values of velocity can be achieved before the EFD wind generator deviates from ideal performance. Above this "rated speed," unlike conventional windmills, the power increases linearly.

We have also included the effects of aerodynamic drag on the performance of an EFD wind driven generator (see References 2 and 4). The performance was calculated for an EFD wind driven generator made of 1-ft (30.48 cm) tubes with various lateral spacing as shown on Figure 3. In Figure 3 the curve parameter "a" is the ratio of the center distance of the tubes to the diameter perpendicular to the flow direction. The parameter "b" is a similar parameter along the flow direction and was held constant at a value of 1.5. The parameter N is the number of electrodes (group of rods) and was set equal to two.

With the large value of "a" (4.69) we have a wide spacing of the rods in the electrodes with low drag and low electric forces. The generator limits performance at very low velocities and the relative output is low at all velocities except the lower velocities.

With the smaller value of "a" (1.56) we have narrow spacing of the rods with high drag and high electric forces. The generator does not limit performance until the velocity is quite high. The output is low because of the high drag until the velocity is very high.

CHARGED COLLOID PARTICLE REQUIREMENTS

Generation of charged colloid particles requires power input. A practical EFD generator must produce power greatly exceeding that necessary to generate the particles. Not only must charged colloids be produced

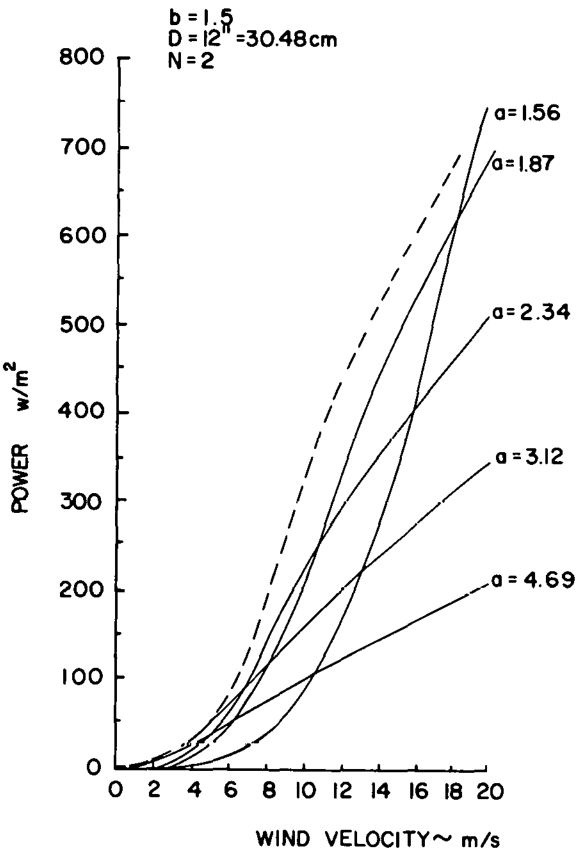

FIGURE 3. TWO-DIMENSIONAL ELECTRICAL EFFECTS AND DRAG EFFECTS COMBINED.

in a sufficient quantity, but also the colloids must have appropriate sizes and mobilities for EFD wind driven generators.

The mobility of a charged colloid particle is a measure of its responsiveness to an electric field. A particle with high mobility will tend to move with the viscous flow. Charged particle mobility, k, is defined as the ratio of the average particle drift speed to the local electric field strength.

The power input to generate charged colloids can be divided into three categories: power to form particle surfaces, power to charge particles, and power to pump a liquid for forming particles. Equations defining these power inputs have been developed to provide the total charge droplet formation power (see References 2 and 3). Using these equations we have developed performance maps of the generator mobility k, radius r, plane as shown on Figure 4 for water droplets in air. We have assumed a collector voltage, V, of 300 kV, charging work Vc of 100 electron volts/electron, a flow gauge pressure of 68,900 N/m^2 (10 psi) and a surface tension of 0.0735 N/m.

From Figure 4 we see that it would be possible to obtain powers in excess of 93 percent of ideal when we consider all loss mechanisms except drag. Particle sizes with a radius less than 1μ are needed to obtain outputs in excess of 85 percent of ideal. Between a radius of 0.1μ and 1μ we can achieve adequate performance as indicated on Figure 4.

CHARGE DROPLET PRODUCTION METHOD STUDIES IN SUPPORT OF GENERATOR TESTING

The testing of generator experimental designs requires low mobility and with a sufficient quantity of drops to produce design charge density levels. It is not necessary to meet the condition of energy efficient production as would be required for the application of EFD wind generators. Early charge droplet production methods that were investigated included condensation of steam, and electrhydrodynamic sprays. Both

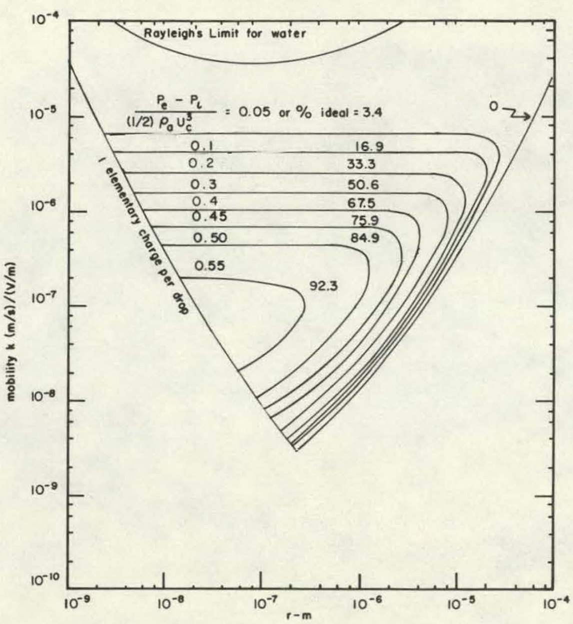

FIGURE 4. PERFORMANCE MAP OF AN EFD WIND DRIVEN GENERATOR WITH V=300 kV, Δp= 68,900 N/m^2, V_C= 100V, T= 0.0735 N/m, AND OTHER PARAMETERS FOR AIR AT 20°C.

methods were unsatisfactory and generator performance was found to be only slightly better than that predicted for high mobility ions.

Parker and Brusse (Reference 8) investigated a combined liquid nitrogen and steam spray in a wind tunnel flow for flow visualization purposes. They described the resulting condensation as resembling a highly reflective smoke which dissipated downstream of the model. Their description could be interpreted to mean that copious quantities of extremely small droplets were formed. If so, this process could provide a satisfactory method for producing droplets for laboratory experiments.

Two steam spray heads were already in place in the UDRI test facility so that only the apparatus for introducing the liquid nitrogen was required. Stationary nitrogen sprayheads were investigated but were not satisfactory in that uniform mixing could not be achieved in the short, four-foot-long section available ahead of the generator. Upstream of this section was a flow straightner section consisting of a matrix of metal channels made from downspouting that would limit the spread of the liquid nitrogen cloud. These considerations led to a rotating-impeller spray nozzle design, driven by a small 8,000 rpm electric motor as shown in Figure 5. The impeller is described in Reference 9. In operation the impeller produces a dense fog which fully envelops the EFD test generator. To charge the droplets, a corona electrode assembly is used which consists of 11 small diameter wires made from piano wire. The first tests of the liquid nitrogen system impeller produced large fractions of the predicted generator maximum current levels while further refinements and tests provided predicted maximum values.

GENERATOR PERFORMANCE STUDIES

Generator performance investigations have been conducted in a low speed closed circuit wind tunnel which was built specifically for this purpose. The tunnel is fully described in Reference 1. The test section has a square cross section, 3 ft by 3 ft (0.91m), which provides an area four times larger than the generator test array. The original generator geometry is depicted in Figure 6. In this picture the flow

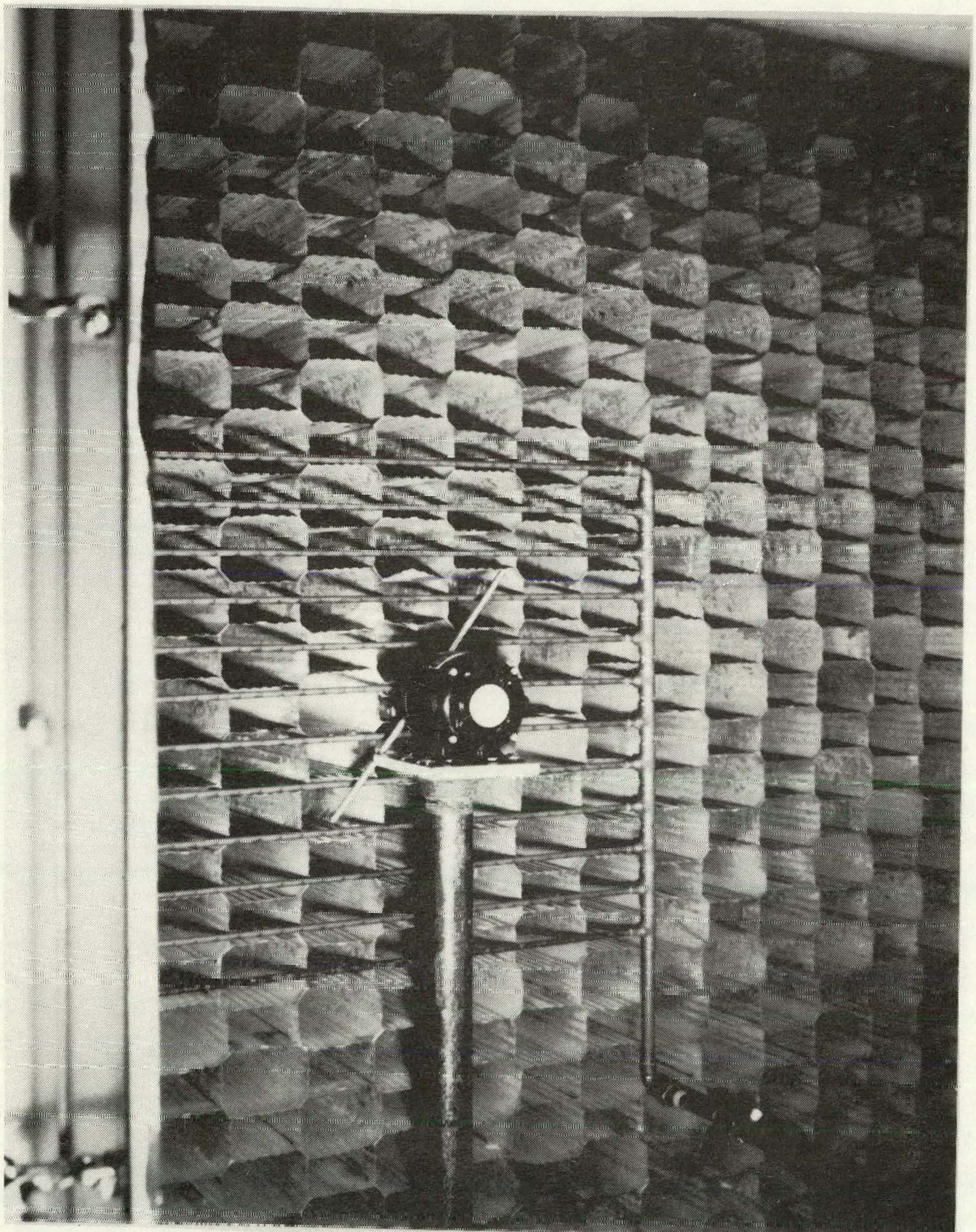

FIGURE 5. LIQUID NITROGEN ROTATING NOZZLE LOCATED UPSTREAM OF TEST GENERATOR.

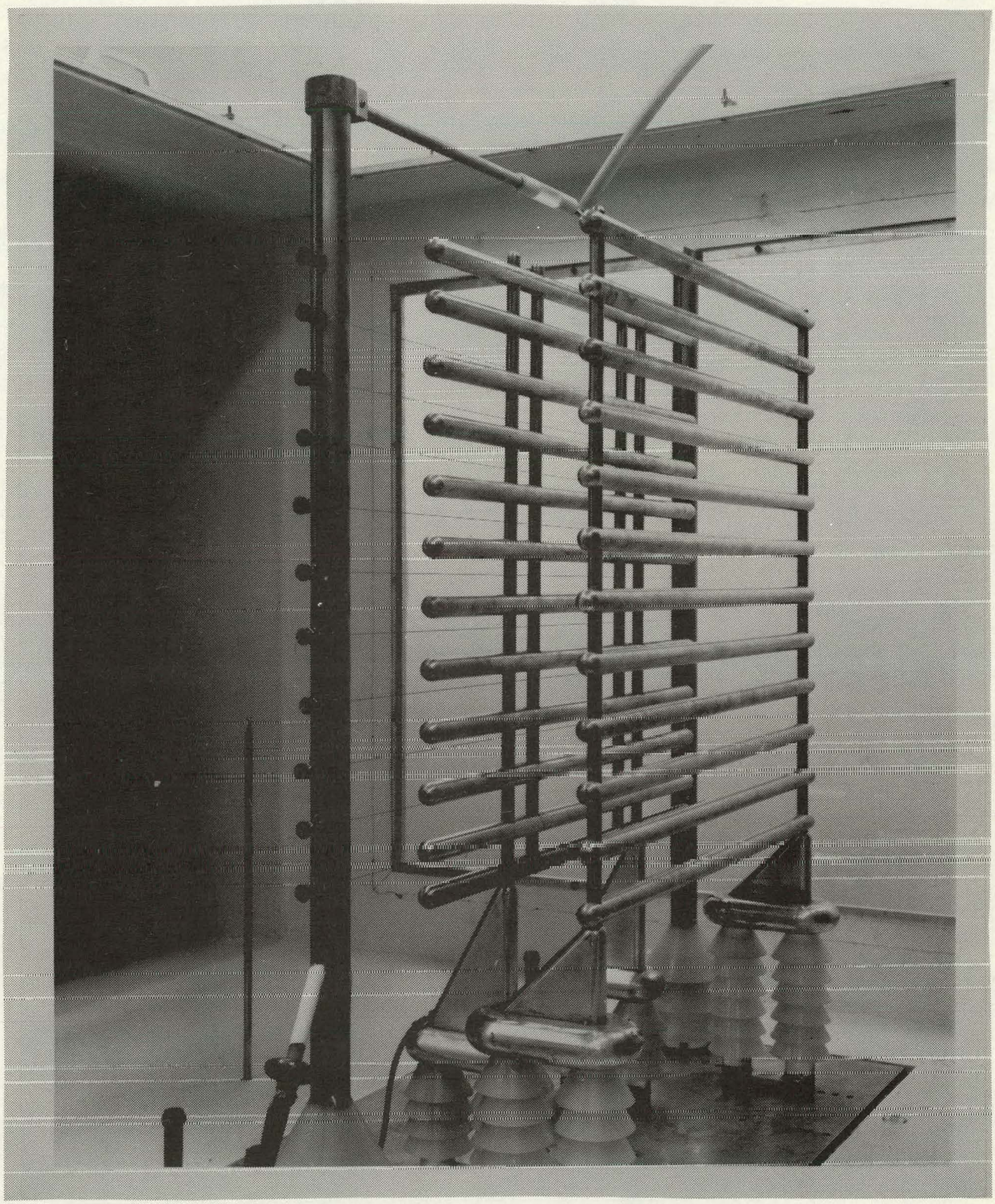

FIGURE 6. TEST RIG WITH ORIGINAL CYLINDRICAL COLLECTOR ELECTRODES.

is from left to right. Ions (normally negative polarity) are seeded into the flow by corona occurring on wires located about 1 inch (2.54 cm) upstream of the attractor. The attractor in this configuration is made up of twelve 5/8-inch (1.6 cm) diameter rods; however, the number of rods can be varied. The space between the two arrays of 5/8-inch rods is the conversion region where work is done by the flow in transporting unipolar charge droplets from near ground potential to a very high potential of the same sign as that of the charge on the droplets. The downstream array of 5/8-inch diameter electrodes is the electrical current collector. At the far left (not shown) there was a steam spray nozzle manifold, which presently is not being used. The electrode arrays, that operate at high potential, are well insulated from ground by shielded plexiglass supports.

Cylindrically shaped electrodes were selected for the first generator geometry because they provide a uniform curvature surface, favorable for electrical fields, and because a large body of experimental investigations and theory exist for determining their drag loss. The present generator design is depicted in Figure 7. The corona wire array and the attractor electrode assembly have remained unchanged while the collector design has evolved to a shielded needle configuration which we term the Faraday cage collector.

In the generator performance tests, maximum current tests were performed first. Such tests entailed high voltage only on the corona wire array: the attractor and collector are at ground potential. Further, there was no load involved in such tests. However, this type of test, supported properly by theory, provides a great deal of information. For the present test generator, we had predicted maximum collector currents of about 500 μA for flow velocities of 11 m/s. The achievement of this level of current did indicate that satisfactorily low mobility charged droplets with sufficient density were being created, and that limiting field strengths were being attained. Further, we felt that we could closely predict the optimum output voltage, about 60 kV, for maximum generator performance. We have achieved what we consider a near optimum operating condition of 68 kV and 240 μA for this geometry. This corresponds to a power of 16.3 watts or a power density of 78 watts per square meter of generator total frontal area. Other test points,which should be considered preliminary values, were run at lower flow velocities. The values of power from these tests are plotted in Figure 8. The absolute level of power compares favorably with that predicted in Reference 2, page 74, for the original geometry where only the collector was different from the present case. Figure 26 of that report has been reprinted as Figure 9, herein.

For an attractor made up of twelve, 5/8-inch (1.59 cm) diameter rods, a 4-inch (10 cm) spacing (conversion section length) and a flow velocity of 20 mph (8.9 m/s) a power of 14 watts was predicted. The present test generator collector is made up of flat plates which may have somewhat lower drag losses than the 5/8-inch rods that they replace. Much higher levels of power are predicted in Figure 9 for smaller spacings which significantly reduce electrode drag losses for cylindrical rod arrays. Actually, the significant parameters which impact drag loss are

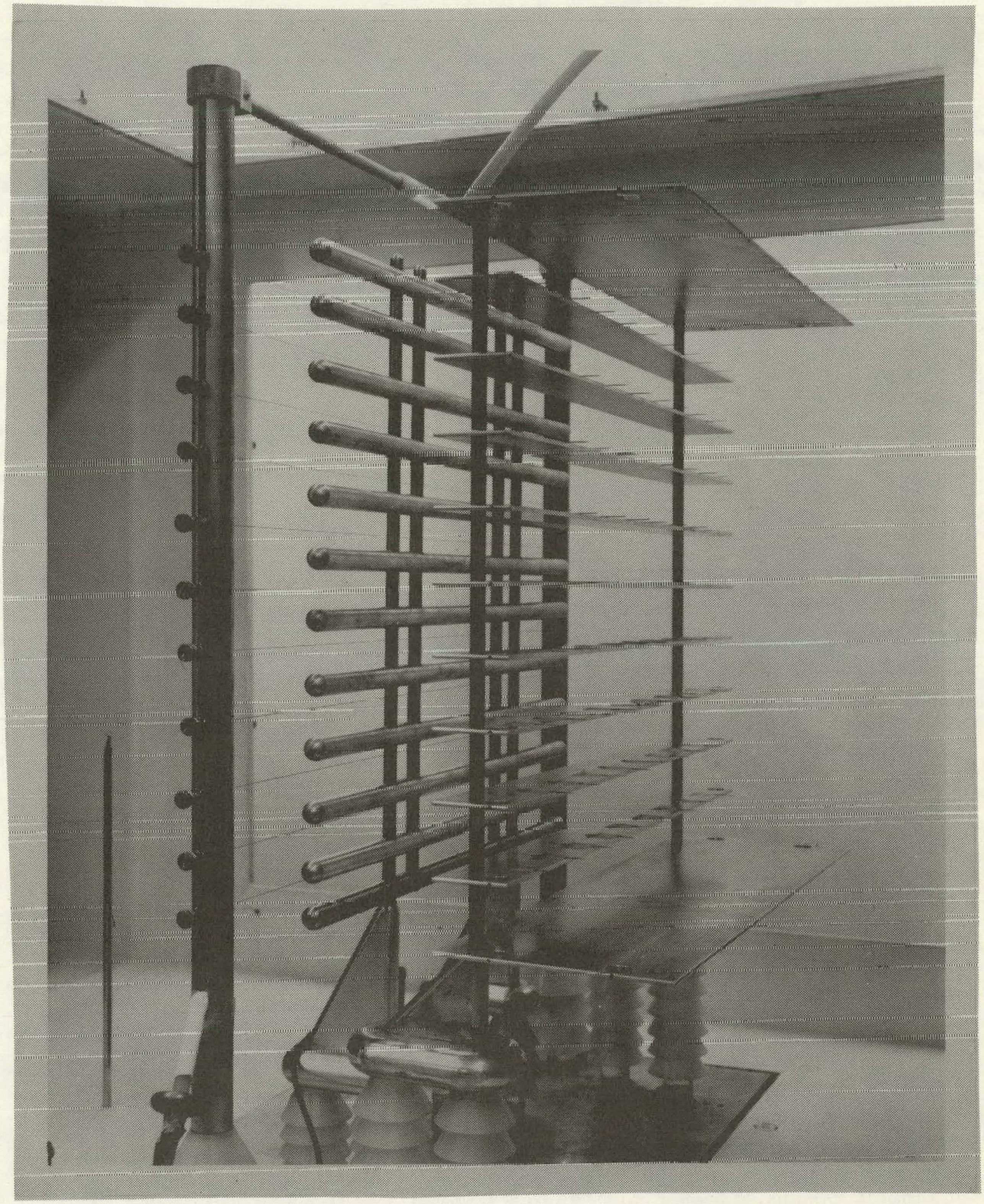

FIGURE 7. TEST GENERATOR WITH IMPROVED FARADAY CAGE COLLECTOR. (THE TWO SIDE PANELS HAVE BEEN REMOVED TO SHOW THE NEEDLES.)

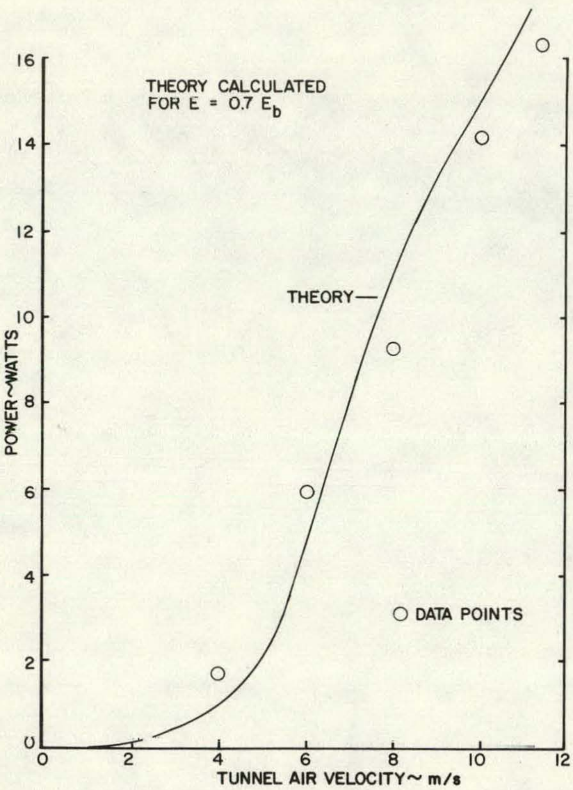

FIGURE 8. TEST GENERATOR DATA COMPARED TO THEORY.

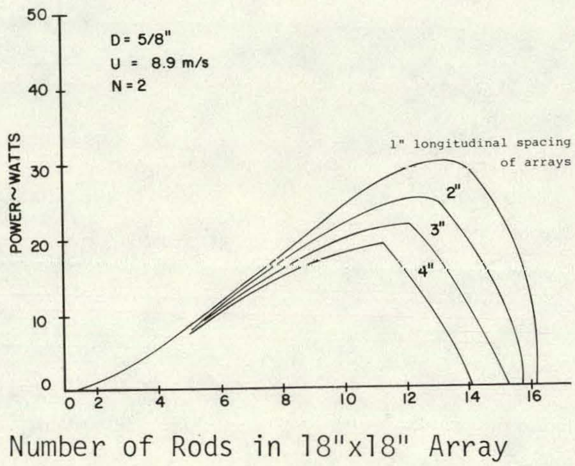

FIGURE 9. THEORETICAL POWER VERSUS NUMBER OF RODS FOR ORIGINAL TEST GENERATOR ELECTRODES.

longitudinal spacing to cylindrical diameter ratio, transverse spacing to diameter ratio, and Reynolds number or diameter of the electrodes. For the same number of attractor rods (12) as in the present geometry, about 29 watts of power is predicted for a 1-inch longitudinal spacing. To achieve the maximum power condition, this reduction of the conversion section length by a factor of 4 would necessitate a charge density increase of 4 and would correspond to a reduced output voltage equal to one-fourth that of the present geometry. It is believed that the present charged droplet production method may be able to provide such a high charge density level. The power density level corresponding to the predicted 29 W would be about 140 W/m^2. It should be noted that the application of large diameter electrodes can provide further lowering of the drag losses without the necessity of such close spacing. This is shown in Figure 3 where the conversion length is 6 inches (15.2 cm) and the diameter of the electrodes is 12 inches (30.4 cm). At a velocity of 10 m/s and a value of a = 2.34, the lateral spacing is 16.1 inches (40.8 cm); the theory predicts about 220 W/m^2 while an ideal wind driven system can produce about 365 W/m^2 (i.e., $(16/27)(\rho_a V^3/2)$). Thus, the EFD wind driven generator, in a full-size version, could produce 61.9 percent of the ideal wind turbine (36.7 percent of the total kinetic power). This efficiency is competitive to the performance of a conventional horizontal axis wind driven generator. Further, we know that a cleaner aerodynamic design can be made using streamlined electrodes in the collector array that would reduce the drag and improve efficiency.

This recent verification of our theory greatly encourages us and we believe that we can develop a system that will produce power in natural wind and have efficiencies close to those of a conventional horizontal axis wind driven system used for producing electrical energy. However, it is believed that the EFD system can be produced at substantially lower cost; and because it does not have moving parts, it should be more reliable and require less maintenance while not being subject to unit power limitations of conventional wind systems.

ACKNOWLEDGMENTS

This work was supported by the Solar Energy Research Institute and the United States Department of Energy, Contract Number EY-76-S-02-4130.

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RESPONSES TO THE MINARDI PRESENTATION

Richard Oman, Grumman Aeospace Corporation: Have you made a life cycle cost estimate for this concept and if so, what are your estimates? The power coefficient that you are quoting is quite interesting and will have an impact on the life cycle costs.

Minardi: It is too early to make any estimates for life cycle costs at this time. By varying the rod spacing the power coefficient will change which will affect the entire system as well as the life cycle cost. Until we get good performance characteristics and the results of some energy economics studies it will be difficult to get the life cycle system cost.

Ernest Rogers, Windworks: In the future, power companies may consider alternative systems. I am concerned about the choice of water as a charge carrier. In this area winter temperatures are about 0°F and in the summer the humidity is low. Can the water droplets function under these conditions?

Minardi: There is no reason why we cannot use any material. However, our calculations have been conducted with water as the best fluid. In most cases water is probably readily available. There appears to be certain disadvantages in using solid particles as these particles would have to be collected.

Edward Uhlig, Tuskegee Institute: Droplets do not remain round, particularly when frozen, which will result in a decrease in the efficiency.

Minardi: The conversion lengths are quite small. The particles may pass through the system, generating electrical energy prior to freezing, in which case the efficiency of the system is unaffected.

Uhlig: Could you give me dimensions of the corona discharge wires and the electrode diameter?

Minardi: The electrodes are 5/8 in. in diameter. We would like to use larger cylinders with wider spacing to reduce drag effects. Piano wire is used to produce a corona.

Gary Johnson, Kansas State University: How many kilograms of water do you use per kilowatt hour of operation?

Minardi: The details are shown on a graph. The mass of the water is quite small when small-sized droplets are used. When larger droplets are used the pumping power becomes large and the efficiency decreases.

Johnson: Mr. Marks showed a single electrode and a ground plane and you show two sets of electrodes.

Minardi: That system can certainly work, but it may be a little less efficient than one with two sets of electrodes. We are attempting to optimize the system.

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WIND/ELECTRIC POWER TRANSDUCTION USING CHARGED AEROSOLS UNDER VARIOUS ATMOSPHERIC CONDITIONS

A. M. Marks
Marks Polarized Corporation
153-16 Tenth Avenue
Whitestone, New York 11357

Experimental data is presented on two methods of producing a charged aerosol under atmospheric conditions. A first charging method utilizes a water jet in an electric field, issuing from a small orifice and impacted by an air jet issuing from another small orifice. A second preferred charging method utilizes a water jet only in an electric field. A charged aerosol was produced in a wind tunnel using the first method and measurements were taken. The electric efficiency was 75 to 97% with atmospheric relative humidities of 25 to 95% and air temperatures of 20 to 40°C, at wind speeds of 2.5 to 15 m/s. These results demonstrate the feasibility of the transduction of wind power to electric power using a charged aerosol.

WIND/ELECTRIC POWER TRANSDUCTION USING CHARGED AEROSOLS UNDER VARIOUS ATMOSPHERIC CONDITIONS

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BACKGROUND

Wind is an inexhaustable source of pollution-free power. Wind power has been used in a small way for thousands of years to propel sailing ships or to operate windmills, which are mechanical devices. The present device is unique in that for the first time a means has been probided for the direct conversion of wind power to electric power without moving parts except charged water droplets.

The Wind/Electric Power Generator is a charged aerosol electrogas-dynamic generator at atmospheric pressure which is powered directly by the wind. It comprises a large area electrode screen of special construction, mounted in a vertical plane to intercept the wind, which emits charged water droplets into the wind stream as a wind/electric power transducer. Wind/electric power generators may be installed at suitable geographical locations (updrafts at mountain ranges, along seashore fronts, etc.) where there is a steady flow of air in one direction in the 5 to 20 m/s velocity range. See Figure 1.

Assuming a wind velocity of 10 m/s, the wind power converted to electric power [1] is 0.45 kW/m^2. For example, a screen 100 meters high and 1,000 meters long or a screen area of 10^5 m^2/km will generate an electric power output of 45 megawatts/km at about 100,000 volts DC. If 10 such screens are spaced 1 km in depth, and extended in length to 100 km, 45,000 megawatts will be produced. These substantial amounts of electric power would be a great contribution to electric power requirements. The wind/electric power generator has relatively low investment and operating costs, and operates without pollution or detrimental environmental effects.

Since 1975 we have been working under U. S. Government sponsorship [1-3] on a research and development program to develop a wind/electric power charged aerosol generator.

A unique wind tunnel, shown in Figure 2, was constructed under a grant [1], and utilized to test charging methods at various atmospheric conditions and wind velocities.

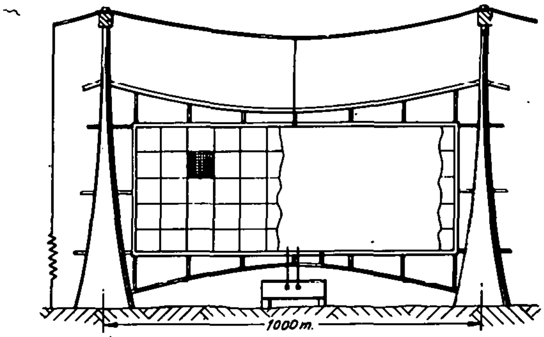
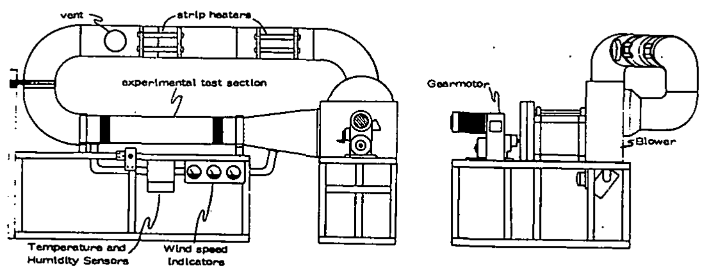


Fig. 1



The Wind Tunnel

Fig. 2

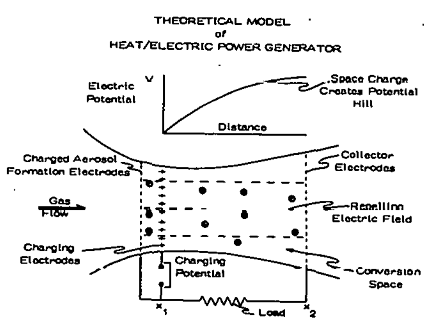


Fig. 3

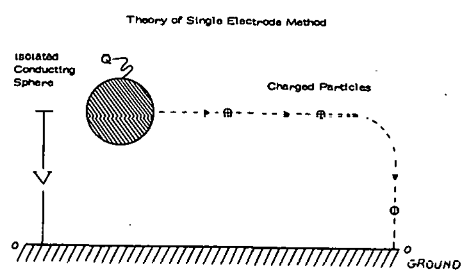


Fig. 4

In previous work, eight methods for the charging of aerosols were identified [1,4], and the critical need for an efficient inexpensive method of charging water droplets to an optimum of about 120 Å per electron charge was determined [5]. Many of these charging methods were investigated theoretically and experimentally [1-3].

The concept of the conversion of wind power to electric power directly through the medium of a charged aerosol was proven feasible [2].

MATHEMATICAL ANALYSIS

A diagram showing a model of a charged aerosol generator is shown in Figure 3, and its theory has been described [6,7].

The electric output power density p_e is given by:

$$p_e = \eta U \qquad W/m^2 \qquad (1)$$

where

$$\eta = \epsilon_o(bk_a)^2/2 = 45.3 \text{ newtons}/m^2 \qquad (2)$$

If air is considered an ideal gas undergoing an isobaric process then it was shown [1.1] that the final state of the air is determined by

$$\Delta T/T = \Delta U/U = \eta/P = 4.54 \times 10^{-4} \qquad (3)$$

The Single Electrode Generator

In Figure 4, there is shown a single isolated emitter source from which charged droplets are removed toward infinity. Work W = qV is done in removing the charges to infinity. The potential V generated at the surface of an isolated sphere of radius r_o is:

$$V = q/4\pi\epsilon_o r_o \qquad (4)$$

Work is supplied by the wind blowing the charged particles away, not from a sphere, but from a charged droplet emitter electrode comprising a single electrode generator, shown in Figure 5. The emitter is powered by a source of input power which may be electrical, water, air, steam, nuclear, solar, etc. The emitter lies within a potential well from which the charged droplets are removed by the wind having a velocity U which does work on the droplets. The charged droplets are eventually dispersed in the atmosphere and discharged to ground somewhere in the distance. The emission of charged droplets from the emitter constitutes an electrical current I at potential difference V from ground and this current returns to the emitter via the load

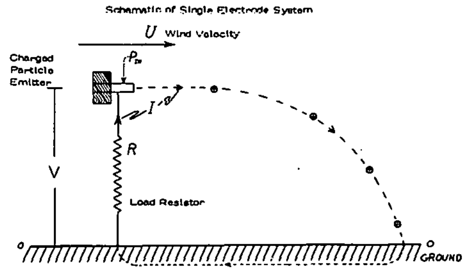


Fig. 5

Linear Array

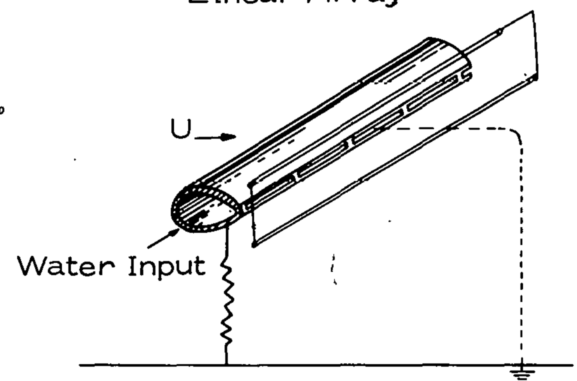


Fig. 6

Square Array

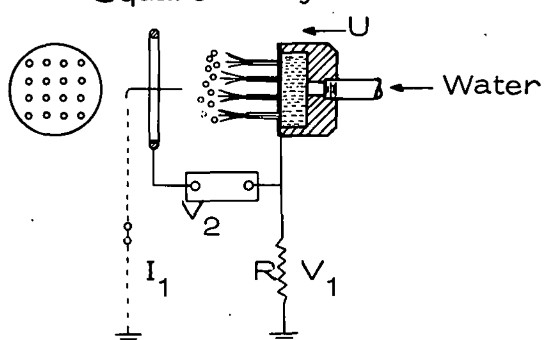


Fig. 7

Method 4.1

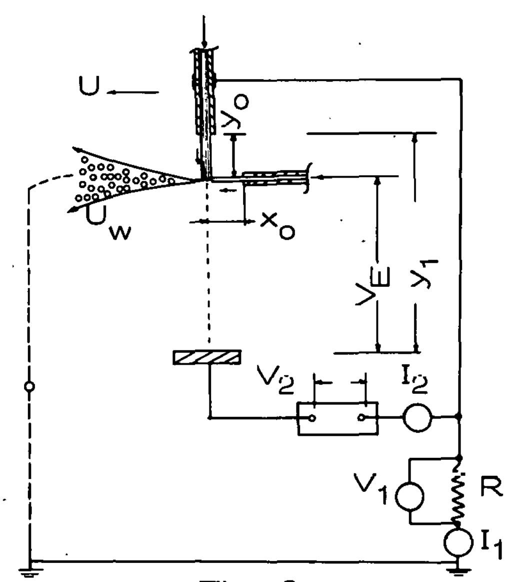


Fig. 8

resistor of resistance R; that is, $V = IR$, and $P_{eo} = IV$.

Hydraulic Relationships

The water velocity U_w is:

$$U_w = Q/A \qquad \text{m/s} \tag{5}$$

Input hydraulic power = jet kinetic power + friction loss power

$$P_h = P_{ri}Q \qquad \text{watts} \tag{6}$$

Jet kinetic power:

$$P_j = (\delta_w/2)\, U^3A = (\delta_w/2)U^2Q = P_{rj}Q \text{ watts} \tag{7}$$

The hydraulic efficiency is:

$$E_{fh} = 100\,(P_j/P_h) \tag{8}$$

In an ideal orifice:

$$1.5P_j = P_h \tag{9}$$

$$E_{fh} \approx 67\% \tag{10}$$

Electrical Relationships

Output Electric Power:

$$P_{eo} = V_1I_1 \tag{11}$$

Input Electric Power

$$P_{ei} = V_2I_2 \tag{12}$$

Electric efficiency % considers only the input electric power P_{ei}:

$$E_{fe} = 100\,[\,1 - (P_{ei}/P_{eo})\,] \tag{13}$$

Overall Efficiency % considers all the input power P_{in}:

$$E_{fo} = 100\,[\,1 - (P_{in}/P_{eo})] \tag{14}$$

Figure of Merit

To evaluate and compare different charging methods, a Figure of

Merit is defined: [1]

$$F_m \equiv 10^6\ I/P_{in} \equiv I\ \mu A/P_{in} \tag{15}$$

Where I is the current in amps, and P_{in} is the input power in watts. The Figure of Merit F_m is independent of the overall wind/electric power generator efficiency. The % efficiency may be expressed in terms of the Figure of Merit F_m and the voltage on the emitter electrode $\bar{V}$:

$$E_{fo} = 100\ [1 - (10^6/\bar{V}\ F_m)] \tag{16}$$

For example, if F_m = 100 μA/watt and $\bar{V}$ = 100,000 volts:

$$E_{fo} = 100\ [1 - (10^6/10^2 \times 10^5)] = 90\% \tag{17}$$

Expressing the Figure of Merit in terms of the input electric power P_{ei} and input hydraulic power P_h:

$$F_m \equiv 10^6\ I/(P_{ei} + P_h) \qquad \mu A/W \tag{18}$$

For an ideal orifice with an orifice coefficient of 0.67:

$$F_m' \equiv 10^6\ I\ (P_{ei} + 1.5\ P_j) \qquad \mu A/W \tag{19}$$

In the single electrode generator shown in Figure 5, all the charged droplet current is utilized:

$$P_{eo} = I\bar{V} \tag{20}$$

System Effectiveness

To visualize system effectiveness, there is defined a ratio R_{oi} of power-out to power-in:

$$R_{oi} \equiv [P_{eo}/(P_{ei} + P_h)] \tag{21}$$

To find the best ratio R_{oi}' obtainable with an ideal orifice, from (9) and (21):

$$R_{oi}' = [P_{eo}/(P_{ei} + 1.5\ P_j)] \tag{22}$$

Charge Density on the Water Droplets

The ratio of current output to water flow rate input is an important practical characteristic of the charging device. It also measures the electric charge per unit volume of the water droplets:

$$\varphi \equiv I/q \qquad \text{Coul}/m^3 \qquad (23)$$

Constraints

To produce an efficient wind/electric charged aerosol generator, these constraints were previously established [3]:

The total water use must be limited to an arbitrary small value such as 10^2 cm^3/sec-m^2; or, 10^{-4} m^3/sec-m^2.

The voltage generated is assumed to be 100,000 volts.

At a wind velocity of 10 m/s the power output for that voltage is 450 W/m^2, and the current is 4,500 $\mu A/m^2$.

The droplet radius r and number of charges per droplet N are such as to provide optimum wind/electric power transduction; that is, low mobility with minimum water flow rate and maximum current. Such an optimum charged aerosol requires droplets preferably with about 120 Å per electron charge; that is, small droplets of about 1000 Å in diameter and about 12 electron charges per droplet [3].

For a power conversion efficiency of 99%, the total input power is limited to less than 1% of the output wind/electric power.

METHODS OF PRODUCING CHARGED AEROSOLS

The methods which appear most likely to achieve the constraints use only water pressure, air pressure and electric charging input.

Single Sources

In the present tests only a single charging device was used to produce a charged aerosol. A single charging source produced a generated voltage of 4 to 16 kV. The current and voltage available from this is limited by space charge, leakage losses, and water jet velocity which is a function of water pressure.

Linear Arrays

A linear array is shown in Figure 6. Assuming the array to be made of 100 1-meter-long pipe elements = 10^4 cm: the array must emit about 0.45 μA/cm of length.

Square Arrays

A square array is shown in Figure 7. The generated current and voltage each increase proportionally to the number of sources n_a and hence the electric power increases as n_a^2. The generated power increases as n_a^2, but the water power input increases only as n_a; hence the efficiency increases with n_a.

EXPERIMENTAL

Charging Method 4.1

In this method, shown in Figure 8, a water jet from a small orifice is directed toward the exciter electrode which is spaced a distance $y_1 = 10$ mm from the end of the capillary tube. An air jet is projected from a small tube in a horizontal direction. The distance between the air orifice and the water jet is $x_o = 2$ mm. A voltage V_E is applied over a distance of 8 mm between the impact point of the water jet and the air jet. A spray of electrically charged droplets expands conically from the impact point. The charge on the droplets is a function of the applied voltage V_E and the water pressure P_r, which regulates the water flow Q of the jet. Typically $V_E = 6$ kV and $P_{ri} = 40$ psi water pressure and air pressure.

Method 4.1 utilizes compressed air power input which presently far exceeds the output electric power. This method was chosen to produce the charged aerosol because this method was best known at the time and the charged aerosol was readily controlled. This method, in its present form, is unsuitable for the efficient production of charging aerosols in a practical wind/electric power generator.

The results of the experiments performed in the wind tunnel using Method 4.1 under various operating conditions are given in Figures 9 and 10. At relative humidities of 25 to 95%, air temperatures of 20 to 40°C, and velocities of from 2.5 to 16 m/s, an electric efficiency of 75 to 97% is obtainable.

Charging Method 5.1

An efficient charging method (5.1) shown in Figure 11 was developed using water pressure only and electric induction charging from an external electrode of water jets issuing from an orifice in a capillary tube. No heat power or air power is needed. Liquid water at ambient temperatures is employed. The electric power input is much smaller than the electric power output. The charged droplets are produced by the instability of the jet issuing into the air stream and by electrical forces.

Method 5.1 was tested experimentally with favorable results, shown in Figures 12 through 16. In the present device, a 2 mm long capil-

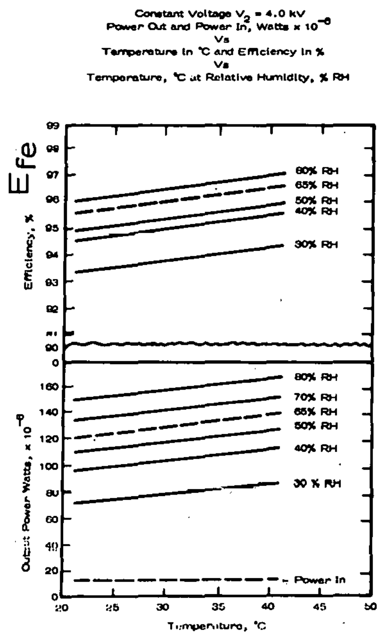


Fig. 9

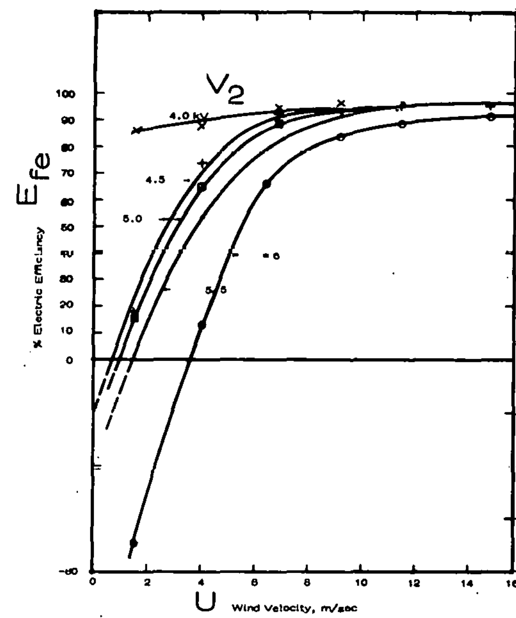


Fig. 10

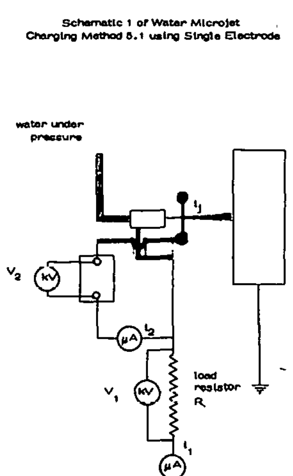


Fig. 11

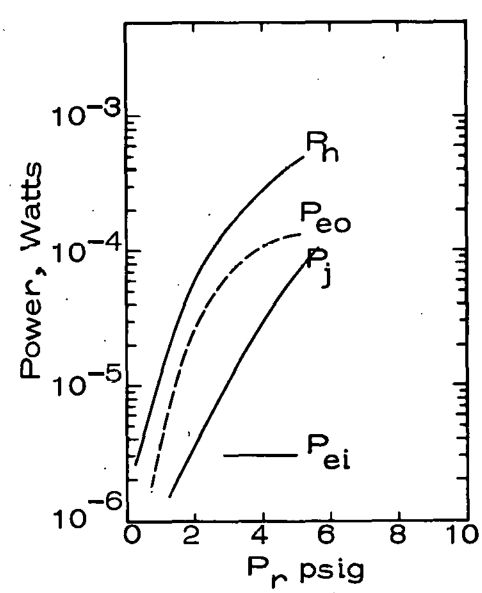


Fig. 12

lary tube 76 μm I.D. was used in which the pressure drop was substantial. A smaller orifice increases the electric disruption force and is expected to produce smaller charged droplets. There is too much water power loss in the capillary tubes. The remaining problems are to substantially decrease hydraulic power input and water consumption. To eliminate most of the water power loss and to produce smaller charged droplets, a circular or slit orifice of 5 to 20 μm in a thin stainless steel sheet (about 12 μm thickness) will be used, resulting in increased hydraulic efficiency, decreased water consumption and the generation of substantial net electrical power.

All tests shown in Figures 12 to 16 were made with charging Method 5.1 shown in Figure 11. The capillary was a stainless steel tube described above. The water pressure P_r is in psia. All power measurements are in watts or mW, plotted versus P_r, the water pressure. The Figure of Merit is expressed in μA/watt.

Figure 12 shows the electrical power output P_{eo}, the electric power input P_{ei}, the hydraulic power input P_h, and the jet kinetic power P_j versus water pressure P_r. The wind velocity U was constant at 9.1 m/s. The voltage V_2 between the exciter electrode and the water jet was constant at 3.1 kV. The exciter was a ring 1 cm I.D. and 1.25 cm O.D., spaced 0.1 cm in front of the orifice. The air was at 25°C and 23% R.H.

Figure 13 shows R_{oi} the ratio of electrical power output to total power input versus water pressure P_r in psi. Curve 1 shows R_{oi} the ratio measured using the capillary tube. Curve 2 shows the same ratio R_{oi}' assuming an orifice in a thin metal sheet.

Figure 14 shows the % hydraulic efficiency E_{fh} versus the water pressure P_r. Curve 1 shows the % hydraulic efficiency E_{fh} measured for the capillary tube, and curve 2 shows the % hydraulic efficiency E_{fh}' for an orifice in a thin sheet.

Figure 15 shows the values of φ in c/m^3, the electric charge per unit volume of a charged droplet, versus the water pressure P_r.

Figure 16 shows the Figure of Merit versus the water pressure P_r:

(1) F_m for a capillary tube and
(2) F_m' for an orifice in a thin sheet.

DISCUSSION

Figure 12 shows the results of measurements of the electric power output P_{eo}, electric power input P_{ei}, hydraulic power input P_h and

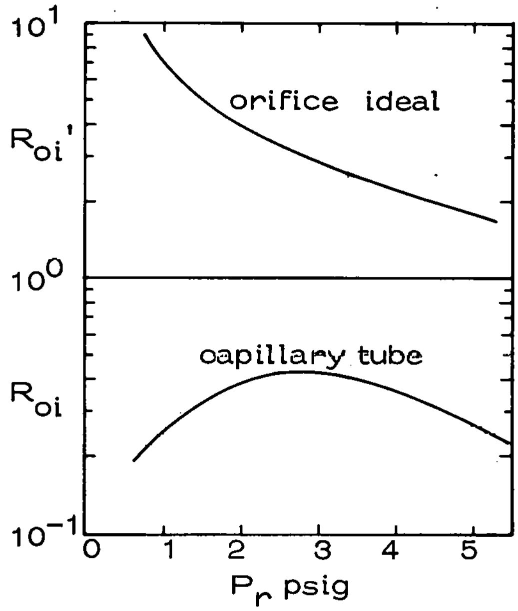


Fig. 13

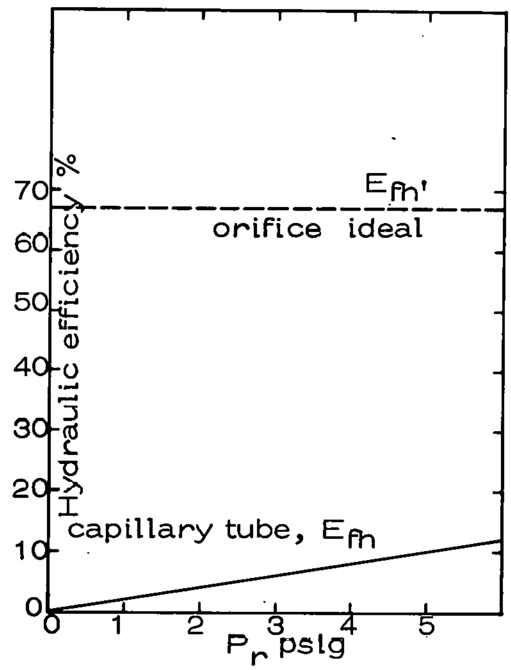


Fig. 14

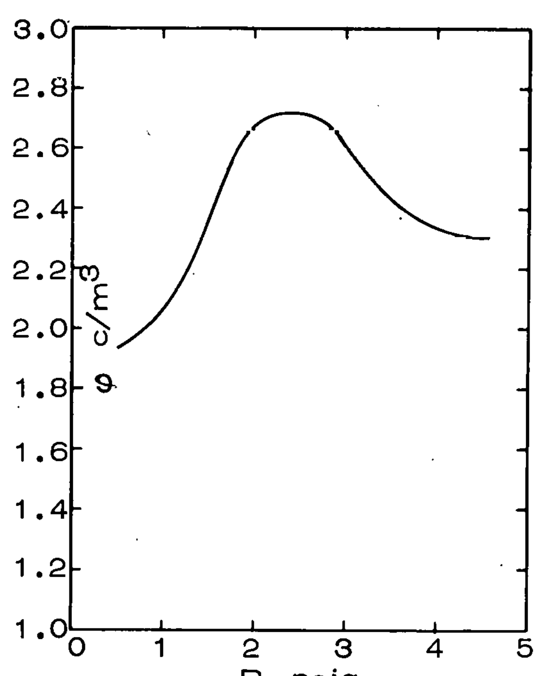


Fig. 15

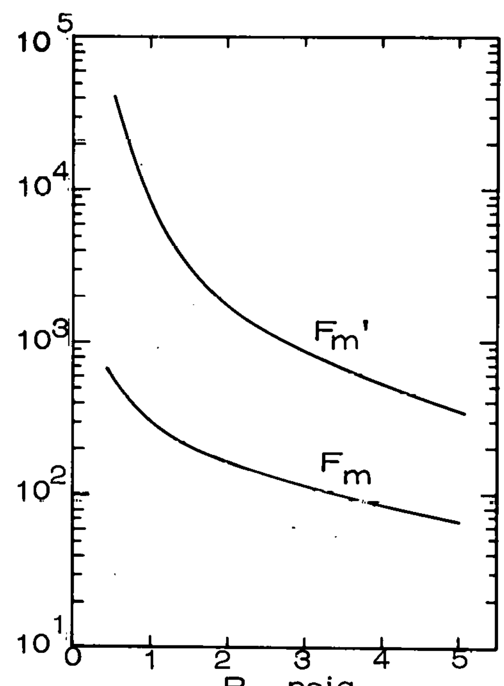


Fig. 16

jet kinetic power P_j. The electric power output exceeds the sum of the jet kinetic power and the electric power input.

In Figure 13, for measurements using a capillary tube, the ratio R_{oi} is less than 1, and there is a net loss of output power compared to input power. Figure 14, however, shows that the % hydraulic efficiency of the capillary tube is small, varying linearly from 0% at 0 psig water pressure, to about 10% at 4.2 psig. Comparatively, an orifice in a thin sheet is used, then R_{oi}', the ratio of output electric power to total input power, varies from about 9 for 0.5 psig to 2 at 4.5 psig, which is a substantial excess of available electric power. These results were at a generated voltage of about 4 kV. As above noted, for a single source $n_a = 1$, the electric output will increase as n_a^2, and these ratios should increase as n_a.

In Figure 15, φ, the ratio of electric current to water flow rate, is a maximum of about 2.8 c/m^3 at a water pressure of 2.5 psig. It is expected that φ will increase substantially with a decrease in orifice diameter.

Figure 16 shows F_m, the Figure of Merit versus P_r, the water pressure. The Figure of Merit varies from 600 μA/watt at 0.5 psig, to about 60 μA/watt at 5 psig. In these tests, the generated voltage varied from about 4.3 kV to about 0.5 kV for a water pressure of 5 psig to 0.5 psig, respectively. A surprising result is that a Figure of Merit, calculated for an orifice in a thin sheet, varies from 40,000 at 0.5 psig to 360 at 5 psig, values which are extremely favorable resulting in substantial net power.

CONCLUSIONS

In a circular or slit orifice in a thin sheet the net generated electric power will greatly exceed the input power, and multiple sources should achieve greater voltage and current output, with decreased water consumption.

Using a multiple source array in which 100,000 volts is generated, the charging device will have an overall efficiency of more than 90%, and will produce a substantial net electrical power output.

With a suitable optimum charged aerosol, the transduction of wind power to electric power occurs efficiently (70 to 97%) at a wide range of ambient temperatures (20 to 40°C) and relative humidities (25 to 97%), at wind velocities of 2.5 to 16 m/s. This shows that a charged aerosol wind/electric power generator can be expected to operate over a wide range of atmospheric conditions.

NOMENCLATURE

A	Area of orifice, or jet	m^2
b	Breakdown strength, air, S.T.P.	V/m
E_{fe}	Electric efficiency	%
E_{fh}	Hydraulic efficiency	%
E_{fo}	Overall efficiency	%
F_m	Figure of Merit $10^6\, I/P_{in}$	μA/watt
I_1	Load Current	amps, μA
I_2	Exciter current	amps, μA
k_a	Charged aerosol breakdown factor ≈ 1	
N	Number of electrons on charged droplet	
n_a	Number of sources	
p_e	Electric output power density	W/m^2
P_{ei}	Input electric power	W
P_{eo}	Output electric power	W
P_h	Input hydraulic power	W
P_{in}	Total input power	W
P_j	Jet kinetic power	W
P_{ri}	Total hydraulic pressure drop	psi
P_{rj}	Hydraulic pressure drop to produce jet only	psi
P_r	Water pressure	psig
q	Electric charge	c
Q	Water flow rate of jet	m^3/s
r_o	Radius of isolated sphere	m
r	Radius of droplet	m, Å
R	Resistance of load	ohms
R_{oi}	Ratio of electric power-out to total power in	
T	Air temperature absolute	°K
U	Wind velocity	m/s
U_w	Water velocity	m/s
V_1	Load voltage	kV
V_2	Emitter exciter potential difference	kV
V_E	Exciter jet potential difference	kV
ϵ_o	Dielectric constant of free space 8.854×10^{-12}	farads/m
η	$\epsilon_o (bk_a)^2/2$	N/m^2
φ	Electric charge per unit volume of droplet	c/m^3
$\bar{\ }$	Maximum of symbol	
Δ	Change	
$'$	Ideal	

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1.1 page 40

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RESPONSES TO THE MARKS PRESENTATION

Gary Johnson, Kansas State University: How much water does it take per kilowatt hour of output and is the water specially prepared?

Marks: Distilled water is used in these experiments. However, there is an indication that the slight conductivity in ordinary water might be better. Our present experiments utilize too much water. However, we are attempting to decrease the water particle size and volume. The droplet size may be reduced to 1.0μ or even 0.1μ, resulting in significant savings in the water used.

Question: In Western Kansas the humidity may be less than 10%. You did not show any data in this range. What happens to the charge if this water comes out and evaporates immediately?

Marks: The water does not evaporate immediately, it takes a finite time to evaporate. Current data goes down to 30% humidity. We really do not know what happend at 10%. The variation due to humidity is not large so you would probably have a useful generator even at 10% humidity.

Edward Uhlig, Tuskegee Institute: You are using a method similar to that used by Portenier in 1937, when he used solid particles and not water droplets. He used a corona charging system.

Marks: The corona charging method is very inefficient.

Uhlig: Is it not true that the water droplets have negative polarity, the same polarity as in atmospheric rain and in clouds?

Marks: The charge may be either positive or negative.

Uhlig: The field breakdown voltage depends on the charge polarity.

Marks: We are not attempting to charge water droplets to the maximum. We must limit the amount of charge on a droplet to have an efficient system.

Uhlig: Can you tell us something about the relative slip between the charge particles and the speed of the air?

Marks: Normally, we would like to have a few percent difference in velocity. We believe that the slip may only be about 10%.

Ron Toyne, Kirkwood Community College: Do you see any losses in converting from DC current to useful AC current?

Marks: That is not my field. There are high voltage DC lines available, 700,000 V, in Canada and in Europe. Apparently successful conversion from DC to AC can be done.

OPEN DISCUSSION 1

J. Ramstetter, Solar & Wind Energy Systems: I have designed and installed wind and solar energy equipment. How many years will it be before these types of systems are on the market?

John Minardi, University of Dayton: I am not a prophet, but within 1 to 2 years we hope to have a system that will produce power in the wind. A development effort normally takes about 5 years so it will probably be about 7 years before our innovative system is marketed.

Richard Oman, Grumman Aerospace Corp: A question for Mr. Whitford. Do you have a problem associated with the momentum stored in the tower?

Dale Whitford, University of Dayton Research Institute: We have not carried out the dynamic analysis as it relates to the tower.

Gerald Leigh, University of New Mexico: We have discussed land use several times during this session. Land can be used for other purposes; for instance, agriculture. There is a finite possibility that the farmer on a tractor might be in the vicinity of a blade when it is thrown. However, this possibility is small. Power lines go over farms but the land is still used even though there is a finite possibility that some harm could occur because of the power lines. The vertical axis machine has a blade pinned at two points and the probability of throwing a blade is even more remote. Land costs may, therefore, not be as important as indicated.

Whitford: In general, for normal turbine farm, the land will be cut up because of access roadways. Fencing may be employed in the immediate vicinity of the machine to protect animals. As wind is a diffused source of energy, large areas must be considered to produce significant energy levels.

Leigh: It is my understanding that an energy system utilizing solar panels developing 1,000 MW will take between 19,000 and 25,000 acres. This land could only be used for mushroom farming underneath the collectors.

Lawrence Rowley, Canadair Ltd: What are the relative merits of the single stream tube and multiple stream tube methods?

Paul Klimas, Sandia Laboratories: The multiple stream tube method allows you to address local phenomenon more accurately than the single stream tube method. Local conditions can be identified by local Reynolds numbers, resulting in higher accuracy.

John Kelly, Fort Carson Utilities: Apparently you are not too concerned with using water in the EFD systems. Do you foresee any problems in having a closed system to operate at low temperatures using glycol?

Minardi: We have not studied such a situation.

Kelly: In the West we are very concerned with water and its use.

Minardi: The water used is quite small, particularly when the droplet size is one micron.

Rogers: When you operate near the space charge limit the field at the collector grid is near zero. In that case can you use chicken wire for the electrode?

Minardi: Chicken wire can be used at the collector, not at the entrance electrode, as high forces exist at the entrance electrode. We are considering other shapes; however, the current one can be readily analyzed.

Edward Uhlig, Tuskegee Institute: You mentioned that the wire system could be replaced by chicken wire. There is a distinctive difference in the electric breakdown field intensity between these two cases. In the first case, where you have parallel wires, you create ultracorona discharge whereas in the case of the use of chicken wire where the peripheral field intensity is not uniform around the circumference of the wire, you create ordinary corona, and the breakdown is then initiated by a streamer discharge mechanism.

Minardi: I agree that alternatives exist in developing the system. However, they probably are not too different from the methods we suggest.

Session III

TECHNICAL DEVELOPMENT OF THE DIFFUSER AUGMENTED WIND TURBINE (DAWT) CONCEPT

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ABSTRACT

An attractive advanced wind energy concept is the Diffuser Augmented Wind Turbine (DAWT). This approach effectively increases the concentration of naturally diffuse wind energy by inducing greatly augmented mass flow rate through the wind turbine than in conventional arrangements. The technical challenge has been to develop very compact diffusers that will minimize the equipment cost and complication accompanying the power augmentation capability.

As a result of a three-year, multi-phased investigation, using three test facilities and a multi-bladed turbine as well as simulated turbines (i.e., screens), several compact diffuser designs have been developed that appear technically and economically attractive. These model tests already demonstrate a relative power coefficient (augmentation) that is over 350% better than an ideal conventional turbine of the same diameter and at the same free wind speed. These test results also point the direction to further DAWT system refinements expected to yield augmentation factors of 6 to 8 times conventional turbines. In addition, because DAWT's inherently have better plant capacity factors compared to conventional bare turbines, the busbar cost of generated electricity potentially can be brought to cost-competitive levels.

INTRODUCTION

For several years the Department of Energy and its predecessors have been sponsoring the DAWT concept as one of the possible innovative approaches to improve the economics of wind energy production. The objective of this approach has been to increase the power generating capabilities of a conventional wind turbine by increasing the mass flow through the rotor beyond bare turbine limitations. Simultaneously, the added capital cost of equipment to foster augmented mass flow must be minimized to reduce the specific cost of generated power lower than conventional devices.

Prior investigators of diffuser augmentation [1-3] have been discouraged from active pursuit of the idea because of the employment of efficient diffusers following conventional tradition. These traditionalists required long, small included angle diffuser designs that obviously would be quite costly.

Our departure with tradition was to recognize from the onset that economics dictated the application of very short and compact diffusers. Therefore we set out to explore and develop innovative methods to produce efficient, short length, high expansion ratio diffusers.

This paper is an in-perspective discussion of what has been technically accomplished so far and what the future needs and prospects appear to be for the DAWT concept. The work has progressed through theoretical and experimental phases; some of the latter will be summarized here. Despite the fact that the major thrust has been to create improved diffusers, preliminary consideration of DAWT operational factors and economic evaluations have been carried out and are touched upon here to provide a more overall insight into the program.

DIFFUSER AUGMENTATION THEORY

The total power in the freely flowing natural wind, for a given area, A_2, perpendicular to the wind vector, V_o, is

$$\mathbb{P}_w = A_2 V_o (p_o + \tfrac{1}{2}\rho V_o^2) \tag{1}$$

For the conventional bare wind turbine there is a theoretical limit [1] on how much of the natural wind power can be extracted. Only a maximum of 59.3% of the wind kinetic energy can be converted

$$\mathbb{P}_{T_{MAX}} = 0.593\ A_2 V_o (\tfrac{1}{2}\rho V_o^2) \tag{2}$$

and at this optimum the cross-section of the free wind which flows through the rotor is smaller than the turbo machinery area, A_2, by one-third.

In the case of the DAWT, for a turbine of the same area, A_2, and free wind speed, V_o, part of the total power of the natural wind is convertible because the pressure recovery of the diffuser duct makes it possible to sustain a greatly reduced subatmospheric pressure level downstream of the rotor. Consequently, the air speed of the DAWT rotor is greater than the free wind speed by a ratio, ε, which is related to the conversion of static pressure to dynamic pressure. Thus, the power into the DAWT rotor is

$$\mathbb{P}_D = \varepsilon A_2 V_o (p_2 + \varepsilon^2 \tfrac{\rho}{2} V_o^2) \tag{3}$$

and the extracted power is

$$\mathbb{P}_e = C_T A_2 V_2 q_2 \tag{4}$$

where: $$C_T = \frac{P_{23}}{\frac{\rho}{2} V_2^2} \tag{5}$$

is the rotor disk loading.

From a one-dimensional theory [4,5] the ideal power coefficient,

$$C_{P_i} = \frac{C_T q_2 V_2}{q_o} = \varepsilon^3 C_T V_o \tag{6}$$

The power coefficient also can be expressed [4] in performance and geometric parameters of the diffuser from an energy balance, as

$$C_{P_i} = [1-K_i-C_{p_4}]\varepsilon + [\eta_D(1-\lambda^2)-1]\varepsilon^3 \tag{7}$$

which shows that the available DAWT power is strongly increased by large area ratios $(1/\lambda)$, high diffuser efficiencies, η_D, highly negative base pressure coefficients, C_{p_4}, and the axial velocity speed-up ratio, ε, into the rotor.

It is now possible to define an augmentation ratio

$$r = C_{P_i}/.593 = \frac{C_T}{.593} \left(\frac{q_2}{q_o}\right)^{3/2} \tag{8}$$

which is the relative power coefficient of the DAWT to the ideal best bare turbine, for the same rotor flow areas and free wind speeds.

Defining a diffuser power recovery coefficient

$$C_{P_R} = \eta_D \, [1-(A_2/A_4)^2] \tag{9}$$

where A_2 also equals the diffuser entrance cross sectional area. Combining the inlet duct losses $K_i q_o$ into an overall C_{P_R}, and with the experimental evidence [3,5] that C_{p_4} is uncoupled from C_T, the maximum DAWT augmentation ratio is

$$r_{MAX} = \frac{9}{8}(1-C_{p_4}) \left[\frac{1-C_{p_4}}{3(1-C_{P_R})}\right]^{1/2} \tag{10}$$

at an optimum rotor load of

$$C_{T_{OPT}} = 2(1-C_{P_R}) \tag{11}$$

and an optimum velocity speed up ratio

$$\varepsilon_{OPT} = \left[\frac{1-C_{p_4}}{3(1-C_{P_R})}\right]^{1/2} > 1 \tag{12}$$

The values of C_{p_4} and η_D or ε must be determined from experiments, so that the presented performance theory is semi-empirical for a given diffuser geometry. It should also be evident that DAWT operation may be stable and yield significant augmentation at conditions of rotor loading other than optimum.

Because of the ε speed-up factor in DAWT turbine approach velocity, the cross sectional area of the free wind that is processed by the DAWT is much greater than the turbine cross sectional area. For the same turbine area and wind speed, the DAWT captures $3\varepsilon/2$ greater free wind than the optimum bare turbines; this fact illustrates the way the DAWT improves on the normally diffuse concentration of wind energy.

DIFFUSER DESIGN REQUIREMENTS

With the guidance offered by the one-dimensional theory it is clear that high diffuser area ratios, A_4/A_2, are desirable for the DAWT. In order to obtain the equally desirable short axial lengths, however, with the large area ratios, geometry dictates large included angles. It is well known that normal axial air flow in ducts, with included angles above about 20 degrees, tends to separate in adverse pressure fields, such as presented by DAWT operations. Therefore, a limited technical objective early in the program was to demonstrate methods of preventing separated flow for area ratios between 2 and 4, and included angles between 40 and 90 degrees. These geometric constraints were further narrowed to result in overall axial lengths less than the diffuser inlet diameter. It was further to be demonstrated that the separation suppression techniques would be compatible with highly subatmospheric (negative) pressure at the diffuser exit plane, and that a high diffuser efficiency could be obtained.

From the structural viewpoint the need to minimize capital equipment cost places strong emphasis on the shortest length, minimum surface area diffuser design, so that some compromise in excellance of aerodynamic performance is tolerable if the economic trade-off appears attractive.

There is still another aspect to the structural design of the diffuser that is quite different from the purely fluid mechanical challenges previously noted. This aspect interacts wtih the issues affecting commercialization of the DAWT, sometimes referred to as cost effectiveness. In a sense this is still another type of major challenge to the DAWT; it involves the ingenuity of the design engineer in fashioning equipment that can withstand long term (i.e., approaching 30 years) natural environment at many different installation sites; be manufactured, assembled, and installed for the lowest possible cost; and be supplied in the sizes or power ratings, and in the quantities, required by an as yet undeveloped and not totally defined market. The latter aspect makes it hard to justify investment to proceed with detailed engineering design. However, without sufficient depth of design and investigation of design alternatives, the economic data base to assure the cost-competitiveness of the DAWT concept cannot be obtained.

DIFFUSER DEVELOPMENT

The experimental work on diffuser development proceeded in four phases and involved three wind tunnel test facilities. The exploratory initial stage employed a 30 cm (11.5 in) diameter open jet and 4.5 cm (1.8 in) diameter inlet models of various diffuser configurations. Based on the exit diameter of the models the test Re was about 70,000. Screens of several different solidities were used to simulate turbine disk loadings because constructing a family of small size of wind turbines was considered impractical for exploratory investigations. From over 150 different diffuser models, some being straight walled employing slot flow to suppress core flow separation and some being flapped ring wings, a baseline design was frozen for the next testing phase. Within the limitations of the state of our knowledge gained from the screen-equipped small models, a baseline geometry appeared to offer the best performance. This design features an area ratio of 2.78, an included angle of 60 degrees, a length to diameter ratio of 0.5, and a two-staged wall slot flow arrangement. Measured exit plane pressure coefficients, C_{p_4}, to about -0.56 demonstrated that significant subatmospheric pressures could be attained and dispelled initial concern about the magnitude of that important factor.

The next phase involved using a 2.1m x 3m (7 x 10 ft) wind tunnel and geometrically similar diffuser models ten times larger than previously examined. The objective was to determine the performance trend at higher Re approaching one million. To minimize technical risk and cost, only the baseline geometry was closely duplicated in the new test model and screens again were used to simulate a turbine. Three variants of the baseline diffuser design also were constructed to guide the program regarding flow separation suppression by sequential wall jets. In this phase, the highly subatmospheric exit plane pressure was again demonstrated and indicated marked improvement, to a C_{p_4} coefficient value of -0.83, with Reynolds Number.

Reinforced by the evidence to this point, it seemed appropriate to investigate the interaction of turbine flow fields with the diffuser characteristics. Again, to minimize technical risk and cost, the test turbine was designed to operate with the baseline diffuser model previously used, and within a rather narrow range of disk loading and velocity speed-up ratio, near the best values obtained with the screens. Test turbine design also was influenced by the wind tunnel stable operating characteristics which established a low flow velocity limit at about 24.4 m/s (80 ft/s); this imposed a narrowed operational capability for the turbine. However, actual wind tunnel operation of the diffuser model equipped with this turbine showed that the DAWT yields much better performance than when equipped with screens. (Further details of these data will be given later in this paper.)

The fourth test phase has been concerned with investigating diffuser design improvements to enhance the C_{p_4} effect and augmentation and to reduce the length to diameter ratio for the same 2.78 area ratio of prior phases. This testing has involved a 1.2 x 1.8 m (4 x 6 ft) wind tunnel and 15 cm (6 in) inlet diameter models equipped with screens; the test Re is about 130,000. Some dramatic improvements in relative performance compared to the baseline diffuser have been obtained, particularly with a design we denote as a dump diffuser (DD). For the same area ratio, but 20% shorter diffuser, the DD design yields 16% greater augmentation than the baseline.

Although these last tests should be confirmed with larger diffuser models and with a compatible turbine, our prior test experience forecasts that the improvement in relative performance should result in about 30% higher augmentation than measured for the baseline model equipped with a 45 cm (18 in) diameter turbine.

Finally, in the foreseeable future, a DAWT field test demonstration appears desirable.

TEST RESULTS AND PROJECTIONS

If one examines the chronological advances in measured DAWT peak performance since this advanced concept project was initiated in mid-1975, it is evident (Figure 1) that major jumps in improvement have accompanied the emergence from infancy; in two years the maximum augmentation ratio achieved has almost doubled. It seems particularly appropriate to examine how these results shape up against our earliest theoretical predictions and hopes before reality was faced.

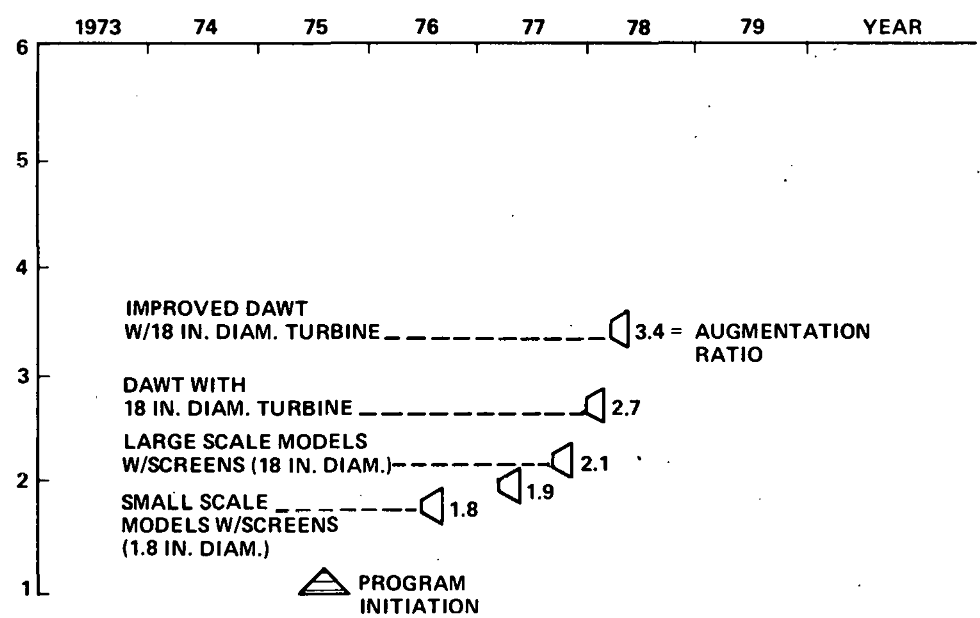

FIGURE 1 OVERVIEW OF PROGRESS - DAWT DEVELOPMENT TESTING

Figure 2 shows typically what the use of equation (7) predicts in the nature of augmentation ratio variation with disk loading (based on local dynamic pressure). The locus of optimum performance for a given C_{p_4} value as given by equations (10) and (11) is seen to move to higher levels of augmentation ratio and smaller values of disk loading as the diffuser efficiency increases toward 100%. It is also evident that off-optimum disk loading produces only moderate decreases in augmentation over a relatively large extent, compared to the larger effects of diffuser efficiency and base pressure. Figure 3 presents the effect on augmentation ratio of four levels of C_{p_4} within the range of observed or considered achievable C_{p_4} values. The augmentation ratio gains attendant to small improvement in C_{p_4} effect become accelerated as diffuser efficiency increases. Superimposed on Figures 2 and 3 are representative data points from our wind tunnel test program, for turbine and screen equipped diffusers.

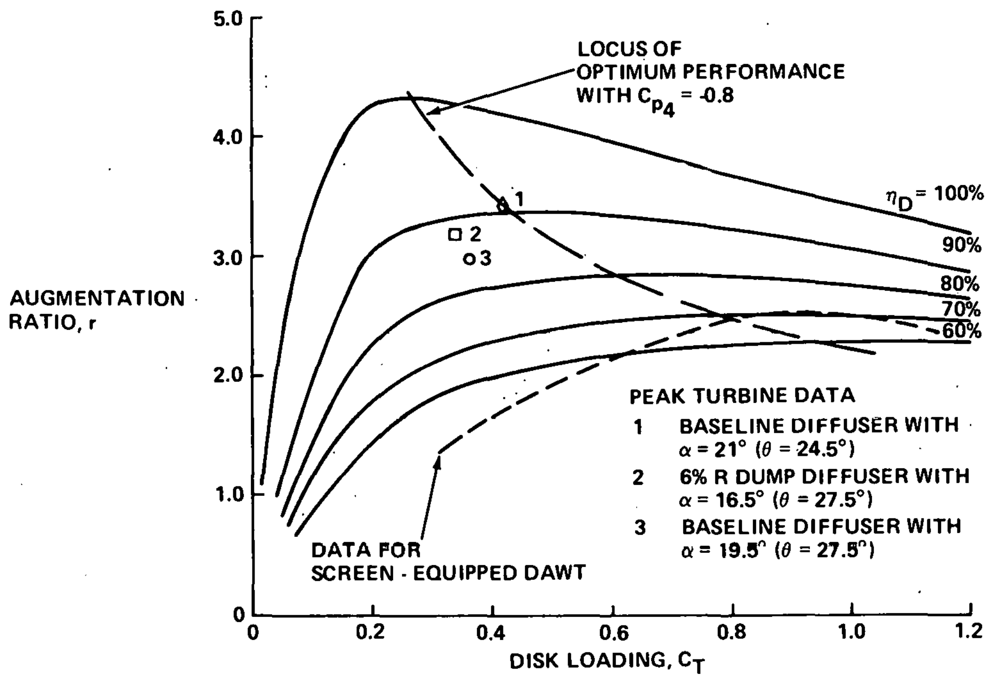

FIGURE 2 COMPARISON OF DAWT MODELS TEST DATA WITH THEORETICAL PERFORMANCE FOR A_4/A_2 = 2.78 and C_{p_4} = -0.8

Although the base pressure data obtained in these tests were not exactly at the C_{p_4} value of the theoretical calculations, they are sufficiently close so as to be useful for analysis. For example, from Figure 2,

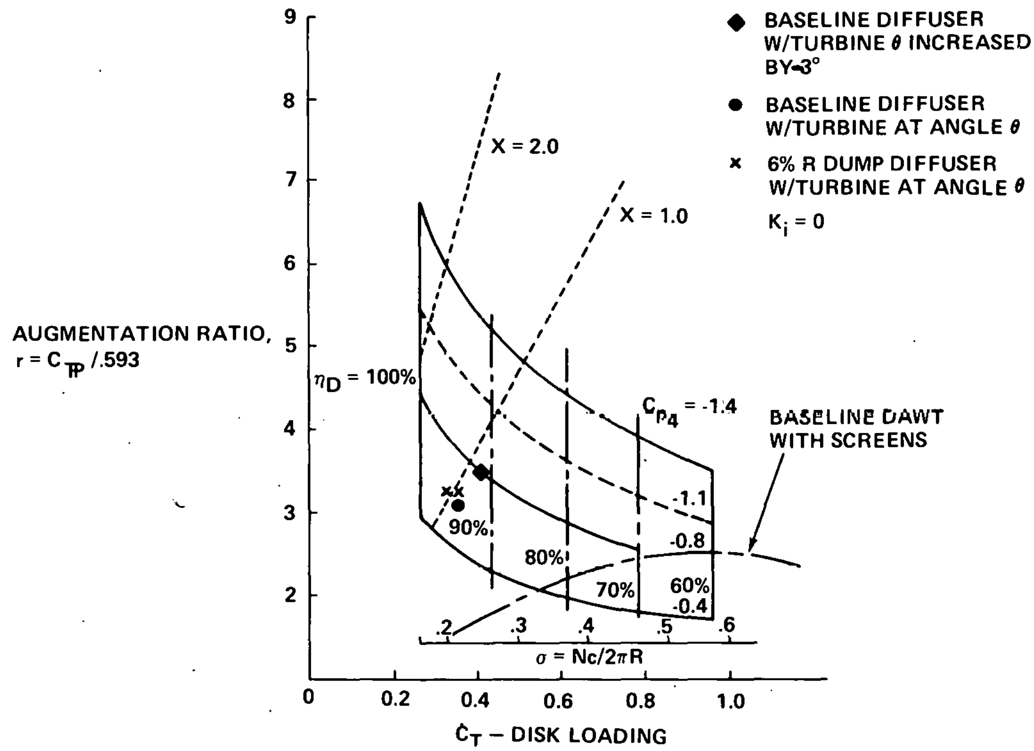

FIGURE 3 COMPARISON OF DAWT THEORETICALLY OPTIMUM PERFORMANCE WITH MODEL TEST DATA, A_4/A_2 = 2.78

the major improvement in augmentation ratio when turbines were employed compared to screen-equipped models appears to be more the result of higher diffuser efficiency levels attained with the turbines than any other single factor. One explanation advanced for this is that the whirl of the turbine wake creates an energizing action at the diffuser walls that prevents boundary layer slowdown and aids the axially injected slot flow. However, detailed measurements are very difficult in the three-dimensional flow field downstream of the turbine so better diagnostics is needed to understand fully the detailed mechanism. The trend of the screen data performance variation with disk loading can be explained as characteristic of a nearly constant 70% diffuser efficiency, and not driven principally by disk loading, as might be concluded just from the test data.

Superimposed on the map of optimum diffuser performance, in Figure 3, are lines of turbine performance for two tip speed ratios, x. The test turbines operated at values of x of approximately 1.0, as shown by data points of best performance. Two observations may be made about the data. First, the higher power coefficient of an early form of the dump diffuser design arises from better C_{p_4} effect (-1.0) than for the baseline diffuser (C_{p_4} ≈ -0.8), using the same turbine at close but not identical operating conditions. The second point is that operating the turbine at a better aerodynamic conditions (e.g., higher tip speed ratios, x) can produce better DAWT system performance by virtue of producing better diffuser efficiency and base pressure (C_{p_4} effect) conditions. Higher tip speed ratios are encountered for larger sized rotor diameters, or lower wind speeds than were possible in the available test facilities and out test models.

Thus, even for the same diffuser geometries already tested, augmentation ratio values in the vicinity of five appear achievable. However, as previously described, the early selection of a 2.78 diffuser area ratio and 60 degree included angle, was predicated on small models with screens, which we now understand wholly underestimate the potential performance of the large scale DAWT equipped with a turbine. If the prospects of larger diffuser area ratios and included angles are examined, as presented by Figure 4 for an area ratio of 4, we begin to understand the kind of results likely with field demonstration and operational DAWT units. In contrast to the region of test experience, for $A_4/A_2 = 2.78$, centered around an augmentation ratio of 3.0, the performance area shown by the shaded portion of Figure 4 now may be contemplated. Thus, an augmentation ratio between 6 and 8 seems well within the realm of possibility if better matched and more efficient turbines are employed than has been used so far.

The redesign for higher area ratio diffusers need not result in longer ducts because the included angle can be increased to the 80 to 90 degree range from the current 60 degree pattern. Based on our experience with turbine wake flow effects, we are optimistic that the core flow can be made to flow unseparated in a higher angled diffuser. Theory, based on the method of singularities [6], indicates that about twice as low (i.e., more subatmospheric) base pressures (C_{p_4}) are possible in, for example, 80 degree included angle diffusers than 60 degree diffusers for the same disk loading. Figure 5 which presents the radial distribution of C_{p_4} at the exit plane, shows that the theory is reasonably confirmed by typical DAWT model test data for 60 degree included angles. Theoretical calculations for an 80 degree included angle and a C_{T_o} of 0.8, not shown here, essentially coincide with the zero disk loading curve for the 60 degree included angle. On this basis, an overall effective C_{p_4} of -1.4 is a reasonable expectation, and may prove to be a conservative prediction; throughout the DAWT program our consistently conservative position has forced us to uprate our expectations as the test results became evident.

ECONOMIC CONSIDERATIONS

No treatment of DAWT development would be complete without at least some discussion of the factors affecting economic evaluation. A widely used economic criterion for non-storage type applications of wind energy devices is the busbar cost equation [7]

$$c_b = \frac{C_c \times F}{C_F \times 8.76} + M, \text{ mills/kw-hr} \qquad (13)$$

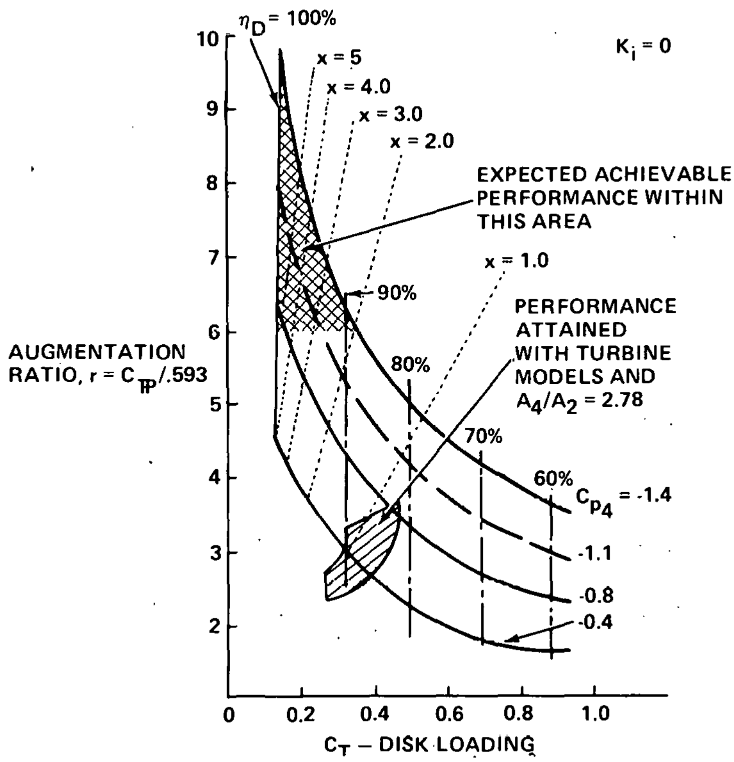

FIGURE 4 COMPARISON OF DAWT THEORETICALLY OPTIMUM PERFORMANCE WITH MODEL TEST DATA, A_4/A_2 = 4.0

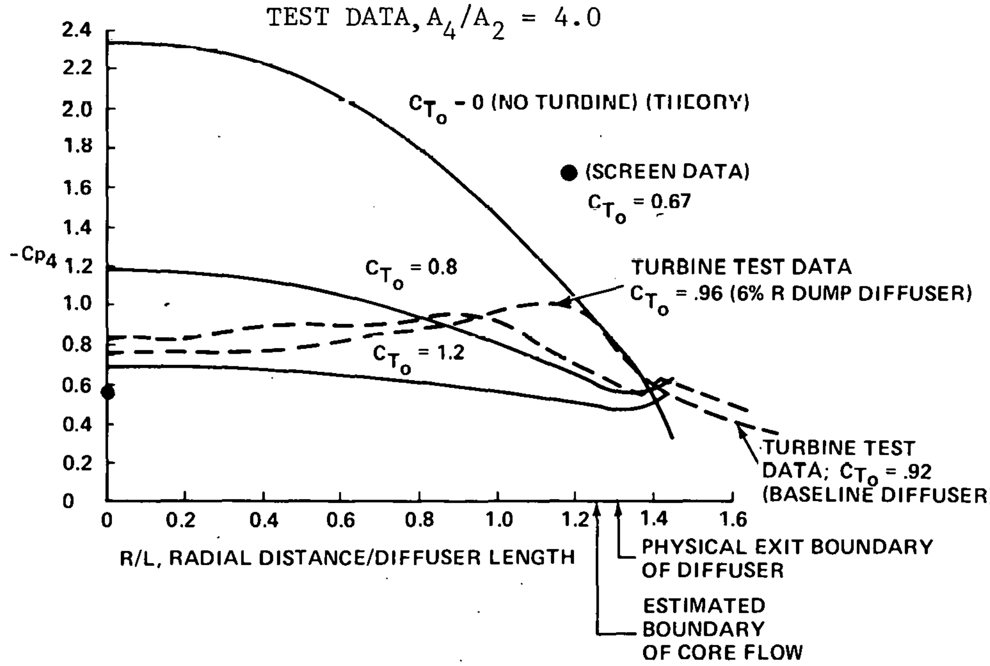

FIGURE 5 PRESSURE COEFFICIENT PROFILE IN EXIT PLANE OF DIFFUSER

where F and M are not dependent on the wind energy conversion system.

Plant capacity factor C_F, is the actual annual power output of the energy conversion system relative to its annual output at rated power. The suggested DoE [8] wind speed duration equation

$$H = 8766 \quad e^{\left[-0.7738\left(\frac{V}{12}\right)^{2.27}\right]} \quad , \text{ hrs} \qquad (14)$$

has been used in computing some typical capacity factors for DAWT and commercial conventional wind turbine design applications at different rating wind speeds. The results shown in the Table indicate that the DAWT applications are 30 to 60 percent better than the conventional horizontal axis machine in the 15 to 150 kW power rating range.

TABLE -COMPARATIVE POWER GENERATION AND CAPACITY FACTORS FOR DAWT AND CONVENTIONAL WIND TURBINES

System	Power Rating kW at mph		Avg. Capacity Factor, % (95% Avail'ty)	Annual Power kW - hrs	Relative Capacity Factor	Relative Annual Power
Conventional Horiz. Axis Turbine 25 ft. dia. rotor	7.3	20	34.6	21,040	1.00	1.00
	20	28	21.9	36,570	1.00*	
DAWT (r=8) 25 ft. dia. rotor	58	20	49.5	239,155	1.43	11.4
	158	28	34.8	457,880	1.59*	12.5*
DAWT (r=6) 19 ft. dia. rotor	25	20	48.7	101,510	1.41	4.8
	70	28	34.1	198,830	1.56*	5.4*
DAWT (r=4) 25 ft. dia. rotor	29.2	20	47.7	116,055	1.38	5.5
	80	28	33.2	221,000	1.52*	6.0*
Conventional Hor. Axis Turbine 50 ft. dia. rotor	15	16	44.8	58,925	1.0**	
DAWT (r=4) 25 ft. dia. rotor	15	16	58.4	76,750	1.30**	
DAWT (r=7) 19 ft. dia. rotor	15	16	59.9	78,750	1.34**	

* Factor based on other 28 mph Power ratings only
** Factor based on other 16 mph Power ratings only

The improved plant factor is a result of the DAWT's ability to speed up the natural wind as it approaches the turbine. As a consequence the turbine can start to produce useful power at much lower cut-in wind speeds than a conventional wind turbine, where the local velocity is up to 1/3 lower than the natural wind speed. Further, at any given intermediate power level below rated the DAWT can generate for a greater number of hours per year than its conventional turbine counterpart; thus, the DAWT can deliver more kilowatt-hours per year than just the augmentation factor times the bare turbine yearly output.

In addition, because the diffuser inherently moderates normal atmospheric turbulence and operates undiminished in performance for off-axis winds up to perhaps 30 degrees, the DAWT's turbine is subjected to less aeroelastic loading excursions than a bare turbine, and need not suffer wind unsteadiness penalties in performance or yaw axis acceleration loading.

The specific power capital cost of the DAWT is

$$C_c = \frac{c_T + c_D}{r\mathbb{P}} \tag{15}$$

Then, the busbar cost, c_b, for the DAWT relative to that for the conventional wind turbine, of equal rotor diameter and rating wind speed, is

$$\frac{c_{b_{DAWT}}}{c_{b_{WECS}}} = \frac{c_T + c_D}{c_T} \times \frac{\mathbb{P}}{r\mathbb{P}} \times \frac{C_{F_{WECS}}}{C_{F_{DAWT}}}$$

$$= \left(\frac{C_D}{C_T} + 1\right) \left(\frac{C_{F_{WECS}}}{rC_{F_{DAWT}}}\right) \tag{16}$$

Within the range of maximum and minimum augmentation ratios considered previously, (i.e., 8 and 4, respectively) and the conditions of Table 1, the DAWT should provide less expensive power if the diffuser equipment cost of the DAWT is less than 11.7 and 4.2, respectively, times that of the turbine. This criterion establishes a cost target for the diffuser, assuming that the same turbine technology costing rules apply in both cases for equal rotor diameters and rated wind speeds.

Because we are at the point of entering a new study phase concerned with diffuser engineering design and costing, the needed realistic cost data to compute busbar costs are unavailable. However, preliminary estimates suggest a production DAWT busbar cost of under 2 cents per kw-hr for a 25 ft rotor diameter equipped machine rated at about 160kW at 28 mph hub speed.

More extensive work concerning cost of commercialized DAWT's obviously is needed, and should be forthcoming within the next year.

CONCLUSIONS

The DAWT concept has been verified by a model test program showing the feasibility of short length, compact diffusers and significant power augmentation ratios. The success in designing diffusers to produce highly subatmospheric exit plane pressures, with reasonably high diffuser efficiencies, appears to be enhanced by wind turbine operations as in a DAWT integrated system. The turbine wake is believed to aid the suppression of flow separation in a very high included angle diffuser through tangential wall slot flow injection and to increase diffuser efficiency.

Performance of model test equipment at an area ratio of 2.78 has demonstrated 350% better power conversion than the best optimum conventional wind turbine and points to an eventual compact diffuser design of about 4.0 effective area ratio and 80 to 90 degrees, included angle. Such a design could be expected to yield power augmentation factors of

6 to 8 times conventional turbines, as a result of combining an exit plane pressure coefficient, C_{p_4} of -1.4 with high diffuser efficiency.

The inherent speed up of the natural wind as the air approaches the turbine, because of the combined effects, results in increased plant capacity factor relative to a conventional bare turbine owing to the earlier cut-in wind speed of the former system. The consideration of plant factor and a wind speed duration profile results in the DAWT having the potential of generating between 6 and 12.5 times the annual power output of a conventional bare turbine, depending on the achieved level of diffuser performance (between augmentation ratios of 4 and 8, respectively). As a result certain cost goals can be set for the diffuser in terms of bare turbine cost for equal rotor diameters.

Although, further DAWT model verification is necessary, including a field test phase, there is reasonable support for an expectation of busbar costs becoming cost competitive, under 2 cents per kW-hr, for a 150 kW rated DAWT system.

ACKNOWLEDGEMENTS

This work was supported by the Wind Systems Branch, Solar Technology Division, of the U.S. Department of Energy under contract no. EY-76-C-2-2616. The authors express their appreciation to Dr. R.A. Oman for his contribution in the conceptual and early experimental phases of this project and his continued interest and guidance in the later phases.

NOMENCLATURE

A	area
C	chord length of turbine blades
c_b	busbar cost of electricity, Eq. (13)
C_C	capital cost for rated power, Eq. (15)
c_D	diffuser cost
C_F	plant capacity factor
C_{P_i}	ideal power coefficient, Eq. (6)
C_{P_R}	diffuser pressure recovery coefficient
C_{P_4}	overall pressure recovery coefficient
c_T	turbine cost
C_T	rotor disk load, referenced to q_2 Eq. (5)
C_{T_o}	rotor disk load referenced to q_o
F	annual fixed charge rate
H	hours
K_i	inlet total pressure loss coefficient
L	axial length of diffuser
M	maintenance and operations costs
N	number of blades
p	static pressure
p_{23}	pressure drop across the turbine (rotor)
$\mathcal{P}$	power of a conventional wind turbine

q_o	free stream dynamic pressure
q_2	local dynamic pressure at the rotor face
r	augmentation ratio, Eq. (8)
R	rotor outer radius
Re	Reynolds Number (based on maximum diameter of diffuser)
V_o	wind velocity
V_2	axial velocity at the rotor face
x	tip speed ratio = $R\omega/V_2$
α	angle of attack of airfoil
θ	turbine blade angle to plane of rotation
ε	rotor station velocity ratio = V_2/V_o
η_D	diffuser efficiency
λ	diffuser throat-to-exit area ratio = A_2/A_4
ρ	air density
ω	rotational speed of rotor
σ	rotor solidity

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RESPONSES TO THE FOREMAN PRESENTATION

Question: Are you assuming that you will get the same performance between the 18 in. and the 25 ft models?

Foreman: We are not matching everything, but we certainly are attempting to match the flow regime mainly because the theory that I've shown with regard to C_{p_4} does not require complete matching as it is an inviscid process. If the C_{p_4} effect is assumed, then the larger system should perform as predicted.

Question: I've had some unsatisfactory results when I did testing at those Reynolds numbers, particularly the range in which you are doing your work. Reynolds number predictions are adequate for airplanes where pressure effects are large and viscous effects are small. I've had similar problems and now utilize the moving vehicle method on a runway. There is absolutely no turbulence, and by accurately measuring groundspeed you can get a very accurate value for a Reynolds number.

David Bailey, Bailey Engineering: Have you considered the effect of vertical shear?

Foreman: We have found nothing significant in the performance of the system due to turbulence and ground plane vicinity effects.

Jain-Ming Wu, Engineering Research and Consulting, Inc.: Have you compared your system with one that has the same cross sectional area?

Foreman: The diameter of the diffuser is not really the critical element as regards the capture area. It is a C_{p_4} effect which is very important in the dump diffuser. The dump diffuser is shorter than a regular diffuser, and there is apparently a better diffusion process. For consistency, we have chosen to use the rotor area which is consistent with other systems. With small models we have been able to suppress separation at angles as high as 40°, and we believe that this may be increased to 45°.

Richard Oman, Grumman Aerospace Corp: The power coefficient achieved by the diffuser system using the base area as reference is higher than the Betz limit. The power achieved by the diffuser system is approximately six times that obtained for the base turbine. Reynolds number effects may be important but we intend to investigate several stages to evaluate this effect.

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RECENT DEVELOPMENTS OF THE TORNADO-TYPE WIND ENERGY SYSTEM *

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ABSTRACT

Recent developments in Tornado-type Wind Energy System will be presented in this paper including the findings that (A) the vanes of the vortex collecting tower can be permanently fixed and opened to winds from all directions, (B) data measured from small models with fixed-vanes give a current level of performance of around 0.10 for the power coefficient based on the tower frontal area, (C) fixed-vane tower design yields major reductions in tower costs and significant reductions in capital costs against some degradation in performance due to some leakage of wind energy from the fixed-vanes, (D) employing a reasonable system cost of $\$100/m^2$ ($\$10/ft^2$) of tower surface area shows that at mass production of full-scale units, the Tornado-type wind energy system would yield a capital cost of \$300 to 500/kW installed and an energy cost of 2 to 4¢/kWh, and hence, (E) even based on current level of performance measured from small models, full-scale Tornado-type wind energy system is seen to be cost competitive against the conventional Mods OA, 1 and 2 wind machines.

* Sponsored by both the U.S. Department of Energy and the New York State Energy Research and Development Authority under Contract E(49-18)-2555.

1. INTRODUCTION

The Tornado-type Wind Energy System (TWES) presents a structurally simple and rugged design (Figure 1) which is free of the severe dynamic stresses that seriously affect the operations of conventional wind turbines. Presence of such severe stresses with the conventional turbines (such as Mods 0, 0A, 1 and 2) limits their unit capacity to below 3 MW's and injects a lot of uncertainty into their ability of survival over a 30-year lifetime as discussed in Ref. 1.

Being freed of such severe stresses, TWES has the potential of achieving large (100 MW or larger) unit capacities which are desired by the utilities. And, its lifetime can be certified through accelerated-life testings in the factory before installation, as discussed in some details in Ref. 1.

In addition, its ability to harness heat energy including waste heat enables TWES to supply power on demand, independent of the unpredictable fluctuations of wind energy and the difficulties in storing large quantities of wind energy. As discussed in Ref. 1, TWES or a similar design is needed to bring out fully our immensely large wind energy potential and to greatly reduce our dangerous dependence on imported oil.

In this paper, we will present recent developments in TWES including results of an economic analysis showing that even based on current performance measured with small models, full-scale TWES can be cost competitive against Mods 0A, 1 and 2 machines.

2. RECENT DEVELOPMENTS

We found recently through our wind tunnel testings, that the vanes of the vortex tower which collects the wind and forms the vortex can be made permanently <u>fixed</u> and opened to winds from all directions. By optimizing the geometry of the vanes, losses due to leakage of wind energy from the leeward vanes can be minimized. Figure 2 shows a photograph of a small fixed-vane model with a height H of 50 cm (20 in) and a diameter D of 25 cm (10 in). This model is equipped with crude turbines of 10 cm (4 in) in diameter and tested in a 1.2 x 1.8 m (4 x 6 ft) wind tunnel at a wind speed of 8 m/s (18 mph). Flaps with several configurations are attached onto the vanes; variations of the vane angle setting, vane positioning and bottom inlet configuration are also made. Some of the data obtained are presented in Figure 3; detailed presentation of all the data will be made in our Final Report.

Figure 3 shows that the power coefficient C_P based on the tower frontal area H x D has reached around 10%, with a best value of close to 14%, versus the best value of 18% which was obtained with a spiral-cross-section tower (Ref. 2). This reduction in performance due to some leakage through the fixed vanes can be more than made up by the reduction in cost of the tower. With the vanes permanently fixed, there is no need for controls and monitors to properly set the vane openings according to instantaneous wind conditions and the vanes themselves become important load-bearing members of the structure. Fixed vanes can also be made of heavier but low-cost matrial such as concrete. Hence, fixed-vane tower design leads to major reductions in tower cost and significant reductions in capital costs, against some degradation in performance. Indeed, the fixed-vane design further enhances the economic credibility of TWES because it is even simpler than the original design with controlled vanes.

Several analyses of the capital cost have been summarized in Ref. 1. It is given by

$$\$/\mathrm{kW} = \mathrm{Cost/m}^2 \times \mathrm{HD}/\mathbb{P} \qquad (1)$$

with

$$\mathbb{P} = C_{\mathbb{P}} \times \mathrm{HD} \times \tfrac{1}{2}\rho V_R^3 \times F$$

and

$$F = \frac{1}{H V_R^3} \int_{H_o}^{H + H_o} V^3 \, dZ$$

$$= \frac{\alpha}{3 + \alpha} \frac{H_o}{H} \left[\left(1 + \frac{H}{H_o}\right)^{(3 + \alpha)/\alpha} - 1 \right]$$

where F takes into account the variation of wind speed V with altitude Z ($V \sim Z^{1/\alpha}$). α ranges usually from 5 to 7; and, $\alpha = 5$ gives for Mod 1 reasonable values of $C_{\mathbb{P}}$ when compared with those for Mods 0, 0A and 2 machines (see Fig. 7 of Ref. 1). V_R is the rated wind speed specified at an altitude H_o. The vortex tower has a height H and starts at the altitude H_o.

The capital cost calculations of Eq. (1) requires a system cost per unit area of the tower walls. With a fixed-vane tower design, the vanes can be made of heavier but low-cost material such as concrete as mentioned above, and the system cost may reach $\$100/m^2$ ($\$10/ft^2$) of tower surface area. Because, concrete retails at around $\$30/m^3$ ($\$1/ft^3$) delivered, and intalled cost is around $\$30/m^2$ ($\$3/ft^2$) for a 20 cm (8 in) thich vane with commercial-grade steel reinforcement, concrete and labor cost all included (Ref. 3). And because, $\$70/m^2$ ($\$7/ft^2$) of tower surface area would adequately cover cost of other components including the "standardized turbines", as discussed in Ref. 1.

Substituting of this system cost of $\$100/m^2$ ($\$10/ft^2$) of tower surface area into Eq. (1) yields the curves of Fig. 4 for different values of α and $C_{\mathbb{P}}$. The capital costs for Mods 0A, 1 and 2 as derived from Table 2 of Ref. 1 are also shown in Fig. 4, where the scale for the abcissa is used to represent both the tower height of the TWES as well as the blade diameters of Mods 0A, 1 and 2, and where V_R = 11 m/s (25 mph) at 10 m (30 ft), the same specification as for Mod 1. Curves for the 1000th unit are obtained based on the usual "90% learning curve" which is discussed and tabulated in Appendix A of Ref. 1. These curves, derived with a system cost of $\$100/m^2$ ($\$10/ft^2$) of tower surface area and our present performance level of C_{P} = 0.1, yield a value of \$300 to 500/kW installed for large systems, in general agreement with the result of a previous cost analysis (Ref. 4). The same curves are obtained if the system cost is increased to \$300/m^2 (\$30/ft^2) of tower surface area while the performance is improved to C_{P} = 0.3. Also, the same curves are for the first unit, if the system cost remains at \$100/m^2 (\$10/ft^2) while C_{P} is improved to reach 0.30.

It was reported in Ref. 4 that small-model data have shown a strong scaling law with C_{P} improving roughly as a linear function of the tower diameter or height (for a fixed aspect ratio). (More specifically, $C_{P} \sim Re^m$ with m = 0.86 to 1.56 and Re is the Reynolds number in terms of the tower diameter). If we take a much more moderate scaling law with m = 0.25, then with C_{P} = 0.10 for H = 50 cm (20 in), C_{P} would reach 0.30 to 0.45 for H = 60 to 300 m (200 to 1000 ft) with the aspect ratio H/D remain fixed. Hence, C_{P} reaching 0.30 is highly possible for large units and taking C_{P} = 0.10 for large systems is a highly conservative assumption.

The capital costs derived above are used to compute the energy cost using the relation,

$$¢/\text{kWh} = \frac{\$/\text{kW} \times \text{FCR} \times 100}{\text{Availability} \times \text{PF} \times 8760} + \text{O\&M} \qquad (2)$$

where FCR is the fixed charge rate (usually = 18%). PF is the annual plant factor which represents the percentage of time during which sufficient wind is available at the machine to produce the rated power as well as cummulative equivalents of rated power, during each year. O&M stands for the overhead and maintenance cost per kWh and is taken as 3% of the capital cost according to Ref. 5.

Taking 0.42 for PF and 0.90 for availability, the energy costs derived from Fig.4 and Eq. (2) are shown in Fig. 5. For large systems and at mass production, Fig. 5 gives an energy cost which is within or below the 2 to 4 ¢/kWh range, the latter is a primary objective in the development of Mods 1 and 2 machines.

Moreover, as discussed in Ref. 1, TWES can have a lifetime which is designed for 30 years and which can be certified in the factory before installation. Hence, Figs. 4 and 5 show that, based on the current level of performance of small models, full-size TWES can be competitive against Mods OA, 1 and 2 in capital and energy costs, with a life-cycle cost that can be acertained in the factory before installation.

Up to now, we have tested in wind tunnels only models up to 100 cm (42 in) in height. We have made a larger model extending up to 5m (15 ft) in height with a 2 m (6 ft) diameter tower and a 0.75 m (30 in) diameter turbine. Fig. 6 shows the turbine rotor which has blades which are casted from aluminum filled epoxy resins and reinforced with steel rods. Each blade has a designed twist and adjustable pitch. The rotor and the stator are connected to an automobile-type electrical generator and installed in a turbine test rig shown in

Figs. 7 and 8. The test rig is powered by a fan and equipped with load cells to measure torque and thrust. The turbine is tested under straight-flow winds with a wind speed of up to 20 m/s (45 mph). So far, the turbine has reached a rotating speed of 1500 RPM with little vibration and has delivered around 1 horsepower based on the torque and RPM measurements. Efforts are being made to complete the debugging of the test rig and to take data at different blade pitch angles and wind speeds. The results will be used for designing an improved turbine. These tests however, do not give a close simulation of the actual operation since the turbine will then exhaust into a vortex. Moreover, the turbine is a kind of non-standard gas turbine. It has a stator and a rotor with many blades as a gas turbine; but its pressure ratio is around 1.007, much less than those of standard gas turbines which have pressure ratios of larger than 2. Hence, much of the cummulated gas turbine design experience are not directly applicable; and much more testing is needed to obtain an optimal design and to integrate the turbine with the vortex tower. Needless to say is that a good priority at the NASA large wind tunnels is needed to fulfill this task. Given the immense potential of our wind energy as described in Ref. 1 and our urgent need for greatly reducing our dangerous dependence on imported oil, it does seem that TWES, with its salient features and commercialization potentials as presented above, deserves a good priority at the NASA large wind tunnels and significant funding from our federal and state government.

A tower with a height of up to 7m (21 ft) has also been manufactured and assembled as shown in Figs. 9 and 10. The turbine with its generator and load cells will be installed at the bottom of the tower. The entire assembly is waiting for testing in a large wind tunnel.

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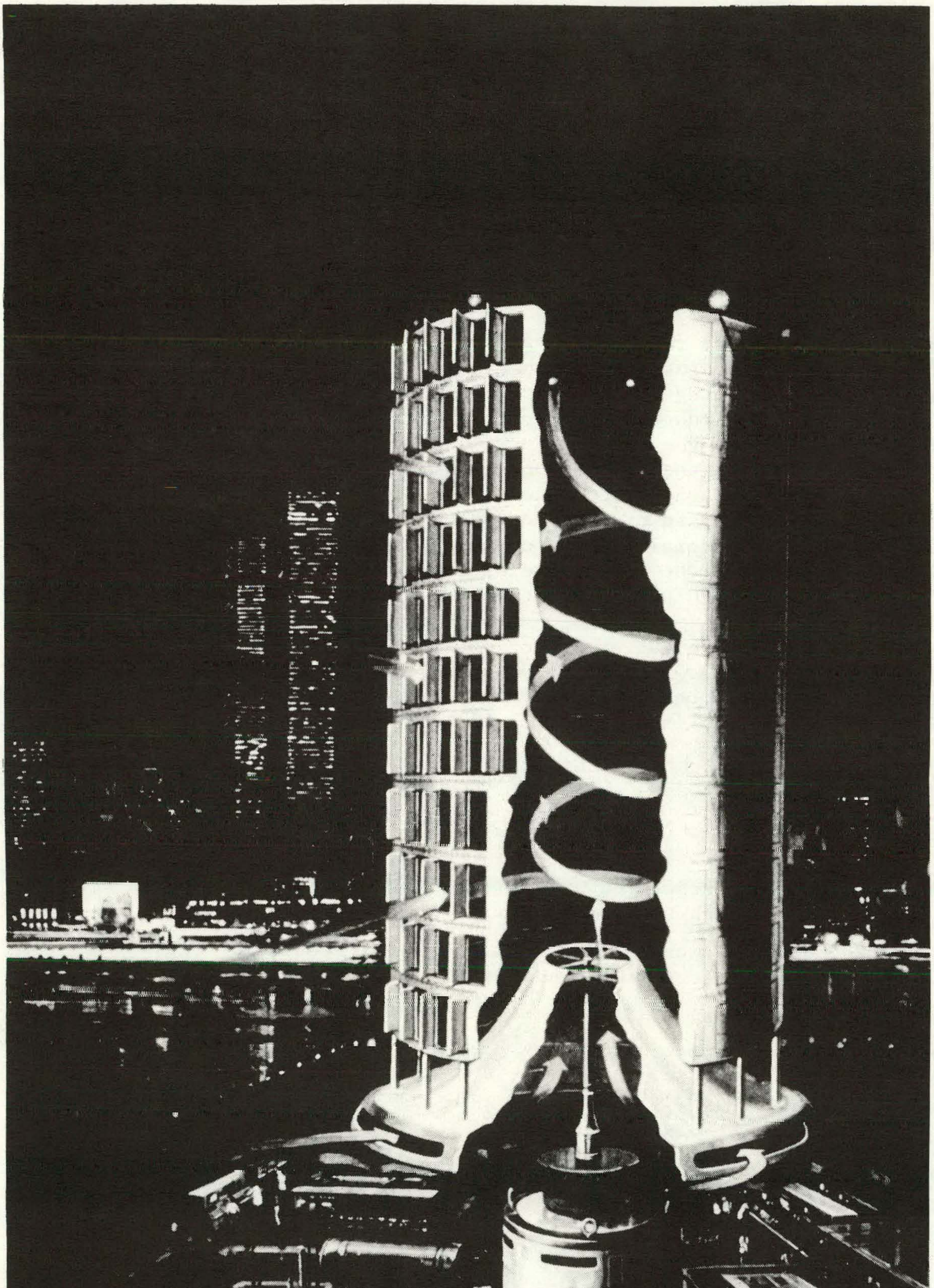
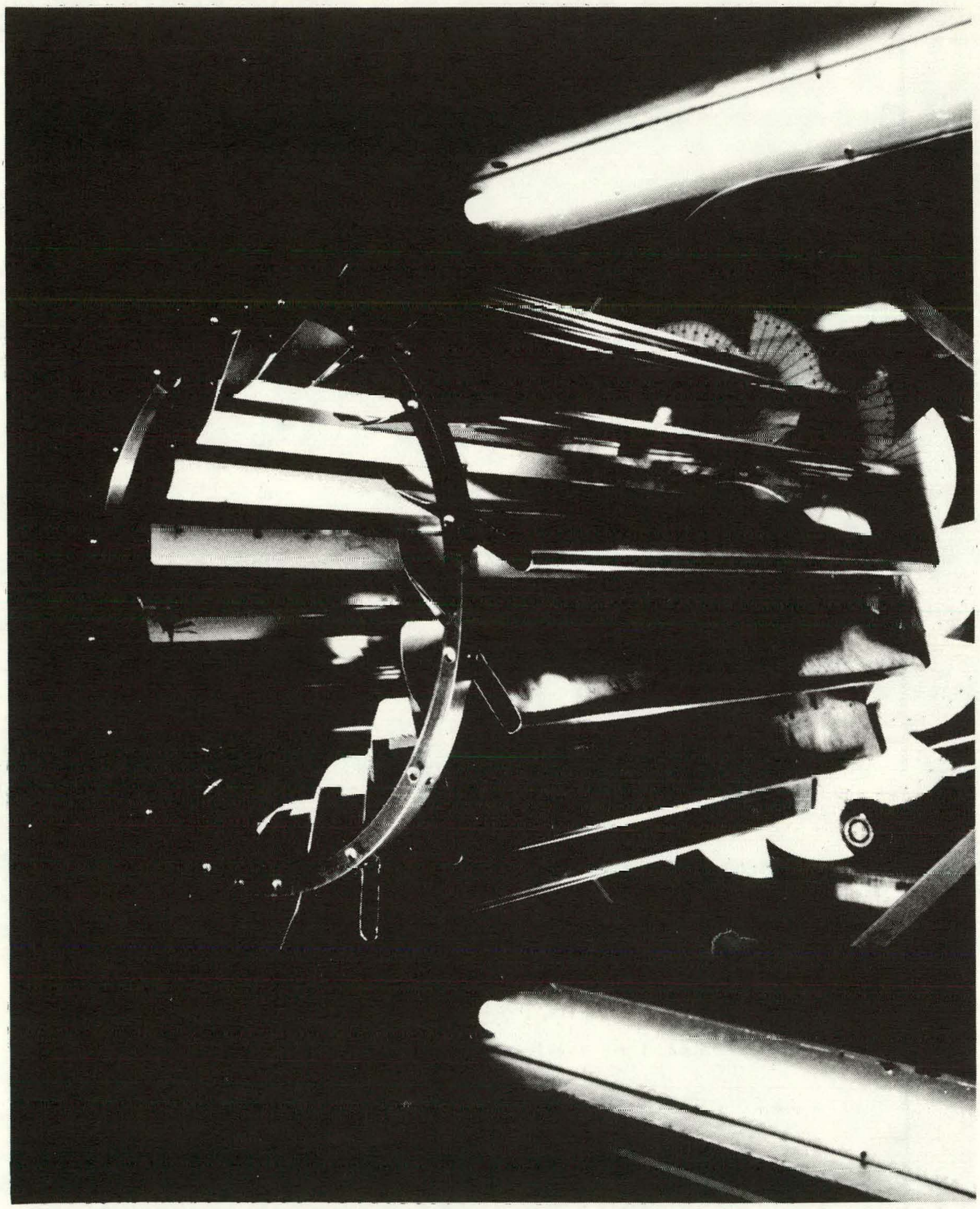




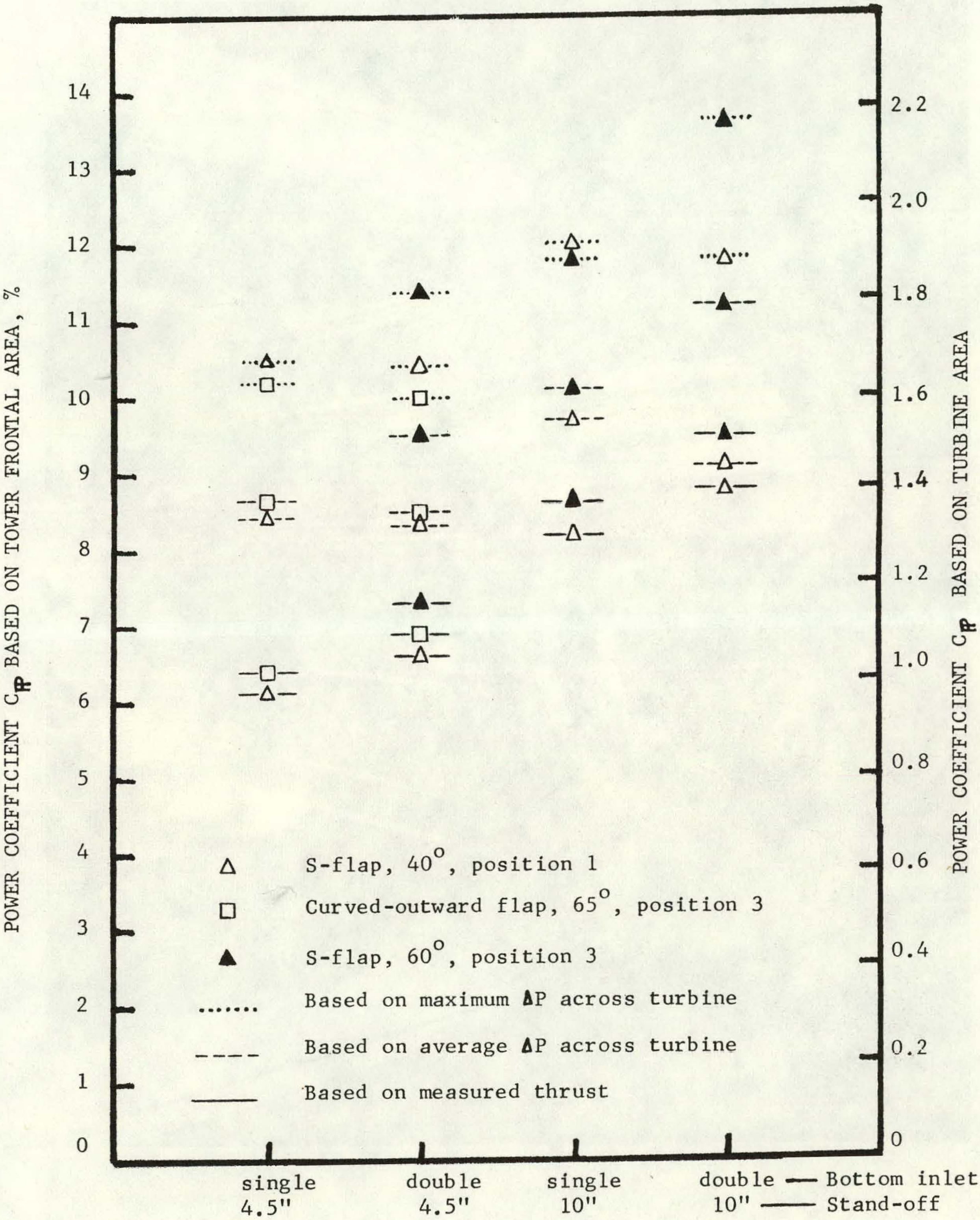


Figure 3 Measured data on the Power Coefficient from testing in 1.2 x 1.8 m (4 x6 ft) wind tunnel at 8 m/s (18 mph) wind speed

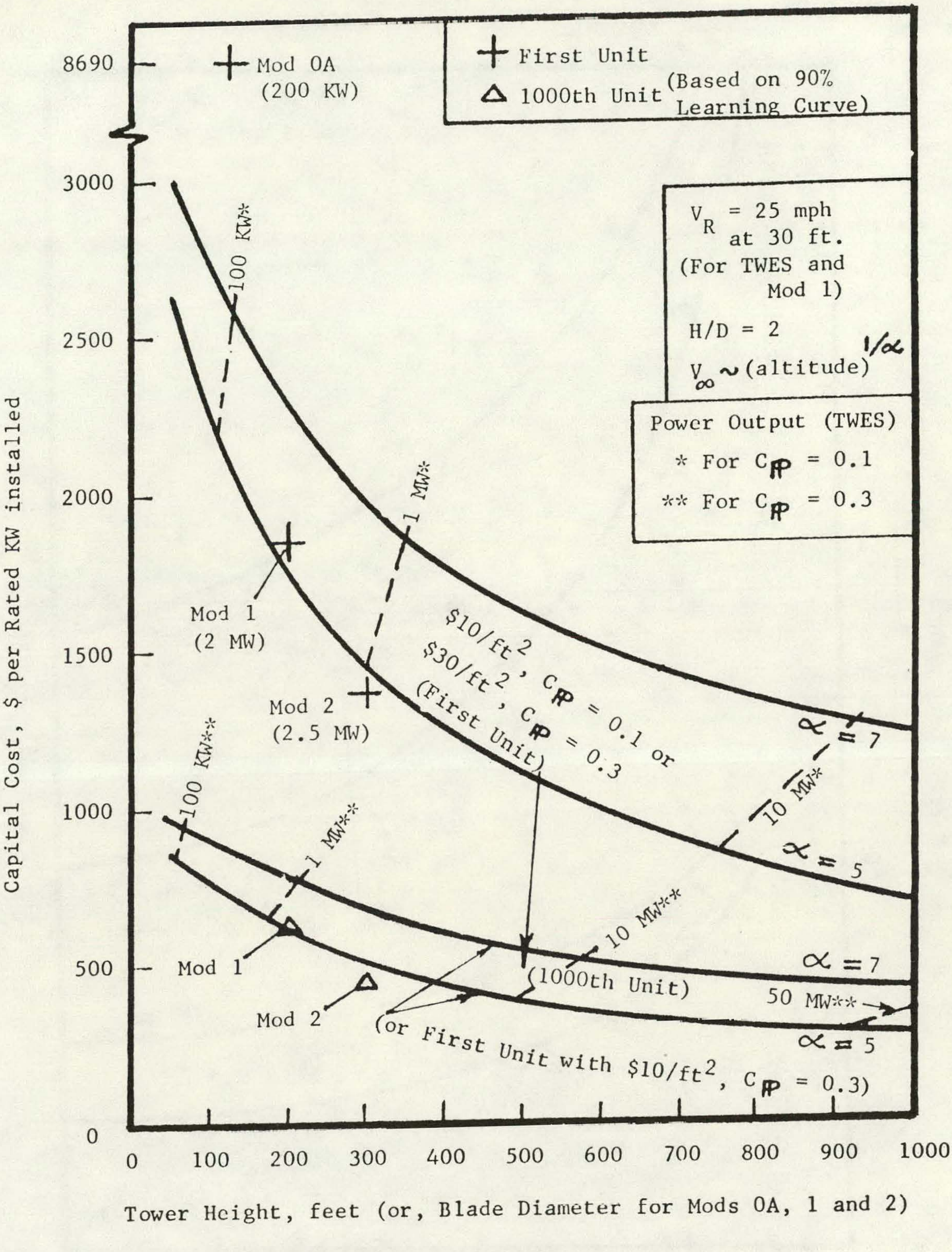


Figure 4 Comparison of Estimated Capital Costs for TWES with the Reported Capital Costs of Mods 0A, 1 and 2

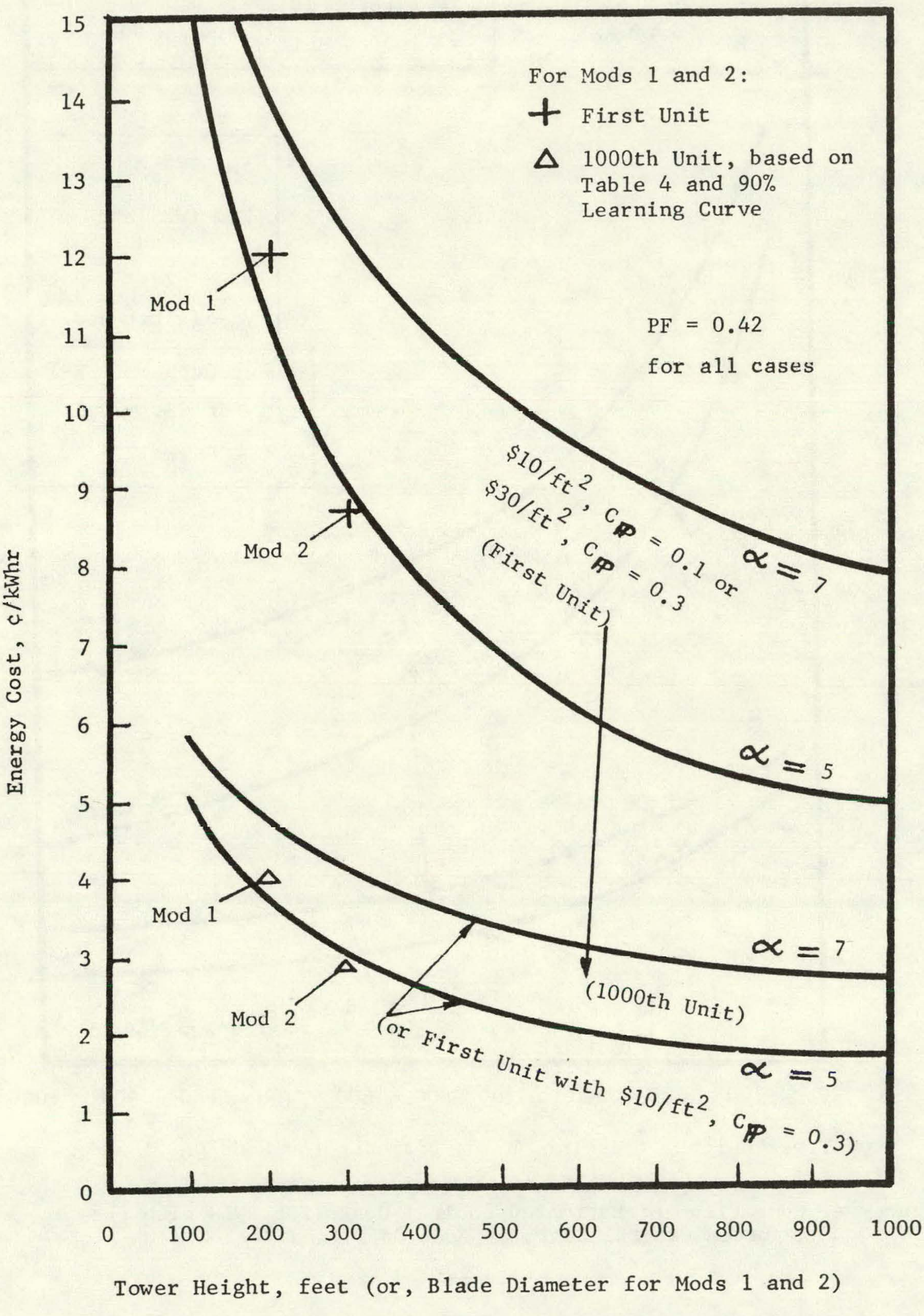
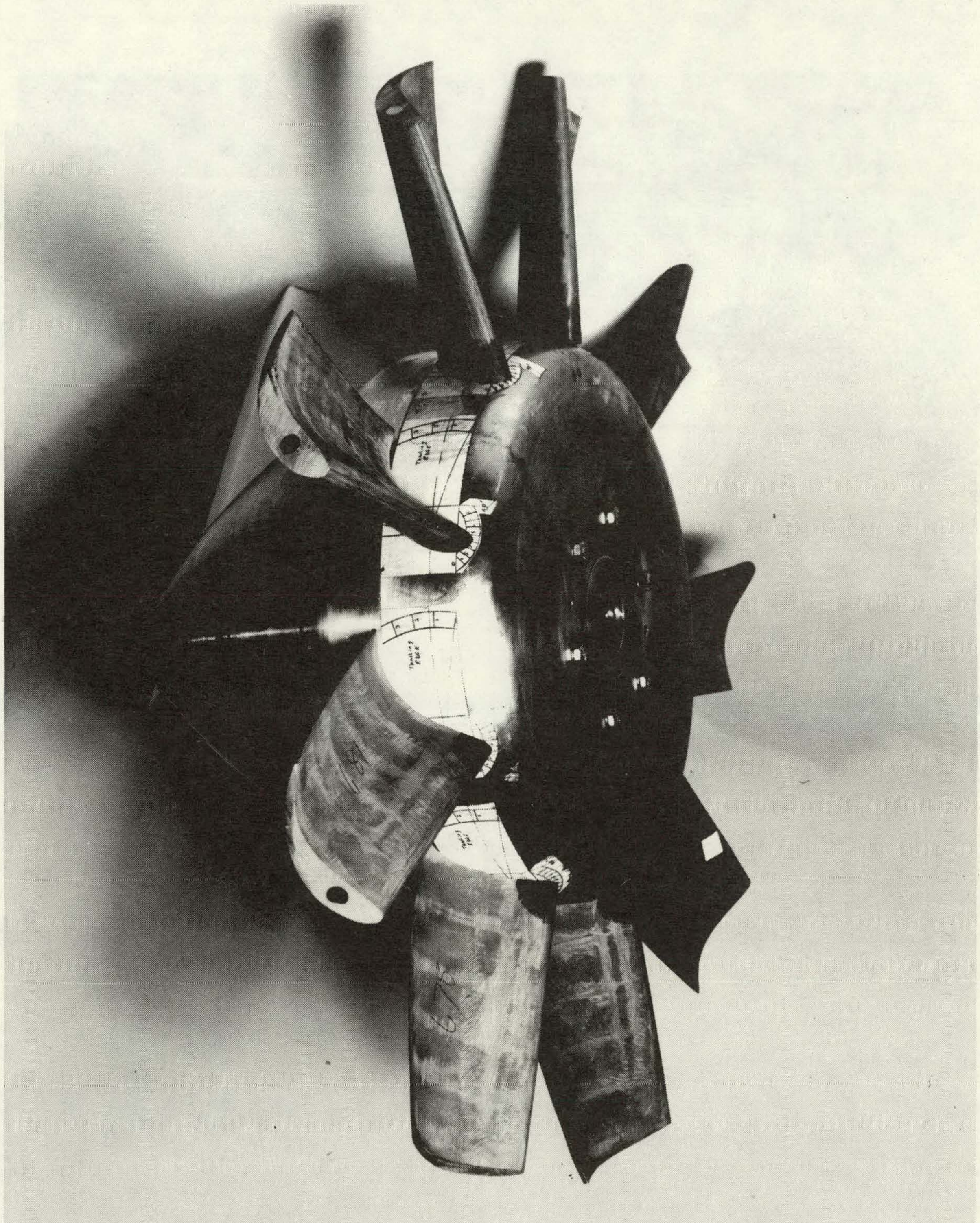
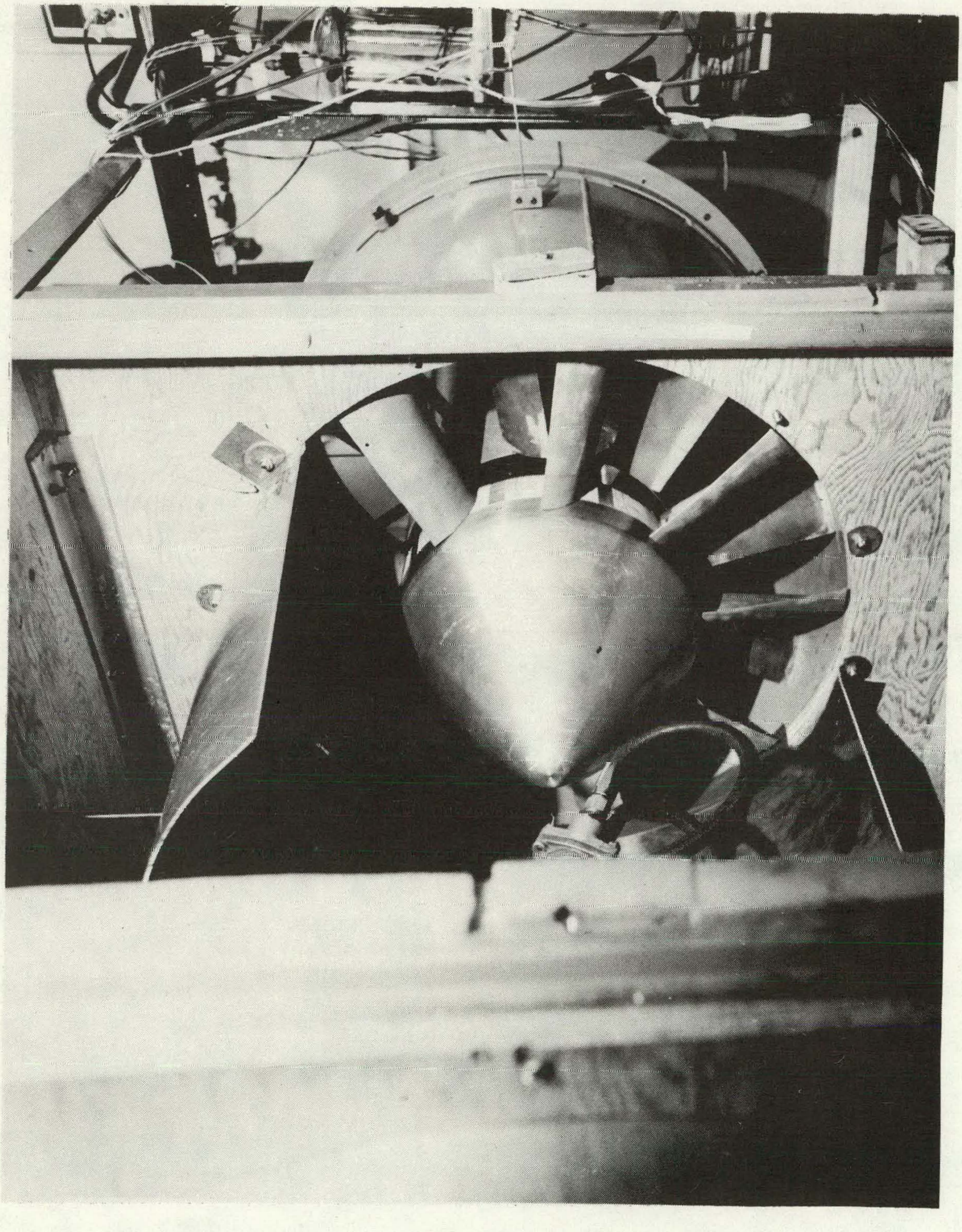
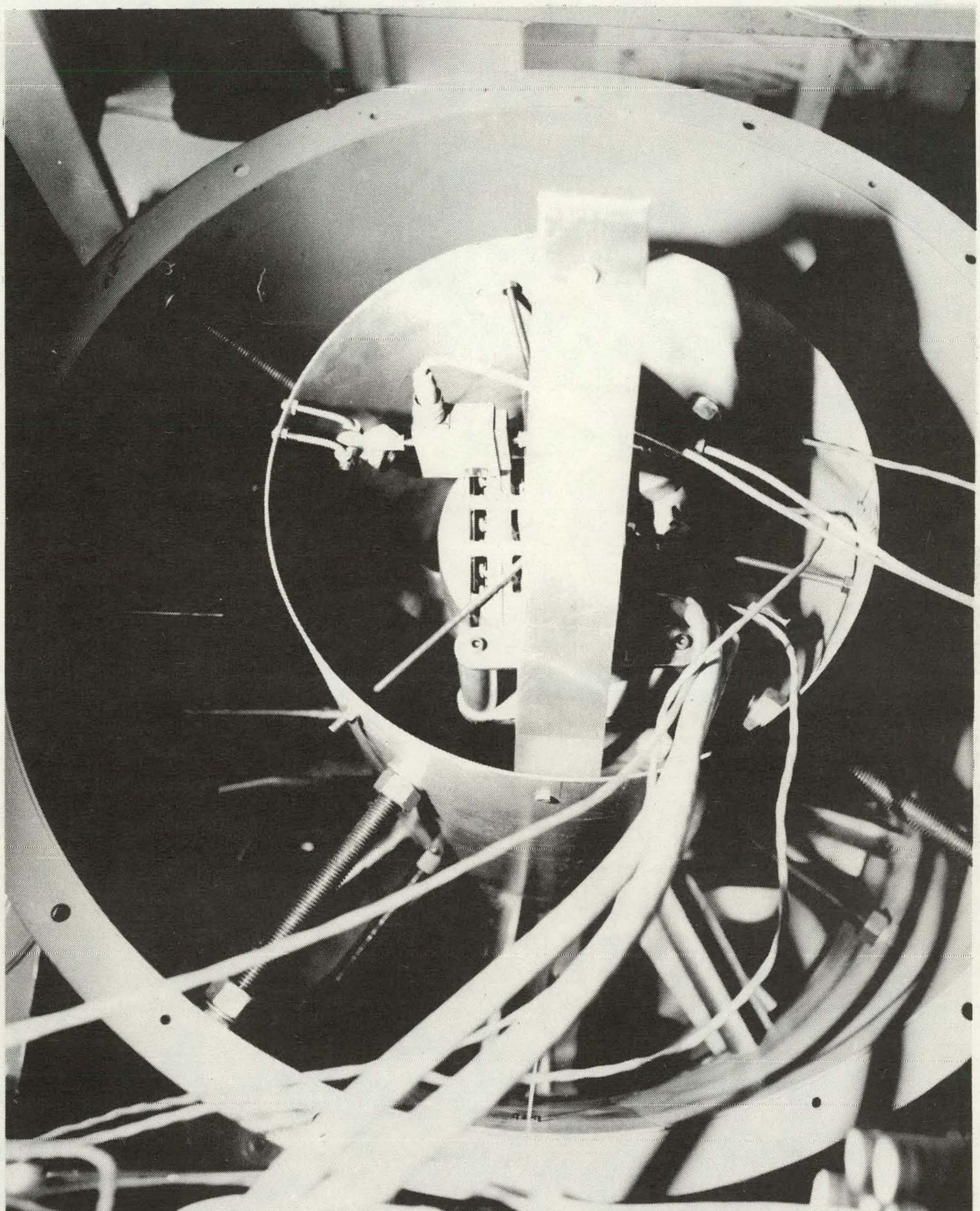
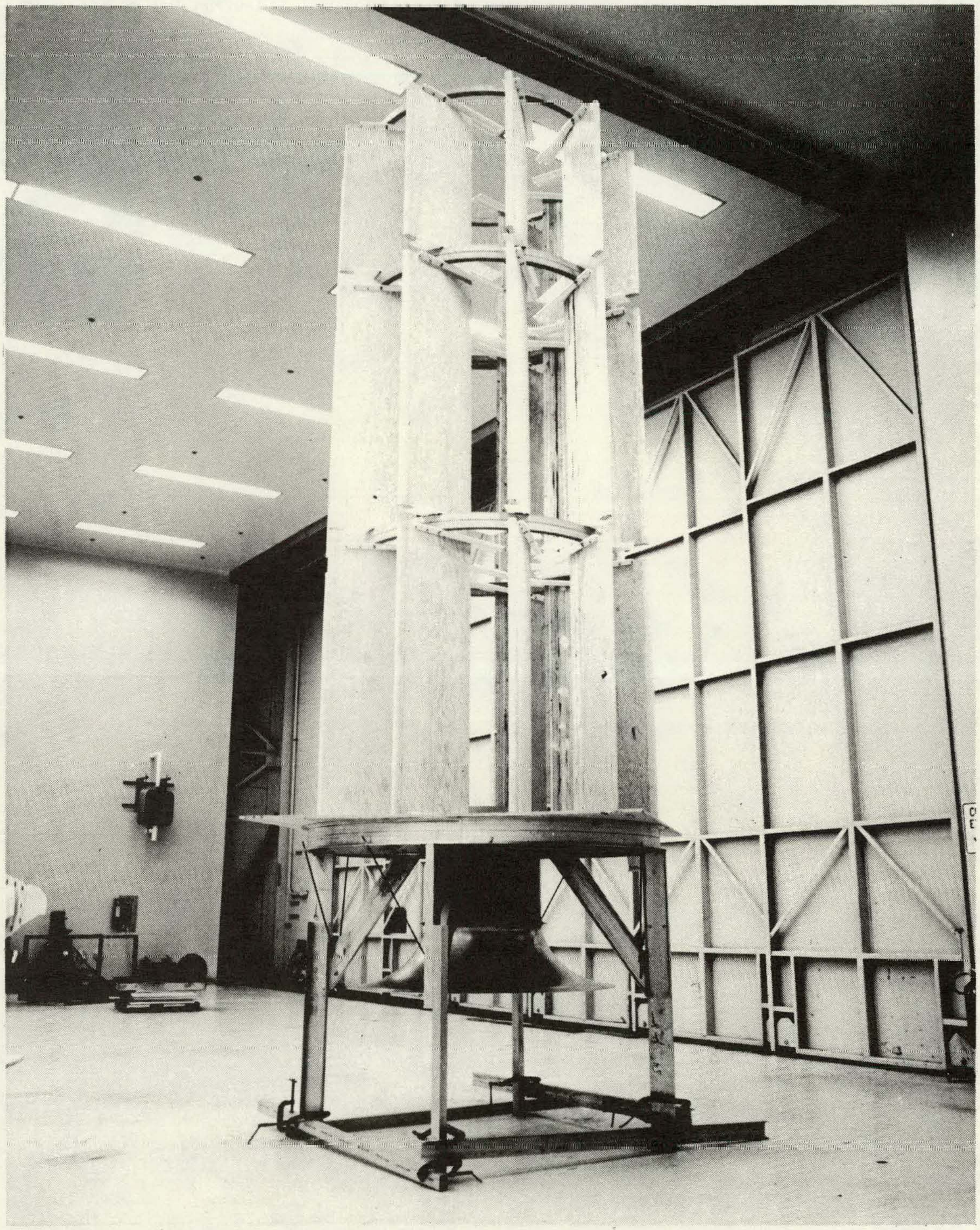


Figure 5 Comparison of Estimated Energy Costs for TWES with the Reported Energy Costs of Mods 1 and 2









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PRELIMINARY TECHNICAL AND ECONOMIC EVALUATION OF VORTEX EXTRACTION DEVICES

T.R. Kornreich, R.J. Kottler, Jr., and D.M. Jennings
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ABSTRACT

Two innovative vortex extraction devices--the Tornado Wind Energy System (TWES) and the Vortex Augmentor Concept (VAC)--are critically evaluated to provide a preliminary assessment of their technical and economic viability compared to conventional horizontal axis wind energy systems. There are many technical uncertainties which still need to be resolved before the technical feasibility of the TWES can be assured. Present experimental work has dealt with very small-scale wind tunnel tests so that available data cannot be used with any degree of confidence to resolve these uncertainties and estimate full-scale system performance. The VAC is not subject to as many technical uncertainties as the TWES but still presents certain problems (such as vortex breakdown) which need to be experimentally evaluated. However, even if all of these technical uncertainties are favorably resolved and the most optimistic TWES and VAC performance claims are met, neither device appears capable of achieving economic parity with comparably-sized conventional wind systems.

OVERVIEW

One of the advantages of the TWES and the VAC is that they are able to produce more power than a conventional wind turbine with the same rotor diameter. This power enhancement feature is referred to as augmentation. Since the rotor subsystem is one of the major cost drivers in a conventional horizontal axis wind system, the TWES and VAC have been proposed as concepts which offer the potential of successfully competing with comparable conventional wind systems. However, the unconventional designs of the TWES and VAC bring with them a number of technical and economic uncertainties which need to be carefully evaluated in order to gauge their future potential.

The basis of economic comparison used in this study is the energy cost that could be achieved by "mature product" versions of the TWES, the VAC, and comparable conventional wind systems. This comparison is carried out over a range of power output and augmentation levels in order to gain an initial impression as to the prospective viability of the TWES and VAC. However, the conclusions drawn must be tempered somewhat by the fact that firm designs have not yet been developed and experimental data are available only for tests of small-scale models of the TWES and VAC.

APPROACH

The approach followed in conducting the economic analysis is shown in Figure 1. A baseline case was established as the fundamental point of reference for each of the devices. These two baseline cases included selection of a representative rated power level and an expected augmentation ratio which was defendable in terms of experimental data already obtained or other supporting evidence. Table 1 defines the baseline case conditions for the TWES and the VAC and indicates the conventional wind systems against which they were compared.

TABLE 1 TWES AND VAC BASELINE CASES

	TWES	VAC
Rated Power (kW)	1000	200
Augmentation Ratio	4.5	6
Conventional Wind System Counterpart	MOD-2	MOD-OA

Required TWES and VAC subsystems were identified and sized for these baseline cases. However, since each of these innovative concepts is a very early stage in its design phase, firm design data were not readily available. Therefore, in conjunction with information supplied by the TWES and VAC principal investigators, a number of design assumptions were made by the study team to conduct the required analysis.

Besides the baseline cases, additional cases (incorporating a range of rated power levels and augmentation ratios) were considered. The higher augmentation ratios were selected based on the most optimistic performance claims of the TWES and VAC principal investigators, normalized to the same conventional system power coefficient to place these data on the same basis. The spectrum of cases shown is presented in Table 2.

The prospective economic viability of the TWES and VAC were evaluated over the performance and power output spectrum shown. The cases considered include the most optimistic performance claims for the TWES and VAC, even though experimental validation of these claims is not yet available. This was done to gain insight into the relative competitive position of the two innovative vortex deivces under the most favorable performance conditions that are contemplated for these devices.

For each case evaluated, the mature product cost for each TWES and VAC subsystem was obtained from vendor price quotations or by computing the material cost for a particular subsystem and scaling this material cost to a total fabricated subsystem cost. The total mature product hardware cost was then obtained by summing all of the fabricated subsystem costs.

FIGURE 1

ECONOMIC ANALYSIS

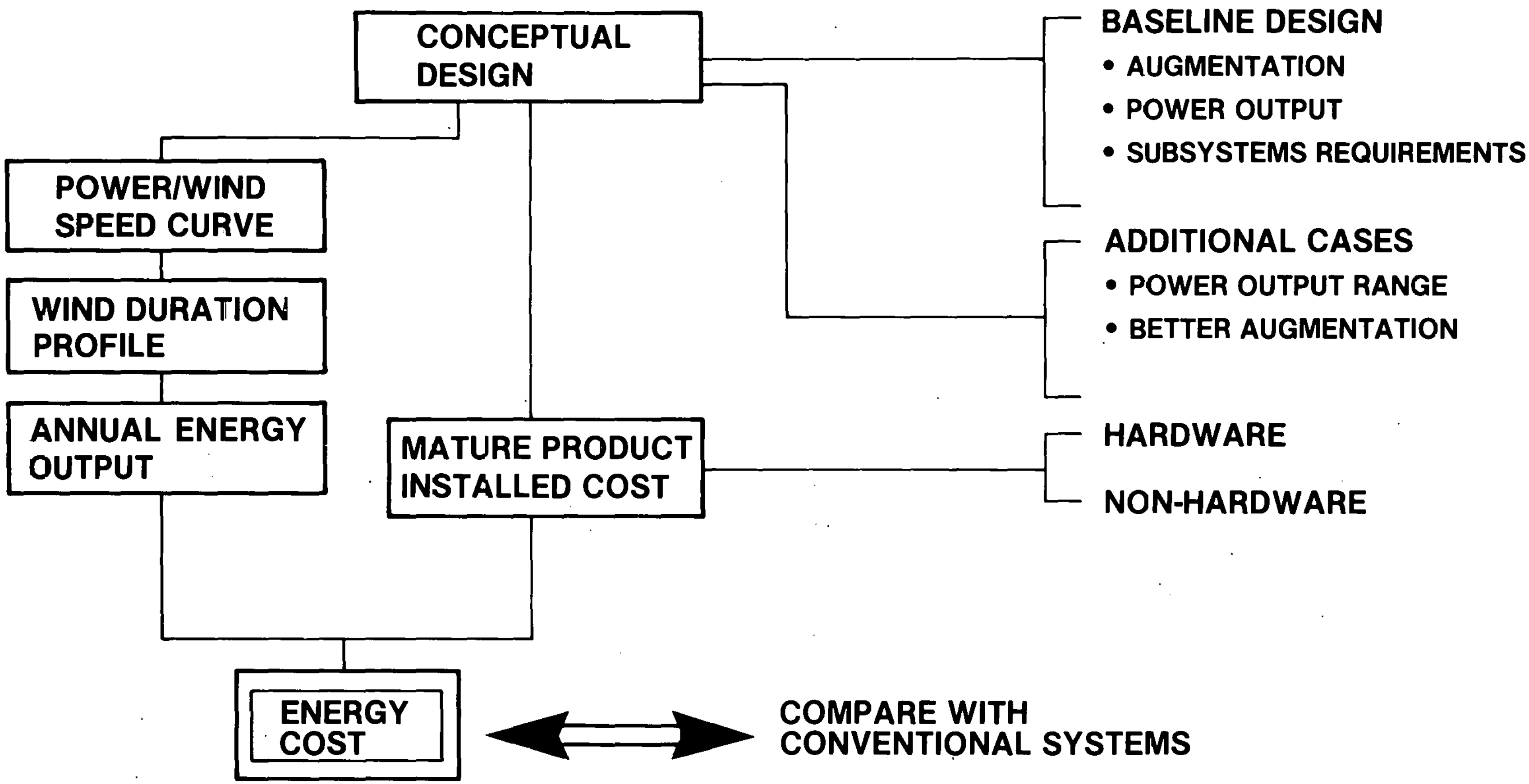

TABLE 2 SPECTRUM OF CASES CONSIDERED

Rated Power / Augmentation Ratio	TWES						VAC		
	0.2MW	0.6MW	1MW	3MW	4MW	12MW	40kW	200kW	1MW
4.5	X		X		X				
6							X	X	X
13.5		X		X		X			
16							X	X	X

Added to the total hardware cost was the mature product non-hardware cost (associated with site preparation, system assembly, installation and checkout, transportation, general and administrative expenses, contractors' fees, etc.) which were estimated (in the aggregate) to be a fixed percentage of the hardware costs. The sum of the hardware and non-hardware costs represents the total installed cost of the TWES and VAC.

For each case evaluated, a power output vs. wind speed curve was developed. The combination of this power output profile and the wind duration profile, appropriate for a site mean wind speed of 5.4 m/s (12 mph), enabled the total annual energy output to be calculated; the total usable energy output for the TWES, VAC and conventional wind systems was assumed to be 90% of the total available annual energy output to account for planned and forced outages. The energy cost for each TWES and VAC case was determined using an annual fixed charge rate of 0.18 and annual operation and maintenance costs equal to 3% of the total installed system costs.

The energy costs for the TWES and VAC were then compared to the energy costs of comparably-sized, "mature product", conventional horizontal axis systems in the same wind regime. This comparison enabled conclusions to be drawn concerning the potential economic viability of the TWES and the VAC across a range of sizes and performance levels.

THE TORNADO WIND ENERGY SYSTEM

The TWES concept involves the creation of a confined, tornado-like vortex within a stationary tower through the injection of the ambient wind flow into the tower. The proposed tower design has fixed vanes, no moving parts and will admit a wind flow from any direction. The tower includes a duct structure which diverges downward from the rotor to the ground plane. This structure houses several of the major TWES subsystems including the rotor, transmission and generator.

Since the tower vane design has not yet been finalized, two alternative design concepts were considered. One has circularly curved inner and outer tower walls with the vane ends assumed to have both inward and outward parabolic curvature (Figure 2). The second vane design uses "wing-like" vanes in an effort to improve the aerodynamic efficiency of the TWES (Figure 3).

A structural analysis of the TWES tower using both vane design concepts was carried out to establish the tower dimensions necessary to withstand maximum winds of 53.6 m/s (120 mph) and provide 1 MW of rated power (baseline case). The results are shown in Table 3. To assure structural integrity of the tower, reinforced concrete construction is required. From the data in Table 3 it is evident that a massive tower weighing approximately 70 to 100 million kg (151 to 219 million lb) would be required in the 1 MW baseline case.

Applying present-day reinforced concrete office building construction costs[1,2] (\$69/m^3 to \$76/m^3 or \$1.95/ft^3 to \$2.15/ft^3), baseline TWES tower costs (by far the major cost driver for the system) are estimated to be about \$2.1 million to \$3.1 million. Table 4 shows that the baseline (1 MW) mature product TWES cost ranges from about \$3.2 million to \$4.5 million. A comparable MW-scale conventional wind system (patterned after the MOD-2) is estimated to have a mature product cost of \$800,000 to \$1,000,000.[3]

A similar analysis was performed for all of the TWES cases specified in Table 2. The estimated installed mature product TWES costs as a function of system size and augmentation ratio are shown in Figure 4. Under baseline augmentation assumptions, the TWES has installed capital costs that are several times as great as conventional systems over the entire size range considered. There is some improvement in TWES cost relative to conventional systems with an increase in rated power level. However, the TWES capital cost is never lower than 2.5 times that of the comparable conventional wind systems under baseline augmentation conditions.

Under optimistic augmentation assumptions, the TWES has installed capital costs that are significantly larger than conventional systems at the 600 kW and 3 MW sizes. At the 12 MW size, the TWES costs cover a range from slightly lower to about 1.5 times as great as conventional systems. However, it should be noted that the total TWES costs presented have been considerably understated. For example, these estimates do not include the cost of the foundation which, for such a massive tower, would add a large cost burden for the TWES. In addition, the unique construction requirements of the TWES tower would impose additional costs beyond the standard office building construction costs assumed.

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1. Source: George Hyman Construction Company
2. This likely understates the TWES tower cost because of its unique construction requirements compared to office buildings.
3. Sources: Boeing Engineering and Construction Company; NASA/Lewis Research Center.

FIGURE 2

TORNADO WIND ENERGY SYSTEM

Base Line Design – First Concept

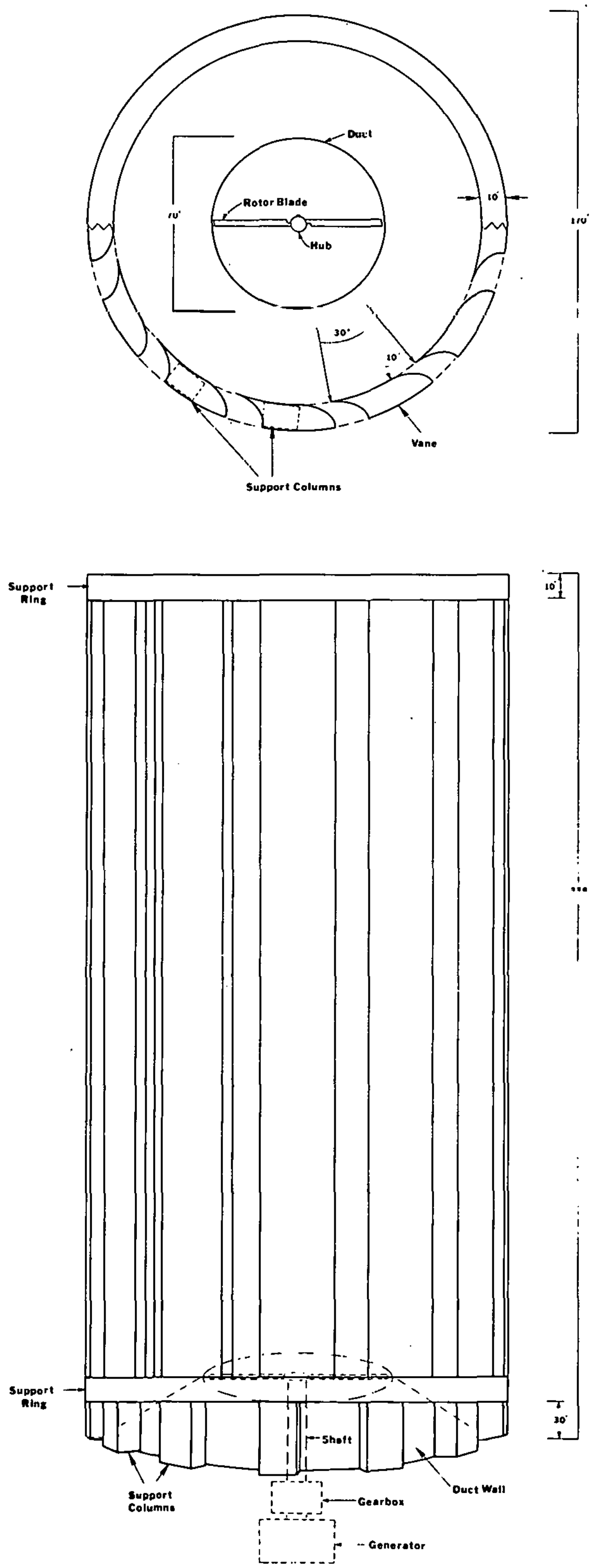

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FIGURE 3
TORNADO WIND ENERGY SYSTEM
Base Line Design – Second Concept

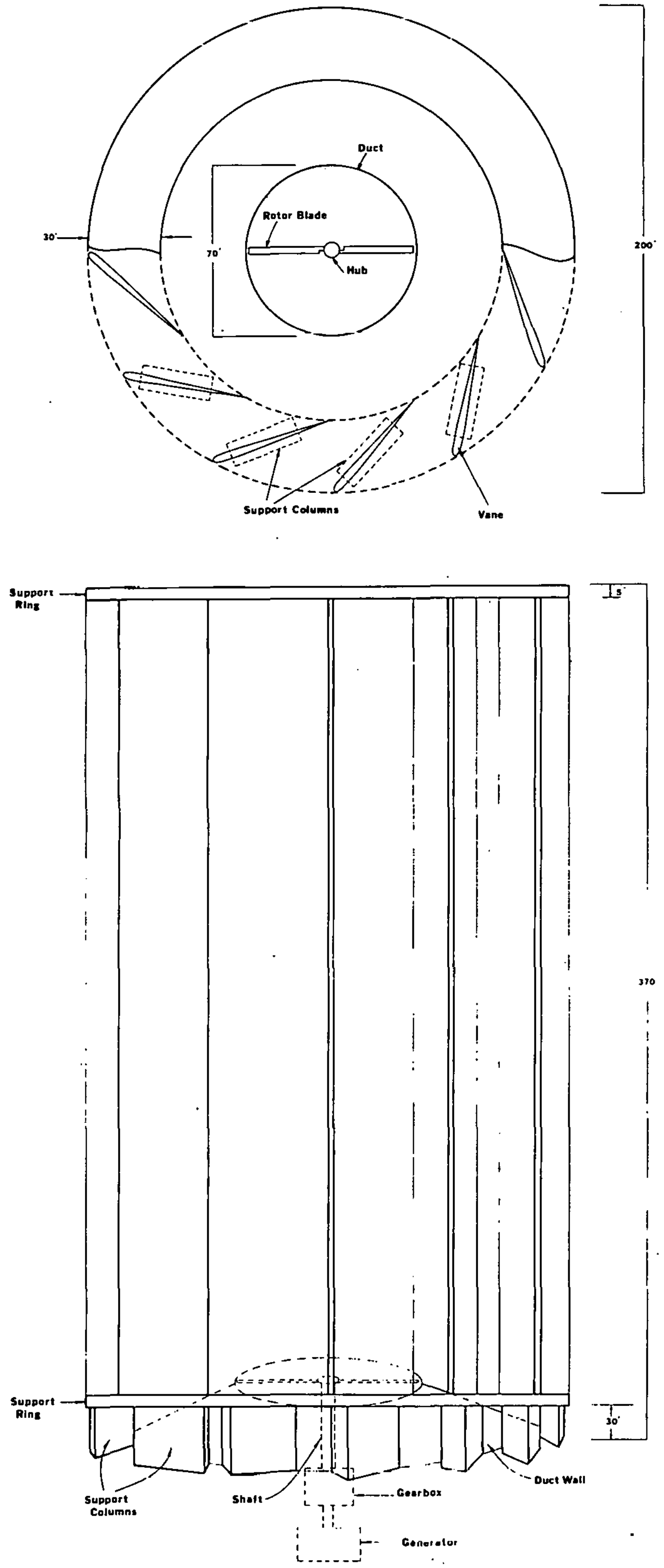

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TABLE 3 STRUCTURAL CHARACTERISTICS OF TWO TWES TOWER DESIGN CONCEPTS: 1 MW BASELINE CASE

	First Concept (Parabolic Vanes)	Second Concept[1] (Wing-Like Vanes)
VANES		
Number	12	12
Length (m)	103	103
Thickness (m)	3	1.2 to 1.8
Cross-Sectional Area (m^2)	27.3	19.3 to 28.8
Total Weight (10^6 kg)	81.8	57.3 to 86.3
SUPPORT COLUMNS		
Number	12	12
Dimensions (m)	4.6 x 3.0	9.1 x 3.0
Total Weight (10^6 kg)	3.6	7.7
SUPPORT RINGS		
Number	2	2
Total Weight (10^6 kg)	6.8	3.3 to 5.5
TOTAL TOWER WEIGHT (10^6 kg)	92.2	68.7 to 99.5

1. Where ranges are given the minimum value is associated with minimum usage of steel reinforcing rods allowed by the American Concrete Institute (ACI) specifications. The maximum value is associated with "good design practice," allowing for reasonable safety factors.

TABLE 4 MATURE PRODUCT TWES COST ESTIMATE:[1,2] 1 MW BASELINE CASE

	Cost (Million Dollars)
Tower	2.14 to 3.10
Generator, Rotor, Duct, Transmission	0.13
Total Hardware Costs	2.27 to 3.23
Non-Hardware Costs[3]	0.91 to 1.29
TOTAL INSTALLED COST	3.18 to 4.52

1. Foundation and site acquisition costs not included.
2. All costs in 1979 dollars.
3. Taken to be 40 percent of total hardware costs. Includes site preparation, TWES assembly, installation and checkout, general and administrative expenses, contractors' fees, etc.

FIGURE 4

TOTAL INSTALLED MATURE PRODUCT TWES COSTS

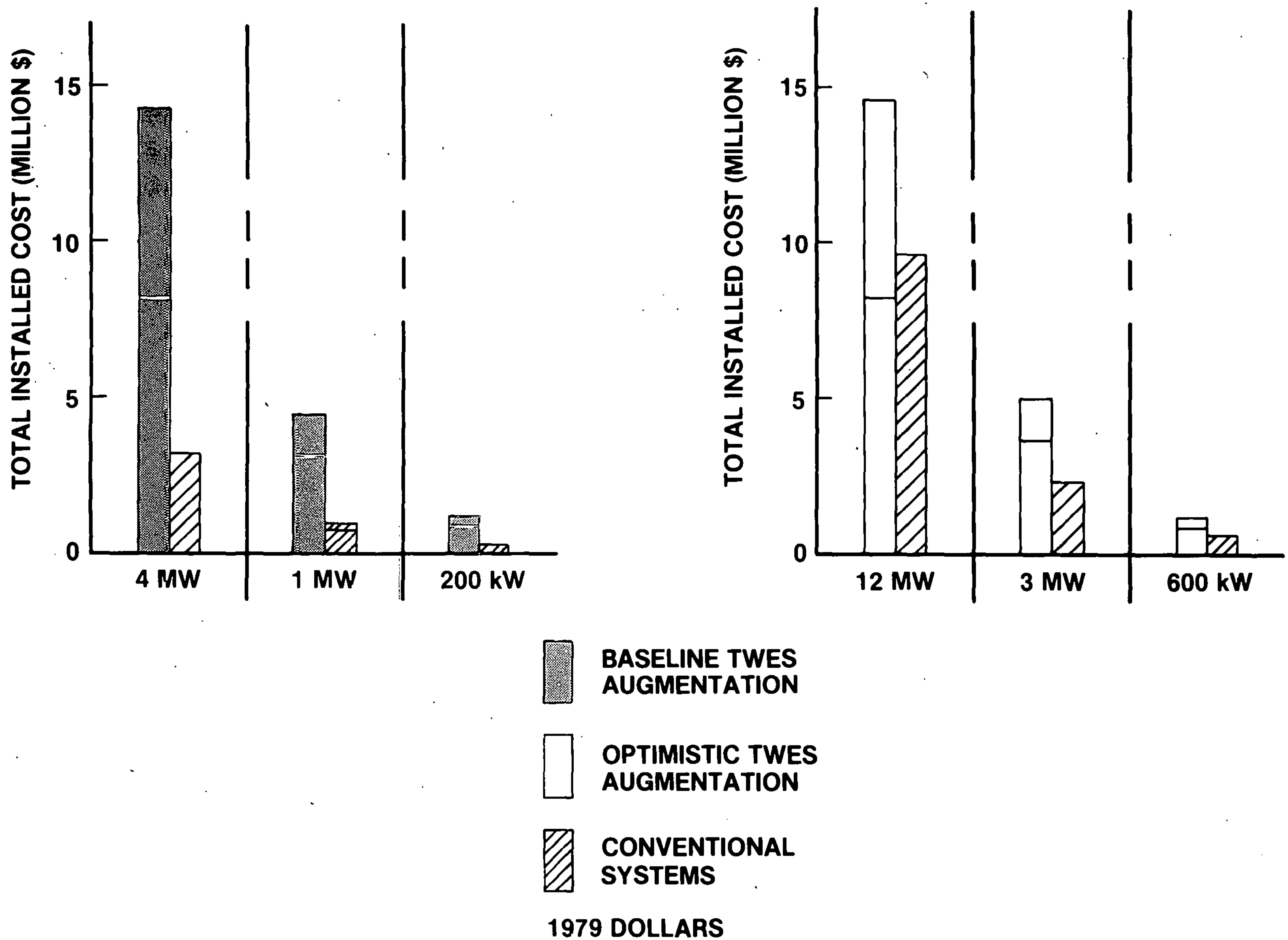


Figure 5 presents the energy cost comparison for the TWES and the competing conventional systems at an annual mean wind speed of 5.4 m/s (12 mph). In only one case (the 12 MW size with optimistic TWES augmentation) is the TWES energy cost comparable to that of the conventional horizontal axis counterpart (5 to 8 cents/kWh vs 7 cents/kWh). However, this apparently favorable comparison for the TWES is misleading because:

- Significant additional cost for the foundation was not included in the TWES cost estimate;
- The energy cost quoted for the conventional wind system at $\bar{V}$ = 5.4 m/s (12 mph) was for a system optimally designed for a higher wind speed regime. If a conventional wind system, optimally designed for $\bar{V}$ = 5.4 m/s (12 mph) were available, its mature product energy cost would likely be less than 7 cents/kWh.
- There is no experimental evidence available to support the contention that the optimistic TWES augmentation ratio could be attained.
- There are many technical uncertainties (dealing especially with the TWES flow regime) awaiting resolution before TWES technical feasibility can be assured.

Therefore, it appears that even if the technical issues and uncertainties relating to the Tornado Wind Energy System are satisfactorily resolved, the TWES cannot be economically competitive with comparably-sized conventional wind energy systems.

VORTEX AUGMENTOR CONCEPT

The VAC uses aerodynamic design techniques, similar to those typically used in the design of supersonic aircraft, to concentrate the natural winds. The "augmentor" of the VAC is a triangular (or delta) aerodynamic surface configuration (see Figure 6). This surface has a sharp leading edge which, when directed into the wind at an appropriately selected angle of attack, causes the oncoming natural wind flow to separate from the surface. It is this flow separation which leads to the production of vortices. The VAC concept incorporates two rotors because the delta surface produces two identical vortices rotating axially in opposite directions along each edge. The VAC output is defined by the strength and velocity of the vortices. The vortex characteristics and the VAC power output are a function of the angle of attack of the augmentor surface.

There are some technical uncertainties associated with VAC operation especially relating to vortex breakdown, structural and aeroelastic considerations and potential drag problems. Resolution of these uncertainties awaits the analysis of field test data which is currently being gathered.

FIGURE 5

MATURE PRODUCT TWES ENERGY COSTS

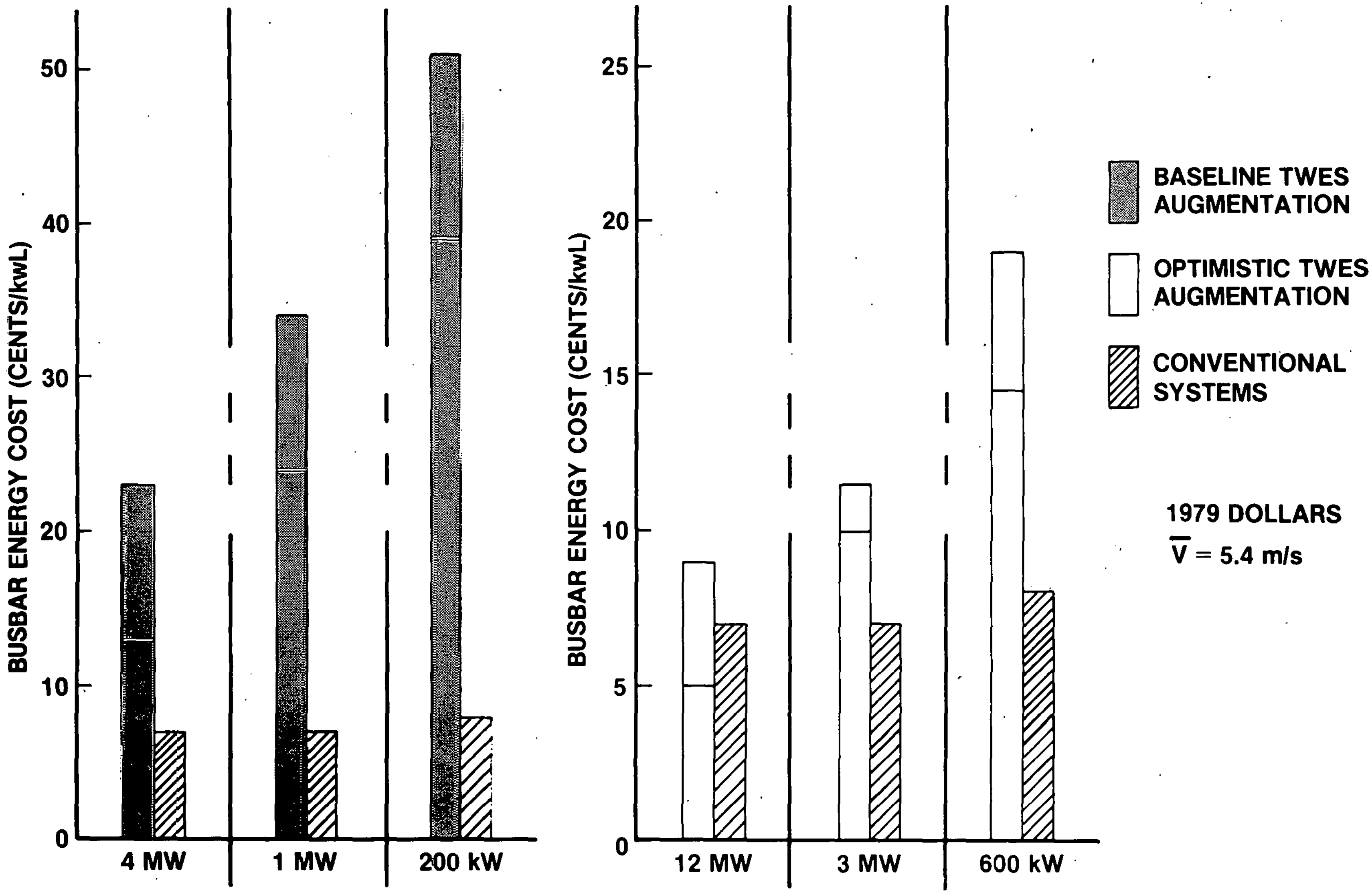
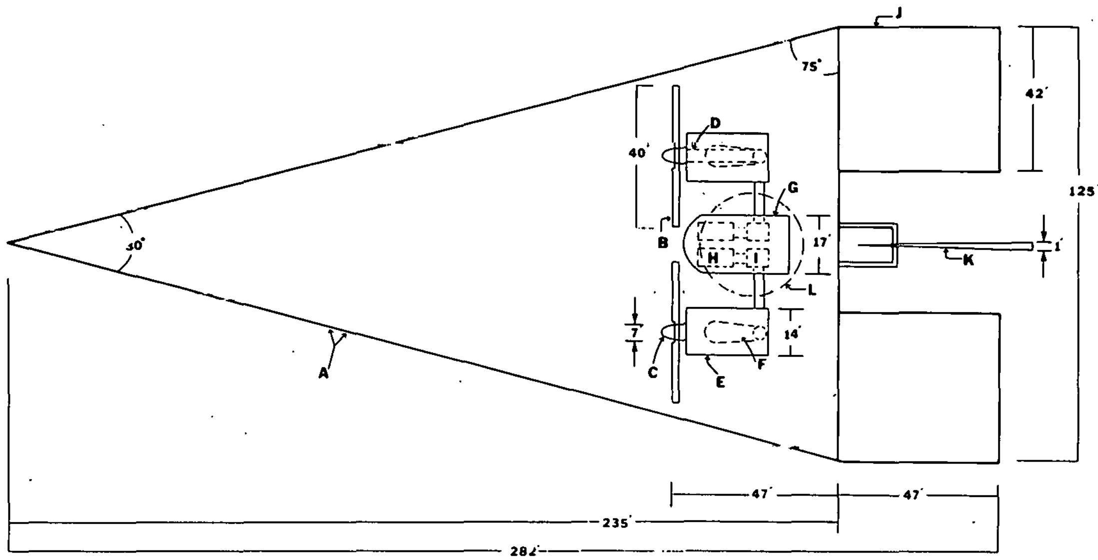
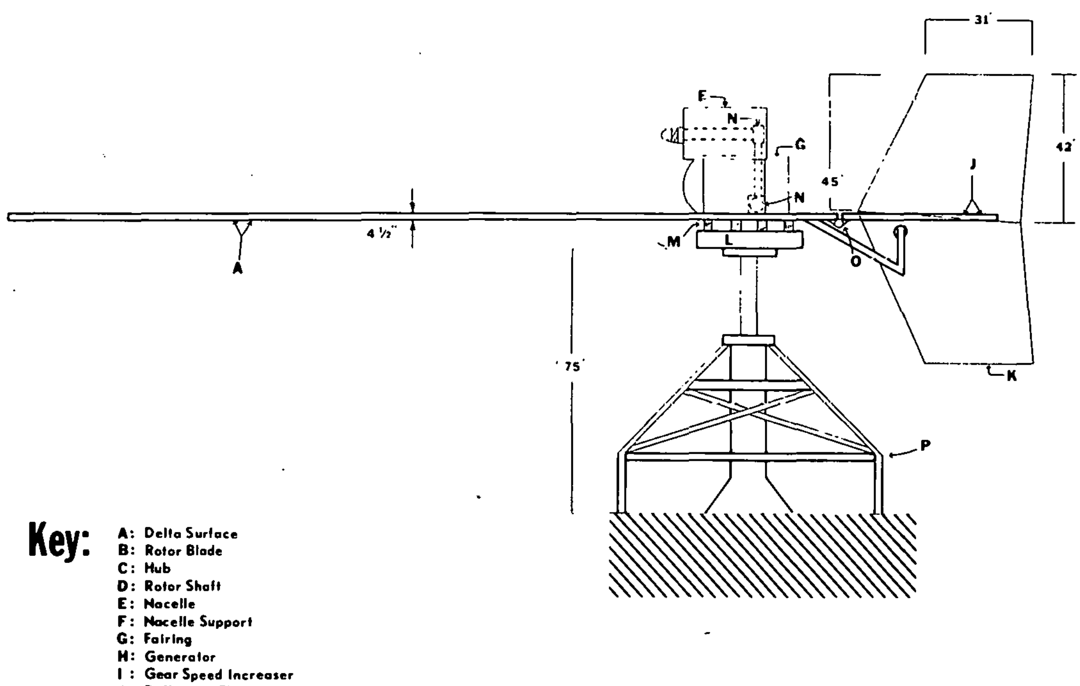


FIGURE 6

CONCEPTUAL VORTEX AUGMENTED WIND ENERGY SYSTEM

Base Case Design





Key:

- A: Delta Surface
- B: Rotor Blade
- C: Hub
- D: Rotor Shaft
- E: Nacelle
- F: Nacelle Support
- G: Fairing
- H: Generator
- I: Gear Speed Increaser
- J: Deflecting Flap
- K: Vertical Tail
- L: Bedplate
- M: Springs
- N: Vertical Right Angle Gearbox
- O: Hinge
- P: Tower

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A structural and cost analysis for a baseline mature product VAC (200 kW rated power) was carried out. The weight and cost for the baseline case is given in Table 5. The baseline 200 kW VAC is estimated to have a total weight of 959,000 kg (2.1 million lb) above the foundation and to have a total installed cost of $924,000. This cost estimate includes a prestressed concrete tower and a concrete foundation assumed to be equal in weight to the weight it supports. Since it is likely that the foundation weight would be several times the weight that it supports in any practical installation, the baseline VAC cost estimate is likely understated to some extent.

A similar analysis was undertaken for all of the VAC cases specified in Table 2. The estimated installed mature product VAC costs as a function of power output and augmentation ratio are shown in Figure 7. Under baseline augmentation assumptions, the mature product VAC would have installed capital costs that are much greater than comparable conventional wind systems over the entire size range considered.

Under optimisitc augmentation assumptions, the installed mature product VAC costs are still greater than conventional wind system costs in all cases. The closest to comparability is the 1 MW size where the VAC is about 30 to 60 percent more costly.

The major cost drivers for the VAC with baseline augmentation are the tower, the transmission subsystem (including two gear drives and four large shafts) and the augmentor (delta) surface. In the optimistic augmentation cases, a much smaller augmentor surface is needed to produce the same power output thereby lessening the augmentor surface cost considerably.

Figure 8 presents the energy cost comparison for the VAC and the competing conventional systems at an annual mean wind speed of 5.4 m/s (12 mph). In none of the cases considered does the VAC energy cost compare favorably with that of the conventional horizontal axis counterpart. The inability of the VAC to be economically competitive is especially striking since:

- o The weight and cost of the VAC foundation are likely to be higher than the values assumed.
- o The energy cost quoted for the conventional wind systems are not for systems optimized for operation at $\bar{V}$ = 5.4 m/s (12 mph). If such systems were available, it is likely that the conventional system mature product energy cost would be lower than the values quoted.
- o There is no experimental evidence available to support the contention that the optimistic VAC augmentation ratio could be attained.

TABLE 5 WEIGHT AND COST ESTIMATE[1] FOR 200 kW BASELINE VORTEX AUGMENTOR SYSTEM

Major Component	Weight (10^3 kg)	Total Fabrication Cost (Thousands of Dollars)
Rotor (4 blades, 2 hubs)	5.5	22.0
Augmentor Surface	167.2	130.0
Deflecting Flap	20.9	14.0
Vertical Tail	17.7	12.0
Fairing	4.5	3.0
Transmission (2 Gear Drives and 4 Shafts)	12.7	143.0
Generators (2 @100 kW)	1.1	9.5
Industrial Springs (9)	3.3	5.1
Bedplate	6.8	6.0
TOTAL ON TOP OF TOWER	239.7	344.6
Tower (Reinforced Concrete)	719.3	240.0
TOTAL HARDWARE	959.0	584.6
Foundation	959.0[1]	105.5[2]
Non-Hardware Costs	---	233.9
TOTAL		924.0

1. All costs in 1979 Dollars; site acquisition costs not included.
2. Foundation cost is $0.11/kg; actual foundation weight would likely be several times the total hardware weight. Estimated weight given is minimum under any circumstances.

Source: Boeing Engineering and Construction Company.

FIGURE 7

TOTAL INSTALLED MATURE PRODUCT VAC COSTS

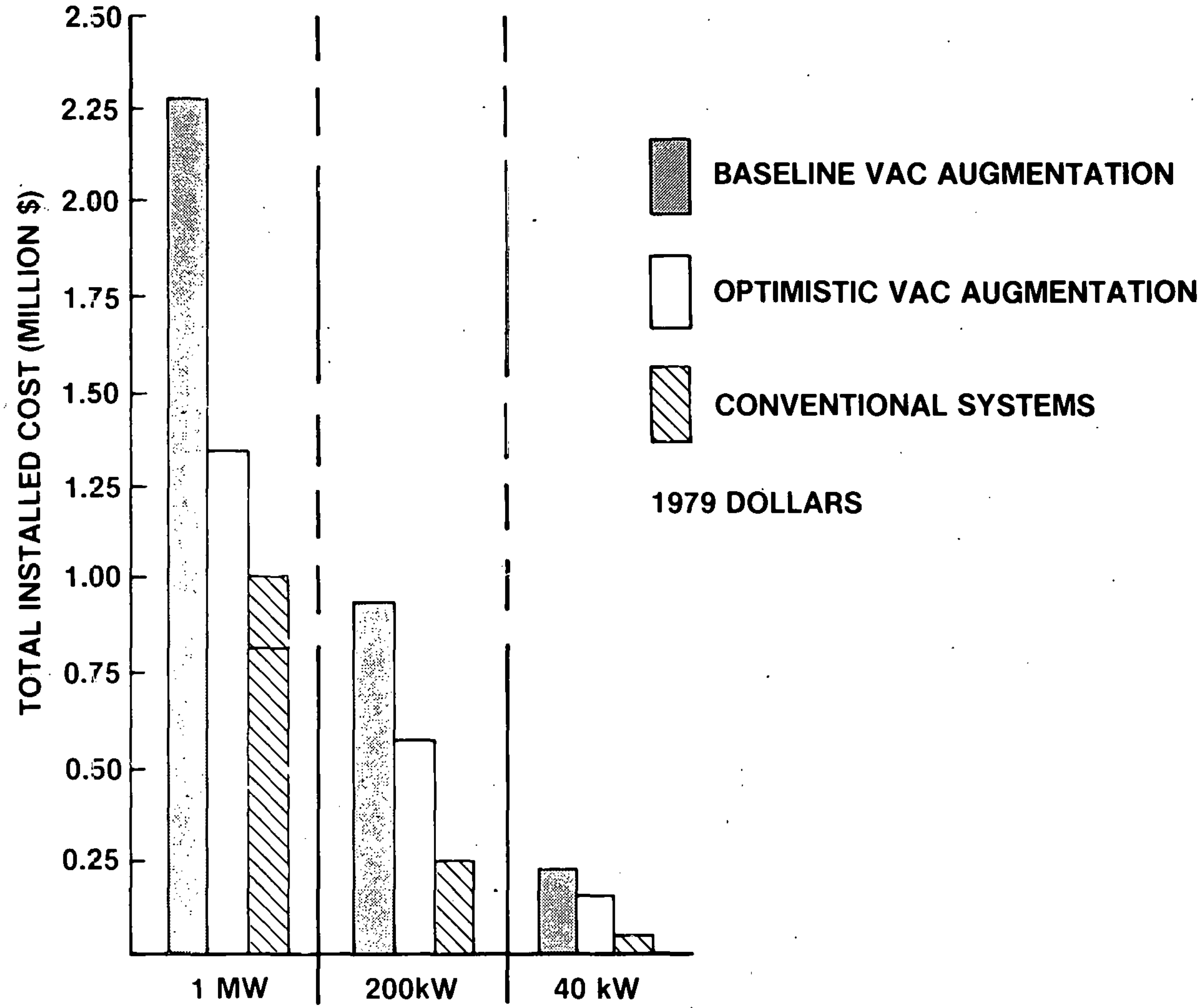
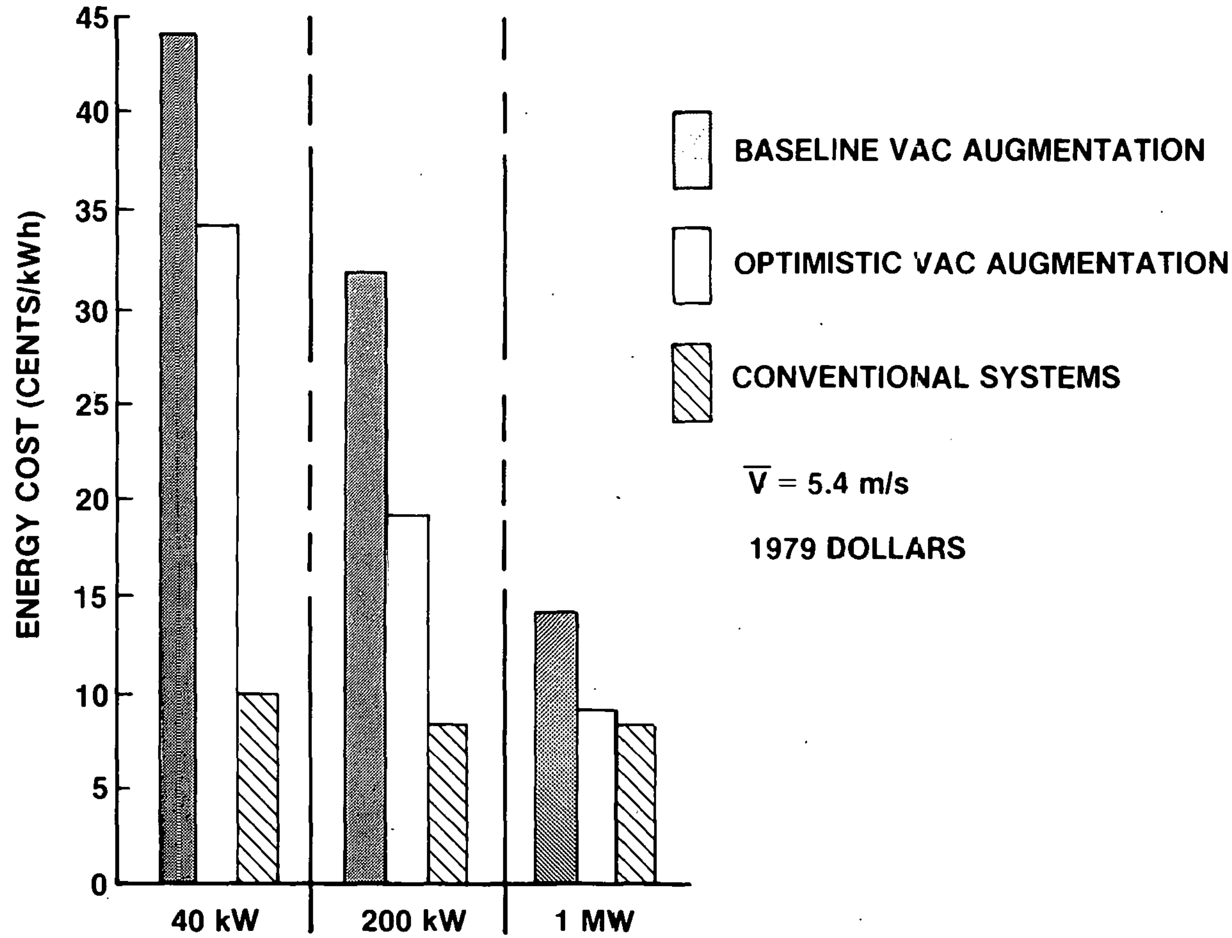


FIGURE 8

MATURE PRODUCT VAC ENERGY COSTS



SUMMARY

The rotor subsystem represents one of the major cost drivers in conventional wind energy systems. Despite the fact that the two vortex extraction systems evaluated have the potential for substantially reducing rotor costs, these cost savings are more than offset by the additional costs required for the augmentation devices and other system features. Therefore, based on a preliminary analysis of the presently envisioned conceptual designs of the Tornado Wind Energy System and the Vortex Augmentor System, it does not appear that either system could achieve economic parity with conventional horizontal axis wind systems even if all of the technical uncertainties surrounding these innovative concepts are favorably resolved.

ACKNOWLEDGEMENTS

The authors would like to express their sincere appreciation to Dr. T.G. Toridis and Dr. K. Khozeimeh, Professors of Civil Engineering at the George Washington University, who performed the structural analyses of the Tornado Wind Energy System configurations, and to Dr. Daniel Schiff who also served as a consultant on this project. In addition, many vendors and material suppliers willingly supplied current price quotations so that the most up-to-date economic analysis could be carried out. Their contributions to this study are greatly appreciated.

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FIELD TESTING THE VORTEX AUGMENTOR CONCEPT

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ABSTRACT

The Vortex Augmentor Concept (patented) for wind energy conversion involves the generation and control of discrete vortices of high power density by appropriate interaction of aerodynamic surfaces with natural winds of low power density. Suitably designed turbines are used to extract the energy from this compacted vortex field. The foundations and laboratory investigations of this concept have been described elsewhere. This report concerns the field test of a large-scale VAC model. Here we present the details of a wind data network, the prototype instrumentation, the data acquisition and processing system, the results of the field tests of system performance, the comparisons to theoretical predictions, and a discussion of the problems associated with field testing as well as recommendations for further research based upon the experience gained in the present program.

THE VORTEX AUGMENTOR CONCEPT

Under certain predictable conditions vortices appear in a flowing fluid. They are real manifestations of an idealized whirling flow field in which the velocity follows circular streamlines with a magnitude inversely proportional to distance from the center of rotation. Vortices are effective as energy storers since they allow, in a sense, an additional degree of freedom, that of rotation, to an originally uniformly translating flow. The thrust of the present work is to utilize the unusual aerodynamic characteristics of vortices to develop improved wind energy conversion systems.

The keystone here is the generation and control of discrete vortices of high power density by appropriate interaction of aerodynamic surfaces with natural winds of relatively low power density. Suitably designed turbines are used to extract energy from this compacted vortex field. This idea developed by the senior author, is termed the Vortex Augmentor Concept (VAC).

The basic effect of the VAC is that of an aerodynamic "lens"; the augmentor surface tends to focus much of the kinetic energy of the oncoming natural wind into compact vortices. In this way it is possible to utilize much smaller and therefore more economical rotors than would be possible without the Vortex Augmentor surface. The evolution of this concept and the various theoretical and laboratory-scale experimental investigations which have been performed in support of the concept are presented in [1-4].

The present study is concerned with a further experimental evaluation of the concept: a field test program on a large-scale prototype Vortex Augmentor. In such an investigation the prototype must function as a unit and must be properly instrumented and controlled. Furthermore, the nature of the field test implies testing in a highly variable wind environment, which in turn necessitates extensive data management capabilities. Here we present a description of a field test facility and VAC prototype capable of meeting the stringent requirements posed by outdoor testing, and report results of such experiments.

THE FIELD TEST STATION

Since flow power and aerodynamic loading are non-linear functions of wind velocity and direction it is most important to accurately acquire such data. The winds are turbulent however, and the velocity varies with both time and space which adds appreciably to the complexity of the problem [5]. It seems clear that sufficient wind data be taken such that spatial correlations of wind velocity can be obtained, that reasonable estimates of wind momentum and energy flux be made over a region of characteristic length several times greater than that of the test model, and that correlations of some set of pertinent wind factors with a set of observed system factors be achieved. Other considerations will arise as experience with the interacting wind-test model system is developed, as in the case of wind-aircraft interactions [6].

To achieve this capability it was considered desirable to establish a wind data network around a field test location and to develop methods, utilizing computer techniques to render useful the data obtained in this "uncontrolled atmospheric wind tunnel". This network has the form of an array of 4 towers, instrumented at 3 different levels, laid out in a circle centered on the test site. All the data is monitored and processed by a mini-computer located in a control center which is remote from the test area. This data is then utilized in various codes in order to determine the factors of interest at the test site.

The test site is located on Polytechnic's Farmingdale campus; the site plan is shown in Figure 1. This site is a large open area, adjacent to Republic general aviation airport. The test circle for the net of wind sensor masts has

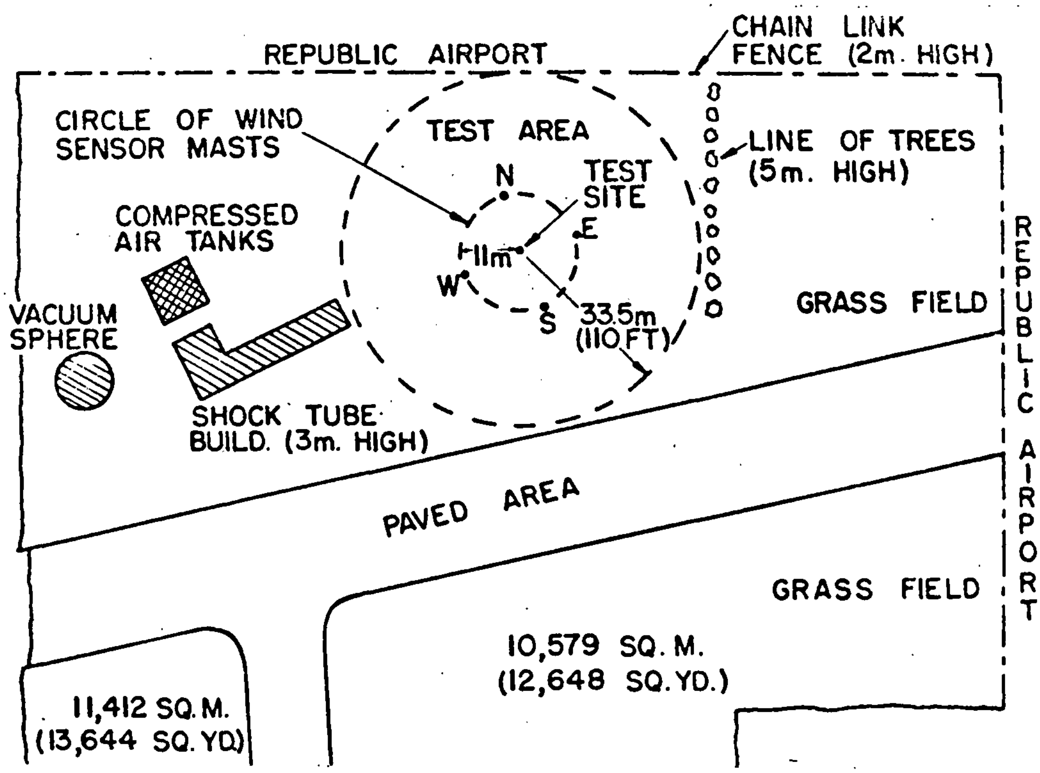

FIGURE 1 SITE PLAN OF THE FIELD TEST AREA

a radius of 11 meters; this dimension was established with the intent of extracting data at points within several characteristic lengths of probable test models. The four masts are located at the cardinal points of the compass and each carries 3 wind speed and direction units, one set at heights of 3, 5, and 7 meters above the ground. With this network it is possible, with appropriate data processing, to study vertical gradients and correlations, horizontal gradients and correlations, wind energy flux through the test site, etc. Wind sensors used are Weathermeasure W121-SD speed and direction indicators. The wind speed and direction outputs are processed by signal conditioning units developed by us and the units were calibrated in the Polytechnic Environmental Wind Tunnel, which has been described elsewhere [3].

The wind sensing network is connected by cable to the control center where all data acquisition and processing is performed. Signal conditioning units for the 24 channels of wind speed and direction data (6 channels per mast) were designed and developed in-house for preparing the sensor outputs for processing. These units convert the AC and DC signals from the sensor into low level DC signals that are compatible with the recording equipment.

The recording and processing equipment consists of a Digital Equipment Corporation PDP 11/34 mini-computer system with supportive peripherals. These consist of a central processor and memory unit, dual floppy disk drive mass storage system, analog to digital converter real time clock, low speed matrix printer and a high speed graphics CRT terminal with hard-copy capability.

The output from the signal conditioning units is tied directly into the computer's analog to digital converter. Under control of a real time interrupt driver software package, data from the sensors can be obtained at precisely timed intervals. This data is then stored on the floppy disk system and is available for analysis at any time after the completion of the test. In addition, using appropriate software, data can be analyzed and displayed on the CRT graphics unit in real time, giving a picture of test conditions as they develop. This is accomplished simultaneously with the normal storage of data on the mass storage devices.

In order to test successfully in the wind, it is necessary to be able to monitor the wind characteristics accurately. This is achieved by the wind data network of the field test station described previously. Wind data can be displayed on the CRT in real time so that developments during the test are in full view of the operator in the control room. A typical display of average wind speed and intensity on one mast, at two different heights, as taken directly from a hard copy of the CRT image is shown in Figure 2. The averaging time in that record is 10 seconds. With this capability, excellent monitoring and recording of the wind field is achieved. Further details on this wind engineering test facility appear in [7].

THE VAC FIELD TEST PROTOTYPE

Having carried out a great deal of basic research on laboratory scale systems which validated the VAC, consideration was given to development of a prototype for field testing. A simple flat plate delta configuration (75° sweepback, 5.6 m long) was chosen, primarily for ease of construction and availability of a fairly complete experimental data base; details of construction are described in [1]-[3]. Performance is monitored by means of a dynamometer contained within a nacelle as shown in Figure 3. The dynamometer consists of torqumeter and tachometer coupled to an electrically activated friction brake. The second nacelle contains a similar brake and a tachometer; therefore power from only one side of the system can be measured. The

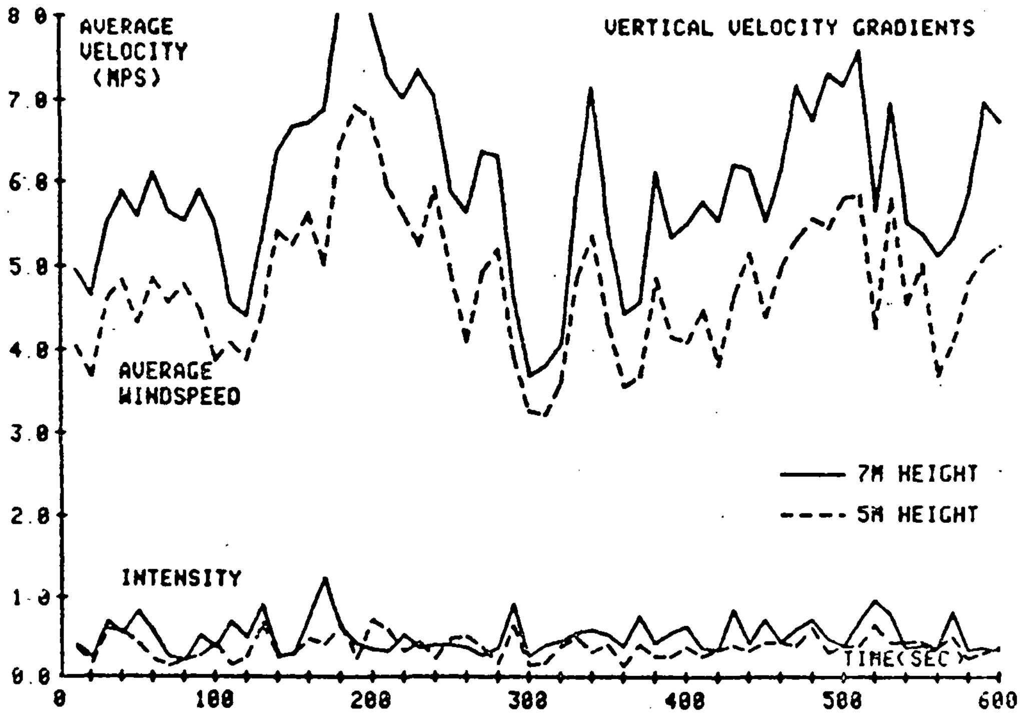

FIGURE 2 WIND SPEED AND INTENSITY IN M/S FOR TWO HEIGHTS ON A SINGLE WIND SENSOR MAST

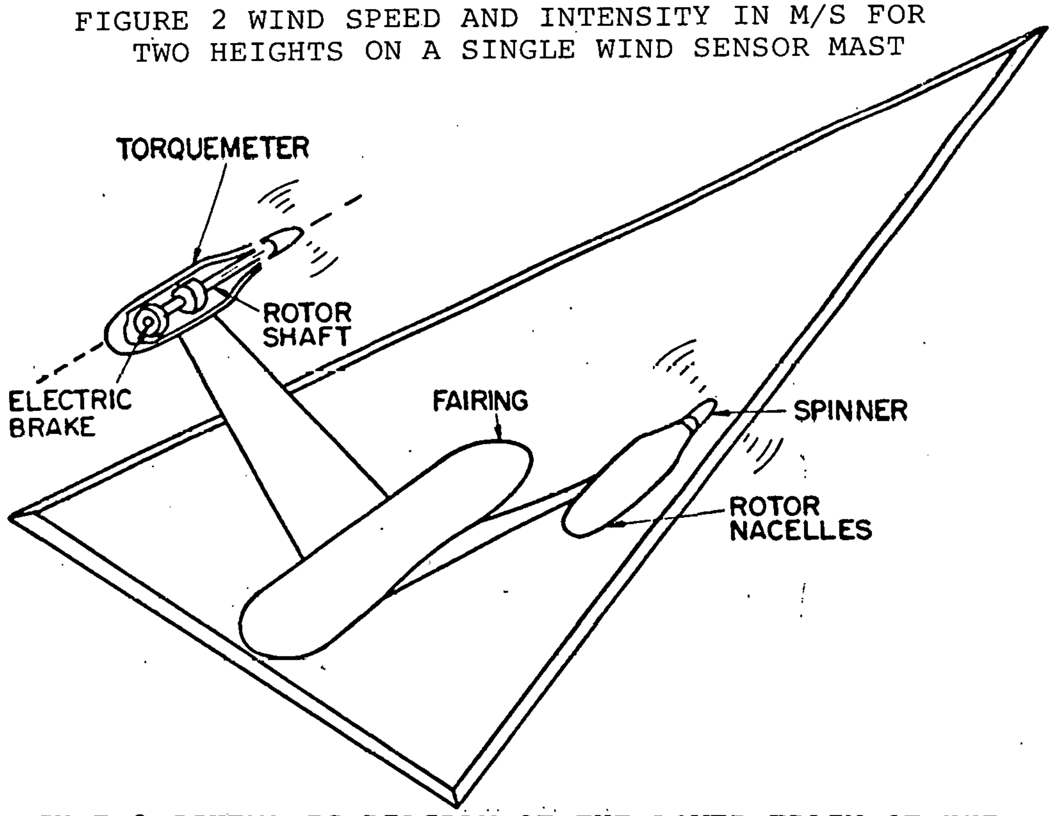

FIGURE 3 SCHEMATIC DIAGRAM OF THE POWER TRAIN OF THE VAC PROTOTYPE

brakes are controlled remotely and data is acquired redundantly, by means of a PDP-11/34 minicomputer as well as analog and digital meters.

Directional control is by aerodynamic means. A vertical fin positioned along the centerline of the vortex augmentor has been designed to provide a characteristic time response of less than 30 seconds to small changes in wind direction. Since this fin lies between the two rotors it will not be adversely affected by their wakes; indeed wind tunnel tests indicate that the velocity in the vicinity of the centerline is on the order of 20% greater than the undisturbed wind speed. The tower which supports the vortex augmentor system is of open truss type construction and is fashioned from welded angle iron. Due to various requirements including hangaring of the complete system, this research tower is quite small, roughly 3m high. In addition, it is mobile, as it rests on a four wheel carriage with steerable wheels and a tow bar. Follow-on systems, for developmental studies, will use higher towers.

A photograph of the complete prototype during field testing is shown in Figure 4. The various components described above are readily seen therein. The sensor system for the field test prototype is shown schematically in Figure 5. The flap system that is shown has been constructed but has not yet been used. As depicted in the diagram, all sensors are tied into the central computer for recording and processing. This system is operational and testing with the complete diagnostic unit is presently being performed. The basic measurements will include correlations between wind characteristics and system variables such as power and rotational speed.

ROTOR TESTING

A simple blade element theory (see, for example, [8] has been modified for use in rotor design in the present program. This approach relies upon detailed velocity measurements in the vortex. The adequacy of such analytic methods is unclear, particularly for the advanced systems considered here and experiments on rotor performance are performed to aid in this assessment. Laboratory experiments on model rotors are conducted in the Rotor Test Facility (RTF)which is described in [3] and [9], in order to determine rotor power generation characteristics and to optimize rotor design for the field experiments.

The 1.5m diameter air jet produced by the RTF has been calibrated for velocity in the case of uniform exit flow. This was performed with the aid of a large (1.5m long), 25 tube impact probe rake and an MKS Baratron pressure transducer. Measurements were taken at the node points of a

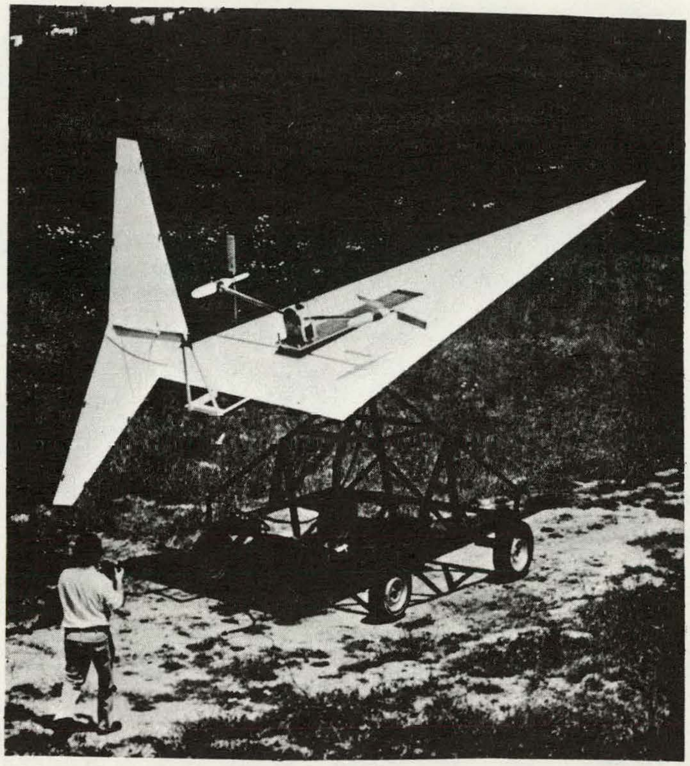

FIGURE 4 VAC PROTOTYPE DURING INITIAL POWER TESTING IN THE FIELD

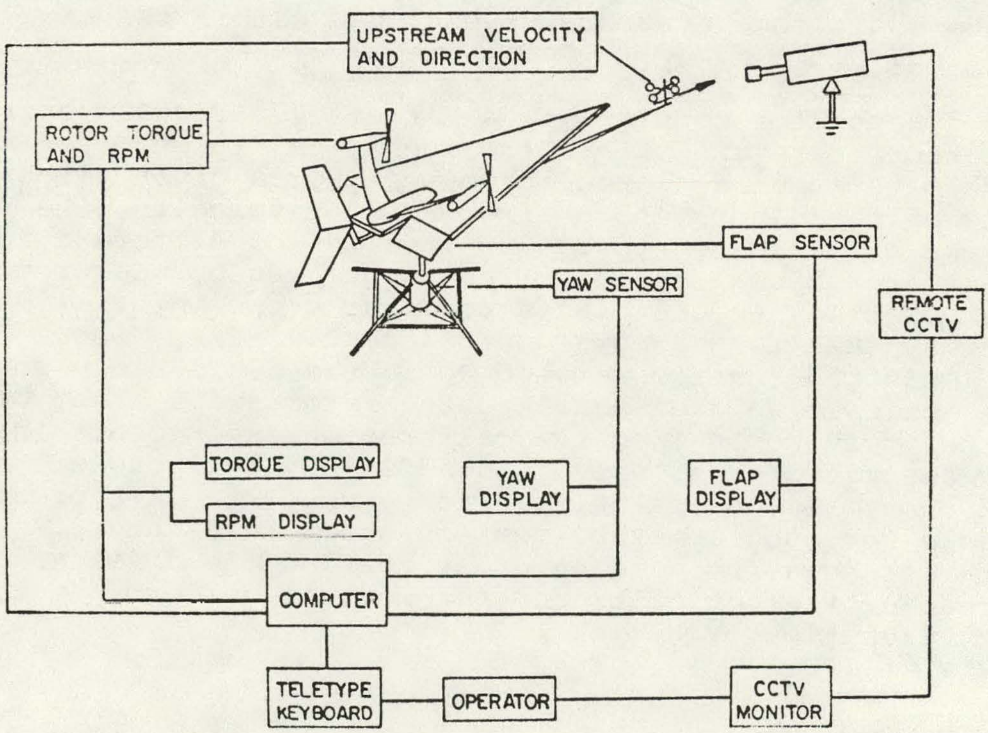

FIGURE 5 SCHEMATIC DIAGRAM OF THE VAC PROTOTYPE SENSOR SYSTEM FOR FIELD TESTS

grid in the plane normal to the jet exit. The grid spanned the entire diameter of the jet with a square mesh 5.85cm on a side. On the order of 500 data points for a given axial location were collected; integration of the point values of $1/2\rho\overline{V}^3$ over a given area of the profile yields the total kinetic energy flux, or power, passing through that area. The power available at a station one diameter downstream of the jet exit was evaluated for three different exit velocities. Since the jet profile at the measurement station has variations in velocity of $\pm 8\%$, an average velocity over a given circular area was determined from the integrated power, $P=1/2\rho A\overline{V}^3$. This average velocity was then correlated to the wind tunnel pressure setting to provide a datum for carrying out rotor power tests at known free stream power levels. Thus, a given tunnel pressure setting produces a certain power density in the RTF jet flow field; the efficiency of various rotor designs can therein be tested.

Model rotor blades are constructed of laminated pine with an imbedded collar at the roots; the hub is made of steel with projecting stub shafts which mate to the collars on the blades. Set screws in the collar which seat in grooves in the stub shafts provide for pitch angle adjustments and for safety in blade retention. The model rotor used is a full-scale version for use in the field test prototype and measures 0.92m in diameter. For the experiments in the RTF it is mounted on the same support apparatus used in the field experiments. Rotor torque is transmitted by the drive shaft to a dynamometer enclosed within the nacelle fairing.

The dynamometer consists of a Warner electrically operated friction brake and an electro-mechanical torquemeter and tachometer unit designed in-house. For a given pitch setting of the blades and a fixed RTF jet velocity, the rotor may be brake-loaded to run at a series of different, constant, rotational speeds. The torque can be measured and the power may be calculated from the known information. One may then form a power coefficient $C_p=P/P_a$, where P is the measured shaft power and P_a is the available power in the jet over an area equal to the rotor swept area. This latter term comes from the calibration experiments in the RTF described previously. In addition, a tip speed ratio, $\omega r/\overline{V}$, may also be calculated for each test. A typical result for such an experiment is shown in Figure 6. The data is shown for a measurement station one diameter downstream of the jet exit, and for several uniform, average jet velocities, $\overline{V}$.

FIELD TESTING

The VAC prototype with its associated instrumentation has been tested in the field test facility described previously

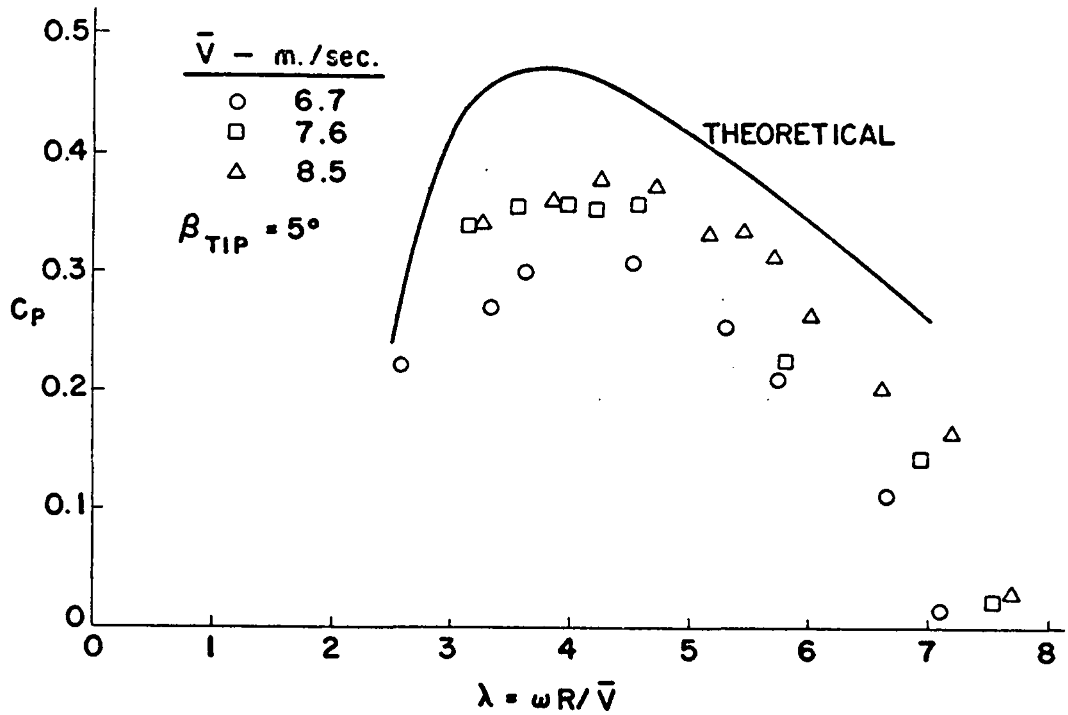

FIGURE 6 POWER COEFFICIENT VS. TIP SPEED RATIO
FOR PROTOTYPE ROTOR IN UNIFORM FLOW

over the past 8 months, when conditions permitted. It should be noted that, for the research experimentation performed in this study, that such conditions require wind speeds in excess of 6 m/s, temperatures above 0°C, no precipitation, and the proper functioning of all instrumentation and the computer. In addition, all these constraints must be met during regular working days to assure availability of the required personnel. Such a coincidence of events is not met with great frequency, and therefore the seemingly long time period available for testing may be misleading in terms of actual logged run time. We have had the fortune to be able to run a good number of tests and thereby tune the facility and its operations to the point where field testing is reasonably routine.

The basic variables available to us in the test program are angle of attack of the delta surface and tip pitch of the rotor blades, both of which are held constant for any given test run. The rotors may be loaded by either of two methods: fixed setting of the electromagnetic brake or "constant" tip speed operation by manual control of the brake. In the former the brake is set at some fixed condition and the rotor is left free to operate under that load. In the latter case, an operator varies the brake setting while monitoring a panel meter rigged to read an effective tip speed ratio, in an attempt to keep that ratio as constant as pos-

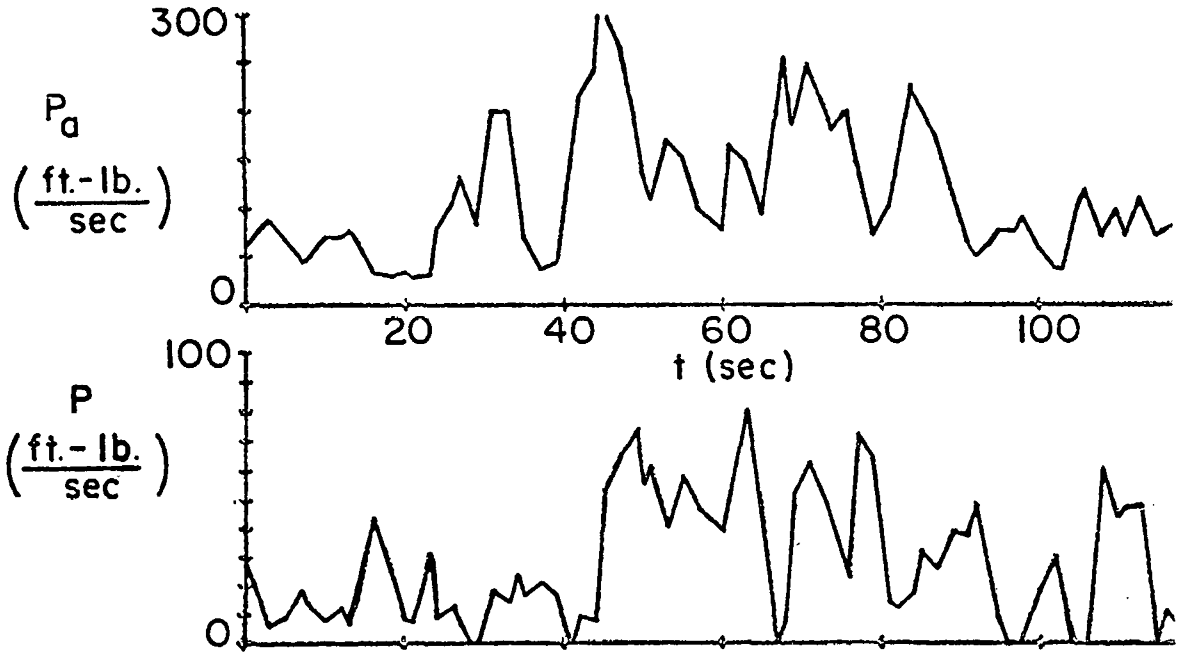

FIGURE 7 TIME VARIATION OF POWER IN THE WIND, P_a, AND POWER AT THE ROTOR, P

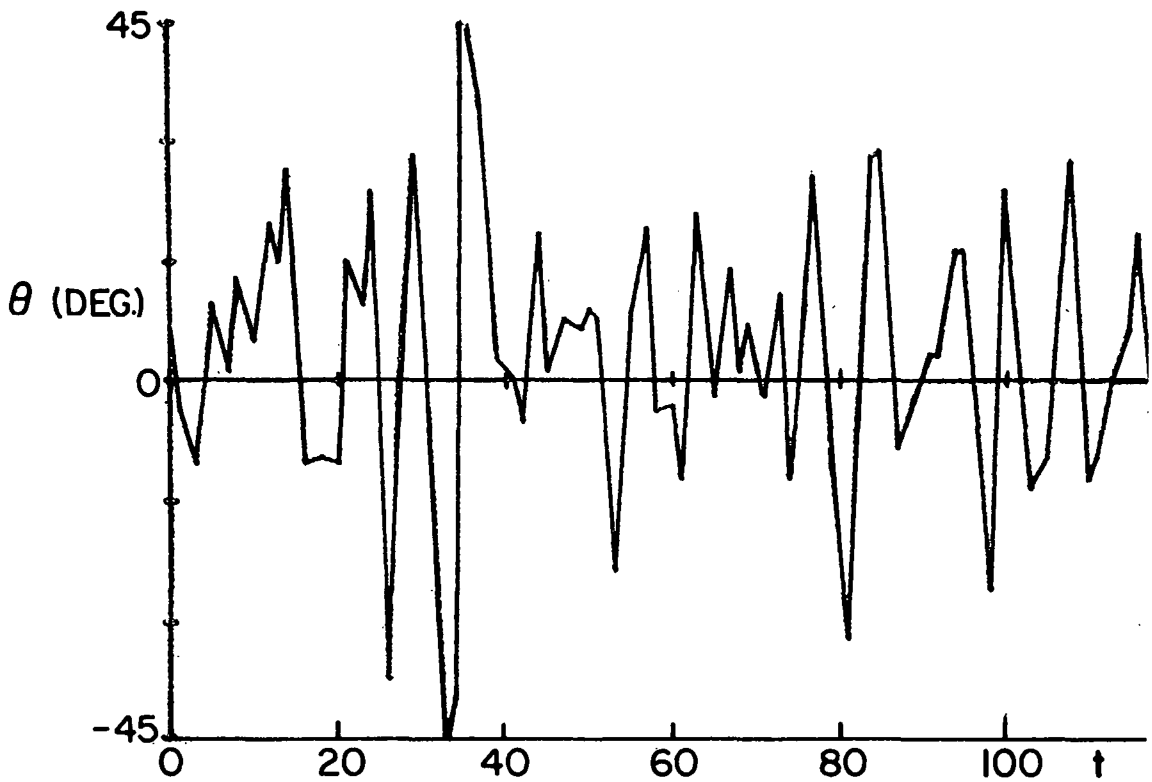

FIGURE 8 TRACE OF ANGULAR FLOW DEVIATION FROM DELTA CENTERLINE VS TIME(SEC)

sible. The basic difficulty with either method is the variability of the wind speed, and in particular the drop of that speed to levels at which the rotor stalls. This effect requires a degree of filtering of the test results to delete the data record where such stalls occur. Our observations during many field tests indicate that the time response of the rotor is so much greater than the characteristic period of the wind variations that the operation of the rotor is nearly always transient rather than steady-state. More detailed studies of wind-rotor interactions of this sort would be of great importance to the field.

The raw data accumulated includes instantaneous measurements of rotor torque, rotor rotational speed, and a reference speed and direction. The reference speed and direction could be that from a sensor, at rotor height, at 0, 1, or 2 delta lengths upstream of the rotor plane. The software permits processing of this data to yield instantaneous values of power (P), rpm (N), power coefficient (C_p), tip speed ratio (λ), angular deviation of flow from delta centerline (θ), etc. A typical trace for instantaneous rotor power P and instantaneous wind power $P_a = \frac{1}{2}\rho\pi R^2 V^3$, where R is rotor radius and V is the reference wind speed, as a function of time during a test run, is shown in Figure 7. The associated record of the angular deviation of the flow is shown in Figure 8. It is evident that the highly turbulent nature of the wind will degrade rotor performance from values predicted by theory or obtained in controlled laboratory experiments. It should be apparent also that instantaneous power coefficients constructed from the data will have wide variations and possess, in themselves, little significance. Clearly more study of the stochastic properties of the wind-rotor interaction and correlation of statistical characteristics of the problem are warranted.

In order to develop a first approximation to the performance of the VAC prototype under different conditions, a time-averaged power coefficient was defined as follows

$$\bar{C}p = \frac{T^{-1}\int_0^T P\,dt}{\frac{1}{2}\rho\pi R^2\left[T^{-1}\int_0^T V\,dt\right]^3}$$

where T is an averaging time suitable for achieving statistical significance; here T typically ranged between 30 and 100 sec. In general, the results for $\bar{C}p$ for $\alpha = 0°$ were not much different than those at high angles of attack $15° \leq \alpha \leq 25°$. A typical case is shown in Fig. 9, where $\bar{C}p$ at $\alpha = 20°$ is approximately 50% higher than at $\alpha = 0°$. It is significant that the results for tip speed ratios in the range $3<\lambda<4$ are superior to those where $4<\lambda<5$. Theoretically, the results should be best at much higher values of λ; indeed, operation at sustained high λ was not possible with the one set of rotors available. It seems apparent that the low tower height in this field test area forces the test rotors to operate in a highly turbulent environment and thus yield $\overline{C}p$ values well below those achieved in the controlled laboratory experiment. In addition, this turbulence, with an integral scale on the order of the characteristic dimensions of terrain and buildings in the area surrounding the test site, precludes establishment of the steady vortex field necessary to provide appreciable augmentation. Tests continue in the hope that at certain times, atmospheric conditions will occur which give reasonably steady wind directions for some useful test time period. The other possibility is to construct a higher tower, or, better still, test at another location, such as the Southampton beachfront on the southeastern shore of Long Island, 50 miles from our present site.

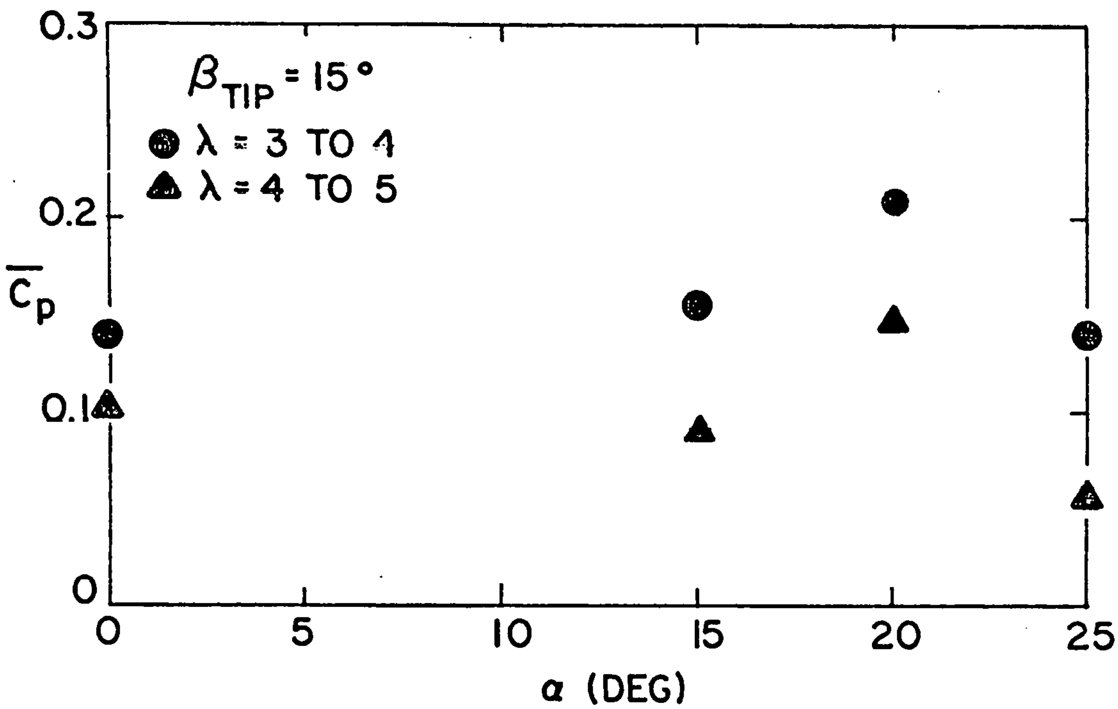

FIGURE 9 MEAN POWER COEFFICIENT VS ANGLE OF ATTACK FOR TIP PITCH β = 15°

CONCLUSIONS

We have developed an operational, well-equipped field test facility for wind energy systems, including extensive data management and processing capability. The difficulties inherent in testing in the uncontrolled wind environment have been learned in practice, and we have been successful in coping with many of them. Such testing can be most fruitful at sites with good wind speed and direction characteristics, although many sites for practical wind turbine generators may not be so blessed, and therefore capabilities developed at the poorer sites, like our own, may be beneficial to the wind energy program.

The VAC prototype did show as much as 50% improvement over the unaugmented mode of operation although this is more attributable to flow velocity enhancement due to the presence of the augmentor surface than to the establishment of the appropriate steady vortex concentrating system in the flow over the delta. This, we feel, is primarily due to high frequency of excursions of the wind direction away from the mean. Motion pictures of the flow above the delta, as visualized by means of a tuft grid normal to the plane of flow, illustrate this effect as rapid movements of the vortex across the tuft grid as the wind direction varies back and forth.

Most design features of the VAC prototype were frozen early on in the program and therefore do not really constitute an optimum configuration, including the rotor blades themselves, of which we have but one pair. Furthermore, a great deal of time was necessarily devoted to the design, construction, calibration and operation of models and associated instrumentation and data processing capability, and only recently has "routine" testing been performed. Much more effort in this experimental arena must be performed in order to incorporate the lessons and techniques learned into the development of a viable VAC wind energy conversion system.

ACKNOWLEDGEMENTS

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AUGMENTED HORIZONTAL AXIS WIND ENERGY SYSTEMS ASSESSMENT

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ABSTRACT

Aerodynamic devices that augment natural winds of low kinetic energy density have the potential for providing a cost-effective energy resource system. Several concepts are discussed in which an augmentor surface is used to increase the mass flow through a turbine, increasing the turbine's power output. Three concepts are assessed. The first is the diffuser augmented wind turbine, in which a diffuser is used to produce a pressure considerably below atmospheric behind the rotor to induce increased flow through the rotor. The second is the vortex augmentor concept, in which the augmentor surface is a highly swept delta wing. This surface creates vortices that concentrate kinetic energy; two turbines are then placed in the vortices to extract this energy. The third concept is the dynamic inducer, in which end plates on a conventional turbine are used to induce increased flow through the rotor.

INTRODUCTION

Because wind is a relatively diffuse energy source, several attempts have been made recently to concentrate this energy. For a conventional wind turbine, the most expensive part of the system is usually the rotor. The idea behind most of the augmentation concepts is therefore to keep the rotor as small and simple as possible, and to obtain a net gain in the power-to-cost ratio. All of the systems to be discussed should work, in that, if properly designed, they will produce power, and probably all of them will produce augmentation; that is, they will produce power greater than an unaugmented system of the same rotor diameter. The central question is whether the augmentation mechanism is cheaper than making the blades and tower of the conventional machine larger to achieve the same energy output per year.

In this paper, technical aspects, performance characteristics, and economic aspects of each system are addressed. A comparison of augmented and conventional systems is made, based on the cost of electricity for each system operating in the same wind environment.

BACKGROUND AND SYSTEM DESCRIPTION

Ducted or Shrouded Turbine Concepts

Work on shrouded turbines, begun in Great Britain in the 1950's, [1] showed that these systems can produce up to twice the power of unshrouded turbines of the same diameter. The first work in the United States was reported at the first national wind energy workshop by

Grumman. [2] Wilson [3] carried out some aerodynamics work on ducted actuators, concluding that they could not be analyzed by any simple method. Work subsequently performed by Ozer Igra in Israel [4] showed an augmentation ratio (power output of the augmented system divided by that of an unaugmented system of the same diameter) of up to four was possible. Grumman has published one report and several papers on its work. [5] [6] [7] The work has concentrated on aerodynamic performance, but includes comparative economics of the diffuser concept compared to conventional systems. A major goal of this research has been to reduce radically the length of the diffuser without sacrificing its performance. The cost of a large shroud would have been prohibitive; the questions now is whether the shorter shroud produces a cost-effective system.

The diffuser-augmented concept is shown in Figure 1. The system consists of a diffuser around a conventional horizontal axis rotor. The diffuser increases the mass flow through the turbine by producing a pressure considerably below atmospheric behind the rotor. The major problem has been to produce a diffuser short enough to be cost effective, but one that does not allow flow separation. Slots are used to introduce external air to energize the diffuser boundary layer. An augmentation ratio (power output of the augmented system compared to an unaugmented system) of about 6 is expected to be achieved with a short diffuser. The diffuser has the effect of quieting flow fluctuations, but whether the short diffuser can avoid flow separation under the influence of fluctuating atmospheric winds remains to be proven.

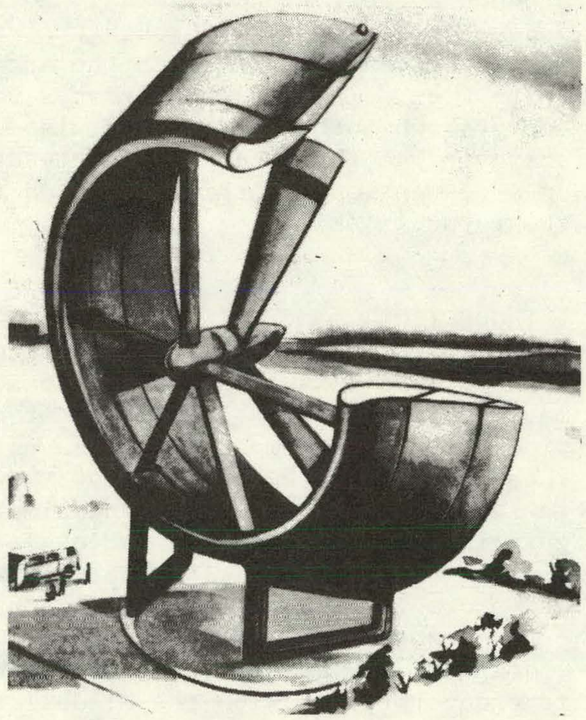


Figure 1. CONCEPTUAL INSTALLATION OF A DIFFUSER AUGMENTED WIND TURBINE

Dynamic Inducer

The dynamic inducer concept can be considered a horizontal axis augmented system since tip vanes are used to try to get some of the same benefits provided by a diffuser system, without the drawbacks of a large duct. The concept was orignated by Van Holten at the Delft Institute of Technology in Holland in 1974. AeroVironment, Inc. tested the concept last year; [8] The work included theoretical work, preliminary engineering estimates of cost/benefits, and field testing of a small system. Augmentation was not achieved during the test program, but Dr. Lissaman continues to believe that it can be achieved with proper design. [9] The dynamic inducer concept is shown in Figure 2. (This figure depicts a test of the tip vane concept on a small 3-bladed conventional wind turbine; larger systems would utilize the tip vanes on conventional 2-bladed systems.)

The dynamic inducer, like the diffuser augmented system, produces power augmentation by inducing increased mass flow through the turbine. The augmentor surface (the tip vanes) is much smaller than the static duct in the diffuser system, but now power is required to drive the tip vanes to overcome their drag.

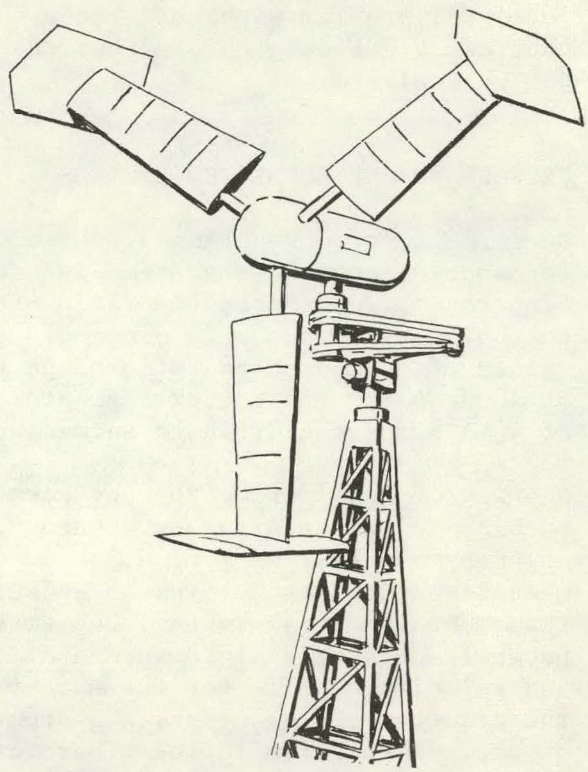
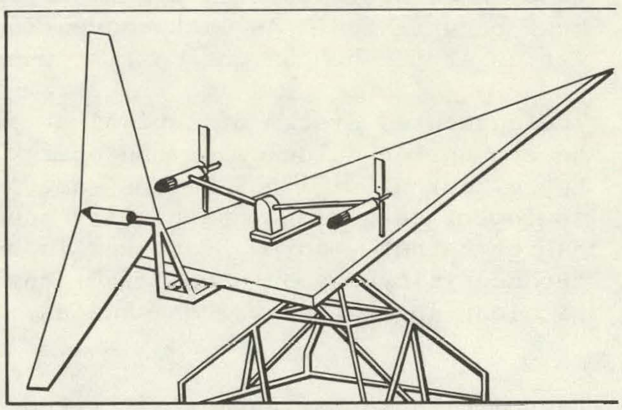


Figure 2. DYNAMIC INDUCER

Vortex Augmentor Concept

Unconfined vortex systems have been examined at both the Polytechnic Institute of New York and West Virginia University. Such systems use wing-like structures to create a vortex. A turbine is then placed in the vortex to extract power. The Polytechnic Institute of New York system is shown in Figure 3. This system uses a horizontal delta wing to create the vortex while West Virginia University used a vertical wing.

Sforza has reported on the Polytechnic Institute of New York project several times. [10] [11] [12] Some data on power as a function of speed was given for a small wind tunnel model, and a prototype for field testing has been constructed, but no data on this prototype has been presented. No cost data on this system has been published. Loth has concluded that the high kinetic energy produced by the vortex is not available for energy extraction by a wind turbine, and therefore West Virginia University has discontinued work on its vortex concept. [13] This concept will therefore not be evaluated in this paper.



Source: U.S. Energy Research and Development Administration, "Vortex Augmentors for Wind Energy Conversion," E(49-18)-2358, December 1976.

Figure 3. VORTEX AUGMENTOR

The vortex augmentor concept, if developed, would allow the use of small rotors, and if a flap on the delta surface were used to control flow, pitch change would not be necessary. Passive yaw control utilizing a vertical stabilizer is also a possibility for cutting cost. A potential problem with this concept is vortex breakdown. If the vortices break down before they reach the turbines, augmentation would not be achieved.

PERFORMANCE OF AUGMENTED SYSTEMS

Performance of conventional systems is discussed in Appendix A. Performance of augmented systems is usually given in terms of an augmentation ratio, defined as the ratio of power output of an augmented system to the power output of a conventional wind turbine of the same diameter. Values of augmentation ratio range from 1.6 for the dynamic inducer, to about 4 for the vortex augmentor concept, to somewhere in the range of 4 to 8 for the diffuser augmented system.

One way of considering the augmentation ratio is to take a conventional turbine and add tip vanes, a shroud, or a delta wing to increase its power by a factor of 1.6, 4, or 4 to 8. Another way to consider augmentation ratio is to find an augmented system with a smaller diameter than a conventional system, but with the same power output. Output power is proportional to augmentation ratio, cross sectional area, and velocity cubed. For the same free stream velocity and power output, the diameter of an augmented system can be smaller by the square root of the augmentation ratio. Therefore, for equivalent power, augmented systems can have rotors as small as 35% of the size of conventional rotors.

To calculate the energy output of augmented systems, the mean wind speed, wind speed distribution, and extrapolation of wind speed with height must be utilized. As with conventional systems, wind speed characteristics at the hub height must be used.

The augmented system of equivalent power to a conventional system can be chosen for calculating the energy output of the augmented system. Energy output will not be the same, however, because cut-in velocity is lower, resulting in a higher capacity factor and therefore a higher energy output. Any differences in hub height will also cause a difference in energy output, a fact that has been ignored by some of the previous augmented systems studies.

Capacity Factor of Augmented Systems

In some of the literature on augmented systems, capacity factor is used to calculate yearly energy output. This has not always been done carefully. One of the equations that has been used for capacity factor is from the work of Justus. [14] This linear relationship was intended to be used only in the range of mean to rated wind speed of 0.4 to 1.[15] Use of this equation beyond its intended limits can result in capacity factors of 100% or greater, which makes no sense in the real world.

This linear approximation for capacity factor has been superceded by a series of tabular values, also developed by Justus. [16] Use of the older linear approximation equation instead of this procedure can cause capacity factor to be overestimated at low values. Figure 4 shows the difference in results between the two methods. At a cut-in to rated speed ratio of 0.5, the results vary very little (bottom two curves). At a lower ratio of cut-in to rated of 0.28 (a typical value for a small conventional wind turbine), the curves differ appreciably (top two curves), especially at low values of capacity factor. The significance for augmented systems is that cut-in velocities are low, so that the choice of methods used for estimating capacity factors is significant.

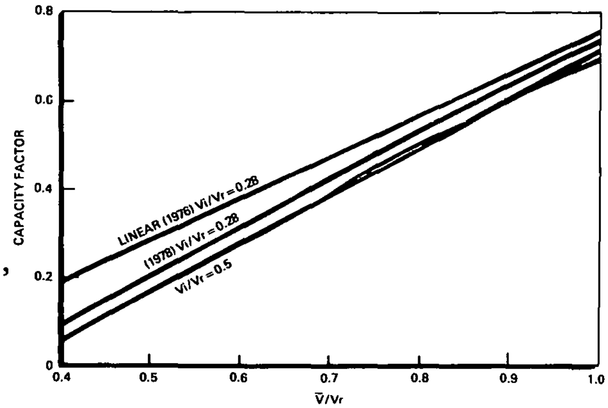


Figure 4. CAPACITY FACTOR

Cut-in speed of an augmented system will be lower than that of a conventional system, so that its capacity factor will be somewhat higher. However, rated speed will not vary significantly. Statements that capacity factors of augmented systems can be twice that of unaugmented systems do not appear warranted. Increases on the order of 10% or less should be expected instead. Similarly, statements that augmented systems can produce 11 to 14 times the energy of the unaugmented systems are not justified.

The Dynamic Inducer

Rated Power

Rated power of the dynamic inducer is a function of rated speed, hub height, rotor diameter, augmentation ratio, and rotor power coefficient. Rotor power coefficient was chosen as 0.36, a typical value for a second generation large horizontal axis turbine. Rated speed for a wind energy conversion system is usually chosen only after a point design for a particular system has been completed. For this project, rated speed is chosen two ways. The first is to choose a reasonable rated speed based on the reference mean wind speed. This allows a general calculation of power as a function of speed. The second way to choose rated speed is to match a conventional system of a specific size. For the first method, rated speed was chosen as 8.9 meters per second (20 miles per hour) at 9.1 meters (30 feet). Rated speed is then 1.67 times mean wind speed at all heights.

Annual Energy Output

Once the power output of the dynamic inducer has been established, it can be combined with the velocity frequency curve (see Appendix A) to calculate annual energy output. The result is shown in Figure 5. Energy output for the augmented system is about 67% higher than for the conventional system for the same rotor diameter because of the augmentation ratio of 1.6, plus another 5% or so because of the lower cut-in speed, which results in a higher capacity factor.

In addition to this general comparison, a comparison to specific conventional systems can be made. A performance comparison of the dynamic inducer and a conventional wind turbine was conducted by Lissaman. [17] The power augmentation factor was assumed to be 1.6 for the dynamic inducer. The two conventional systems chosen for comparison were the 100 Kw MOD-0 and a conceptual 1000 Kw system. The systems chosen were intended to be near optimal design, and were intended to operate in the vortex-synchronous state. This state is one in which induced drag is zero because the tip vane vortex system is self-cancelling in the wake. Several difficulties occurred in attempting to verify and update the AeroVironment work. The 38 m (125 ft.) 100 Kw system was not optimal; 200 Kw is easily achievable with this system. On the other hand, the 8 m/s (18 mph) rated speed given made their 60 m (197 ft.) 1000 Kw system violate the Betz limit, and the rpm given meant it did not satisfy the vortex-synchronous state. The NASA 200 Kw system (MOD-X) has been chosen as the medium size system and the MOD-1 as the large system for performance comparison in this paper.

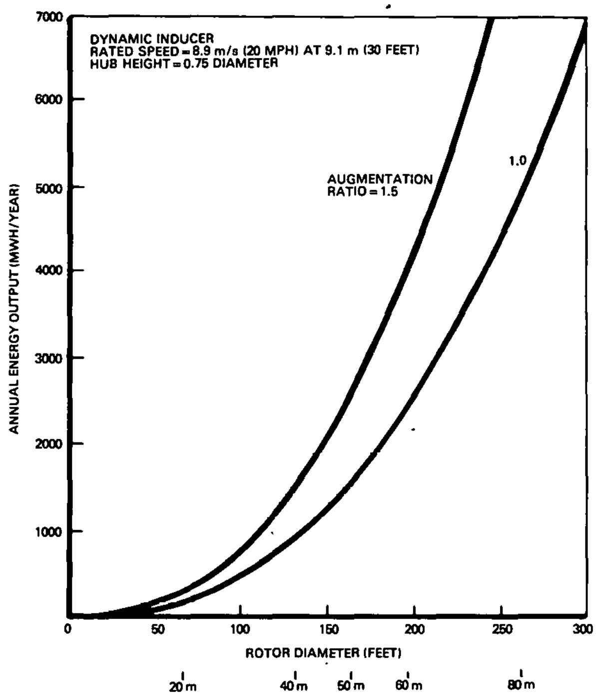


Figure 5. ANNUAL ENERGY OUTPUT OF THE DYNAMIC INDUCER

The conventional 200 Kw system produces about 612,000 Kwh per year for an availability of 0.9. An equivalent dynamic inducer producing the same output power is a machine with a rotor smaller than the conventional system by a factor of the square root of the augmentation ratio of 1.6. This system produces about 588,000 Kwh/yr., or 4% less than the conventional system. This decrease is due to two opposite effects (both neglected by AeroVironment): The decrease in tower height causes a decrease in available power; while the decrease in cut-in velocity increases the capacity factor.

For the larger systems, the MOD-1 produces about 6% less energy per year than the dynamic inducer. In this case, the increased capacity factor caused by the decrease in cut-in velocity has a greater effect than the decreased hub height. However, this increase is partly due to the relatively high cut-in velocity of the MOD-1, a machine designed for a better wind site of 8 m/s (18 mph) at 9.1 m (30 feet), and therefore a poor choice for a 5.4 m/s (12 mph) site.

The Diffuser Augmented Wind Turbine

Rated Power and Annual Energy Output

Grumman has carried out some performance analysis of the diffuser augmentor. [18] In this analysis, variations in hub height were not considered, and the linearized equation for capacity factor was used beyond its intended range. Two conclusions that resulted that do not appear justified are that capacity factor of the augmented system is twice that of a conventional system, and that the annual energy produced by the augmented system can be 11 to 14 times that of an unaugmented system.

In this paper, rated power for the diffuser augmented wind turbine was calculated in the same way as the dynamic inducer for a 8.9 m/s (20 mph) rated speed. The range of output power considered is from about 20 Kw to 200 Kw. Hub height was chosen by using the Grumman design for an 18 foot system, and scaling linearly with rotor diameter. The Grumman Windstream 25, a typical small conventional wind turbine, appropriately scaled up or down, was used as the rotor.

Annual energy output was calculated using the turbine characteristics, an augmentation ratio, and an appropriate velocity frequency curve. The results are shown in Figure 6.

The Vortex Augmentor Concept

Rated Power

Rated power of the vortex augmentor concept depends on the diameter of the two rotors, the power coefficient of the rotors, the hub height, the augmentation ratio, and the free stream velocity. The power coefficient of the rotors was taken as 0.34, a representative value for small simple blades such as those of the Grumman Windstream 25. Rated speed was chosen as 8.9 m/s (20 mph) at 9.1 m (30 feet), a reasonable value for the 5.4 m/s (12 mph) reference mean wind speed. Both the mean wind speed and the rated wind speed then vary the same way with increased height.

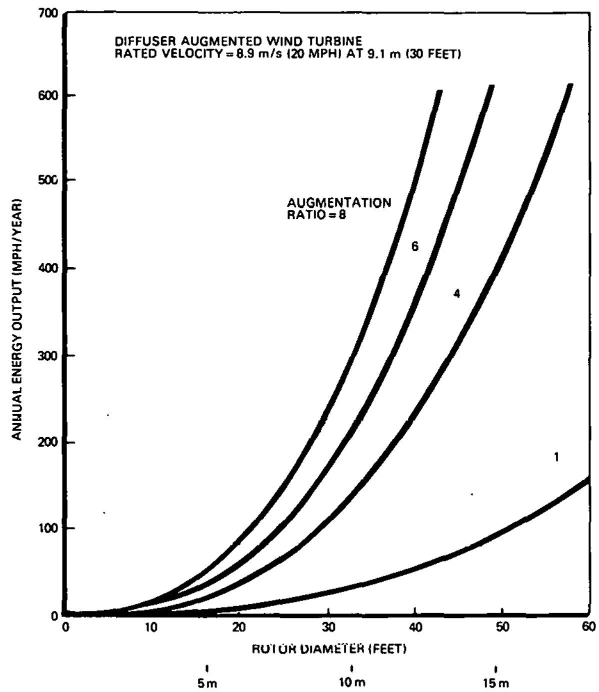


Figure 6. ANNUAL ENERGY OUTPUT OF THE DIFFUSER AUGMENTED WIND TURBINE

Annual Energy Output

Annual energy output can be calculated using rotor characteristics, the augmentation ratio, and the velocity frequency curve at the appropriate height.

Annual energy output of the vortex augmentor concept was estimated for augmentation ratios of 2, 3 and 4 as a function of rotor diameter for an 8.9 m/s (20 mph) rated wind speed. The results are shown in Figure 7. Results are proportional to augmentation ratio, with an additional slight increase of capacity factor with augmentation ratio. Energy output also increases faster than the square of the diameter because of the increase in hub height as the system gets larger.

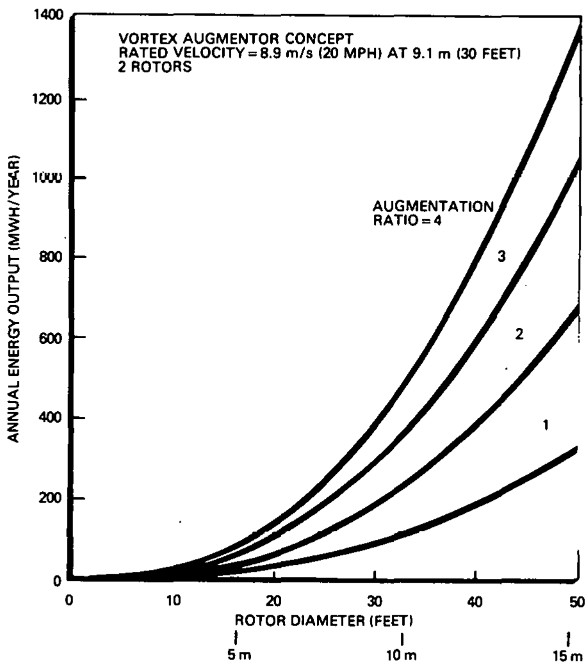


Figure 7. ANNUAL ENERGY OUTPUT OF THE VORTEX AUGMENTOR CONCEPT

COST ANALYSES

Analyses were conducted to estimate the comparative capital investment and annual operation and maintenance costs of both conventional and augmented wind energy conversion systems. The basic approach was to estimate the costs of producing and acquiring the augmented systems at power ratings comparable to those of conventional systems. We scaled the sizes of the augmented systems to the point where they could be expected to achieve the required power ratings and estimated their costs as a function of size -- primarily weight and physical dimensions. Each WECS was divided into three subsystems -- turbine, turbine support structure, and augmentor -- to estimate capital investment costs. Annual maintenance costs, a small part of total costs, were estimated as percentages of capital costs and vary with each system's characteristics. The costs of the 100th unit were estimated using a 90-percent cost improvement curve for large systems, owing to a preponderence of on-site labor for fabrication; a 96 to 97 percent curve was used for smaller systems assuming mass production in a factory. It should be noted that while cost improvement curves were used to reflect the cost advantages of commercial production, they do not affect the comparative costs of the alternative systems.

The costs that Tetra Tech estimated for the augmented systems are parametric estimates and not the result of detailed, engineering analysis. This is because, with few exceptions, the augmented systems are concepts or preliminary designs and have not been built or even designed to the level of detail required for estimation of production and fabrication costs. With respect to conventional systems, the data were insufficient to permit a detailed, component-by-component, analysis of cost. The costs of these systems were not well documented nor were they delineated in a consistent manner. Consequently, we were constrained to estimating turbine and turbine structure costs as a function of rotor dimensions and tower height, respectively. The costs of the diffuser and delta-wing augmenting surfaces were estimated from their overall dimensions and factors for cost per unit areas of their various materials; that is, aluminum, steel, and ferrocement for the shroud and fiberglass encased trussing for the vortex. On the other hand, sufficient data on the dynamic inducer permitted a more detailed analysis and more reliable cost estimates of its major components, particularly the rotor, tip vanes and supporting tower.

Our analyses show that rotor and tower capital costs are the major components of the total costs of the conventional systems and the dynamic inducer. The dominant cost item in the vortex augmentor system is the augmenting surface (delta wing).

Dynamic Inducer

Lissaman has conducted a cost comparison of the dynamic inducer and the conventional system for nominal power ratings of 100 Kw and 1000 Kw. [17] The systems were compared on the basis of initial cost for systems producing equal output power. The comparison was conducted by performing a limited structural analysis to derive the amount of material required, and converting that estimate to total system costs. Only aluminum blades were considered. The conclusion was that the dynamic inducer rotor (excluding hub and pitch change mechanism) is about 20% cheaper than the conventional rotor, and that the total system cost is about 6% less for the dynamic inducer. These cost advantages decrease as the size of the systems increase.

We compared total costs of the dynamic inducer and two conventional systems, the MOD-ØA and the MOD-1 at power ratings of 200 Kw and 2000 Kw. In order to compare the dynamic inducer to the conventional machines, the dynamic inducer was scaled up in rotor weight (blades, tip vanes and attachments) to reflect 200 Kw and 2000 Kw machines (MOD-ØA and MOD-1 respectively). Candidates for blade and tip vane materials included steel, wood, fiberglass, and aluminum; however steel was assumed to be the tip vane attachment material in all cases. Of these materials, fiberglass proved to be the cheapest, followed by wood, steel and aluminum, in that order. If aluminum is used, the dynamic inducer appears to have a cost advantage over the conventional system; however aluminum is the most expensive material. When the other materials were substituted for aluminum, there appeared to be very little difference in cost between the dynamic inducer and conventional systems.

Diffuser Augmented Wind Turbine

Grumman has conducted a cost comparison of its augmented system and a conventional system in its draft report and in supplementary material.

The range of output power considered was 15 Kw to about 160 Kw. Steel systems were considered in the draft report, and aluminum in the supplementary material.

Tetra Tech considered four rotor diameter systems: 18, 25, 46 and 60 feet, with power ratings up to 200 Kw. Diffuser dimensions were scaled up linearly with rotor diameter. We scaled up the Grumman rotor cost by a curve fit of conventional wind turbine costs. To find costs of larger diffusers, we applied a six-tenths power factor to the 18-foot diameter diffuser costs given by Grumman. Tetra Tech considered steel shroud costs from the Grumman report and unreported Grumman costs for an aluminum shroud. According to these data, the aluminum shroud results in an 82 percent reduction in costs from the first steel design study.

The 60 foot diameter first design (steel) diffuser at the 100th unit would cost $3,349/Kw compared to a MOD-ØA at 100th unit at $3,785/Kw. The parametric redesign 60 foot diameter would cost $1,863/Kw, which would be cheaper than the MOD-ØA. If the costs for the aluminum shroud design are believable ($1,168/Kw), this design would cost less than one third the cost per kilowatt of the MOD-ØA. In addition to steel and aluminum materials for shrouds, Tetra Tech looked at the possibility of a ferrocement shroud. A ferrocement shroud appears to be about 37 percent cheaper than an aluminum shroud. The $/Kw for the 60 ft. diameter, 200 Kw diffuser with a ferrocement shroud would be $996/Kw, cheaper and more competitive by far than the MOD-ØA. Fiberglass would also be an attractive material for shroud construction and probably would be between the costs of the ferrocement and aluminum shroud costs. Lack of good cost data prevented an estimate of the fiberglass system cost.

Vortex Augmentor Concept

Although work on the vortex augmentor concept has been going on for four years, no cost analysis of this concept has been published by the Polytechnic Institute of New York. A draft report that included economics had been expected during our project. Since this did not occur, an independent analysis was conducted to determine the cost of the system. A steel structure with a steel skin was considered, but it was determined that a fiberglass skin would be cheaper.

The delta-wing augmentor was costed out in three sections: the delta-wing (a steel truss structure with a fiberglass skin), the support tower (steel truss), and the turbines. A range of rotor diameters from 18 to 50 feet was considered. The delta-wing and support tower were then scaled accordingly. The dominant cost component is the delta-wing itself, accounting for a little less than half the system cost, followed by the two turbines. We determined that concrete would not be a good material for the larger delta-wing because of its heavy weight and lack of flexibility.

COST OF ELECTRICITY

Dynamic Inducer

The equation for the cost of electricity is discussed in Appendix A. From the yearly energy output and initial costs, and an assumed annual operation and maintenance cost, the cost of electricity can be calculated. Annual operation and maintenance cost for the dynamic inducer is assumed to be the same as for a conventional system (two percent of the initial cost).

For the 200 kilowatt system with aluminum, steel, fiberglass, or wood blades, the cost of electricity for the dynamic inducer was found to be virtually the same as for the conventional system. The prime reason for the similar cost of electricity is that the 1 to 5 percent lower cost of the dynamic inducer is offset by the approximately 4 percent lower energy output. For the 2000 Kw system, the dynamic inducer cost-of-electricity is about 6.7 to 9.5 percent less than for the conventional system. The 9.5 percent value is for aluminum blades and 6.7 percent is for steel, fiberglass, or wood blades; it is expected that future blades are more likely to be made of steel, fiberglass, or wood than aluminum.

The dynamic inducer appears to offer a 7 percent cost-effectiveness advantage, at most. However, this system has yet to be tested successfully in terms of producing power and augmentation. In addition, the weight, and therefore the cost, of the tip vanes assumed by AeroVironment seems very low. The area of the tip vane is about 1.75 times that of the blade, yet its weight was assumed to be less than one third of blade weight. While centrifugal and lift forces may tend to cancel on the tip vane, it still seems hard to believe that the weight per area of the tip vane would be less than one fifth that of the blade.

Diffuser Augmented Wind Turbine

To determine the cost of electricity, the performance was calculated using an augmentation ratio of 6. This value may be optimistic, but Grumman believes it can be even higher. Also, a shroud length of one-half the rotor diameter was used; Grumman believes the shroud can be even shorter, and therefore less expensive.

The cost of electricity for steel, aluminum, and ferrocement diffuser systems is shown as a function of rated power in Figure 8. Uncertainty of the cost estimate increases as the rated power increases. The cost of electricity for steel shrouded systems at the lower power ratings is higher than that of the conventional Windstream 25; it is not expected that a steel shroud would be cost effective in this size range. The cost of electricity for this system at 200 Kw is less than that of the expensive MOD-ØA, but still is likely to be more than that of an advanced conventional system, such as the MOD-X. It is not expected that steel diffuser systems will be cost effective.

Aluminum diffusers may be cost-effective. Using primarily the Grumman data, the cost of electricity appears to be less than for conventional systems. More work is needed to determine if aluminum shrouds could really be this cheap.

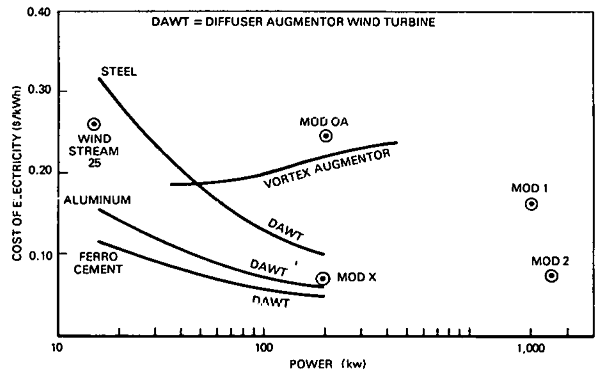


Figure 8. COST OF ELECTRICITY

Ferrocement shroud cost of electricity values may be even lower than the estimates for aluminum. Ferrocement costs were derived from the cost of building boats of this material. While the estimates are somewhat crude, and the scaling laws are not well known, the results appear promising enough so that a closer look at the economics of ferrocement shrouds is justified. As was mentioned previously, fiberglass costs for the diffuser were not established. It does appear that they could be cost-effective, and further work appears justified.

Vortex Augmentor Concept

To calculate cost of electricity for the vortex augmentor, an augmentation ratio of four was assumed. Since performance data is still lacking on this system, this is only a rough estimate. The cost of electricity for this concept, shown in Figure 8, appears to be too high to be competitive with the conventional system in all but the smallest sizes. In addition, the cost of electricity increases with size because the augmentor surface will be more difficult to build in the large sizes.

CONCLUSIONS

Dynamic Inducer

The cost of electricity of the dynamic inducer may be slightly less than that of a conventional system at the larger (MW) sizes, if an augmentation ratio of 1.6 could be achieved. However, augmentation has not yet been achieved, and tip vanes may be heavier and therefore more expensive than has been assumed to date. The choice of material does not appear to affect this conclusion.

Diffuser Augmented Wind Turbine

Of the augmented systems examined, the diffuser augmented wind turbine with a ferrocement, fiberglass, or aluminum diffuser appears the most promising. Steel shrouds for the diffuser augmented system do not appear to be cost effective in any size range. Ferrocement does appear promising for this application. In addition, fiberglass and aluminum shrouds may be cost effective.

More work is needed to establish the augmentation ratio achievable. Augmentation ratios of about 3.5 have been achieved, but reaching values of 6 or more depends on several trends and assumptions. A test of the best diffuser combined with an appropriately designed turbine, running at the proper tip speed ratio, is desirable. If this test is successful, the next logical step would be to test a system in the real wind environment.

More work on the economics of diffusers built of ferrocement, fiberglass, or aluminum is also recommended. Some of these materials may have real promise, but not enough is known yet to reach firm conclusions.

Vortex Augmentor Concept

Performance data on the vortex augmentor concept are still scarce, so that quantifying cost effectiveness is difficult. It appears, however, that the system requires too large and therefore too expensive an augmentation surface, especially at medium to large sizes. Unless the data forthcoming shows very high augmentation ratios, further work on medium or large size does not appear to be justified.

ACKNOWLEDGEMENT

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APPENDIX A

CONVENTIONAL WIND ENERGY CONVERSION SYSTEM COST OF ELECTRICITY

The cost of electricity for a conventional wind energy convernsion system can be determined from wind characteristics (mean wind speed, distribution of speeds, and variation of speed with height), performance characteristics of the wind turbine, and costs associated with the wind energy system.

For this project, the velocity duration profile was specified as

$$H = 8766 \exp\left[\frac{-\pi}{4.06} (V/\overline{V})^{2.27}\right] \qquad \text{(A-1)}$$

where V is the velocity, and $\overline{V}$ is the mean velocity. At an elevation of 9.1 meters (30 feet), the mean velocity $\overline{V}$ was specified as 5.4 meters per second (12 miles per hour).

It was also specified that mean wind vary with height as follows

$$\overline{V}_z = \overline{V}_r \left[\frac{\ln (Z/Z_o)}{\ln (Z_r Z_o)}\right] \qquad \text{(A-2)}$$

where $\overline{V}_r$ is the mean wind speed at a reference elevation Z_r, V_z is the mean velocity at elevation Z, and Z_o is the surface roughness length, specified as 0.05 meters (0.16 feet).

Power in the wind is proportional to the velocity cubed. This is converted to power out of the rotor by multiplying by rotor power coefficient. Other losses are then also accounted for, such as drive train, gearbox, generator, accessory, and transformer losses. The velocity duration profile and the extrapolation of velocity with height are combined, using a methodology developed by Justus, [14] to develop a velocity frequency curve at the hub height. This curve gives hours per year that the wind velocity is in each velocity increment. For each increment, power can be obtained from the power-velocity curve. Multiplying power times hours in that increment gives the energy output contribution of that increment. Summing these contributions gives the total energy (AKWH) produced each year.

For electrical generation, the cost of energy is calculated using the following formula:

$$COE = \frac{(IC)(FCR) + (AOM)}{(AKWH)} \qquad \text{(A-3)}$$

where IC = initial cost,
FCR = fixed charge rate = 0.18 yr^{-1},
AOM = annual operation and maintenance cost, and
AKWH = annual KW-hr produced, including planned outages.

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A DEFINITIVE GENERIC STUDY OF AUGMENTED HORIZONTAL AXIS WIND ENERGY SYSTEMS

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ABSTRACT

Augmentor systems are intended to increase the energy flux through a conventional wind power extraction machine above that associated with the free-flow condition. The ultimate cost-effectivenes of such augmented systems depends upon the trade-off between any resulting increase in energy output and the added costs associated with the installation of the augmentors themselves. Two basic design considerations are common to the installation and operation of all augmentors. These are the increased flow speed (mass flux) through the power extraction device, and the aerodynamic force on the augmentor. Two fundamental types of augmentors were considered: dynamic, and passive. The passive designs included both an axisymmetric duct (shroud ring) surrounding the actuator disk, and also a planar delta wing in the vicinity of the actuator disk. The dynamic design involves attaching airfoil tipvanes to the rotor blades themselves. Aerodynamic performance of all of the systems were computed and then were sized to produce the same power output as the NASA Mod-X wind turbine. Estimates of the cost of each resulting augmented system was performed; the cost of power was then calculated and compared to the Mod-X. For all augmented designs, the power costs varied between 1.2 and 3.0 times those of the baseline Mod-X. Thus, all of the augmented systems appear less cost-effective than the Mod-X. However, the dynamic augmentor (cost ratio of 1.2), in spite of the limited development devoted to it is comparable to the Mod-X and, perhaps merits further optimization. An outline plan of recommended future augmentor research for wind turbines is given.

INTRODUCTION

A turbine provides useful work by extracting a portion of the kinetic energy contained by the flow in the natural wind. Only two methods are available to increase the energy extracted. Either the energy extracted from a given stream tube of the flow can be increased by either increased aerodynamic or mechanical efficiency, or the available energy flux operated upon by the machine can be increased. The latter effect is accomplished by magnifying the area of the stream tube flowing through the machine. The flux magnification principle is called augmentation.

Augmentation methods can be classified into two broad categories, passive and dynamic. Passive augmentation methods involve the addition of auxiliary surfaces to the wind turbine system, designed to increase that mass flow through the actuator. The reaction of the flow to these auxiliary surfaces produces an outward force on the stream tube, causing it to diffuse downstream, thereby increasing the stream tube capture area, resulting in an increased mass flow through the actuator.

Two techniques of passive augmentation are considered. The first is an axisymmetric duct, where the duct ring vorticity is coupled with the axial flow to produce a radially inwards force on the duct. The reaction to this effect is a radial outward force on the stream tube increasing its size and mass capture. The second passive augmentor is a planar wing. The power extracting device in this system is located above the suction side of the wing, where the flow speed has been increased by the wing bound vorticity. The augmentation here is not due to the swirl of the vortex, which cannot increase the net energy of the flow, but actually due to the greatly increased axial flow speed in the vortex, causing an increased mass flow through the actuator.

The other major class of augmentation is achieved through what can be described as dynamic augmentation. In this case, moving elements are used to create an increased flow through the actuator. The technique of dynamic augmentation considered is a tip-vaned rotor system. This system, called the Dynamic Inducer, when applied to a propeller-type actuator may be likened to a static duct where the radial force is developed by vanes on the tips of the power rotor (the propeller).

Although the dynamic induction system will produce flow augmentation, it must be noted that the dynamic inducer vanes do work on the flow and thus require power to operate. The net power is obtained by subtracting the power required to drive the induction system from the overall power obtained from the wind.

The scope of the present analysis is to investigate the three described wind energy augmented systems applied to the performance and cost-effectiveness of horizontal axis rotor systems in relation to the NASA Mod-X 200 kW free rotor wind turbine concept. The augmented systems performance analysis will be based on the following investigations:

Axisymmetric Duct

The Grumman Aerospace Company has developed a short, cost-effective diffuser for wind energy conversion applications, with theoretical guidance provided by a one-dimensional fluid dynamics model. Many compact diffuser configurations have been evaluated by Grumman Aerospace Corporation. The most promising diffuser emerging from this work employs slot-injected external air to prevent core flow separation and a trailing edge flap for rapid divergence of the flow from the diffuser. The Grumman diffuser design features are proprietary; however, the basic specifications feature an included angle of 60°, a length-to-inlet diameter ratio of 0.4, and an area ratio (the ratio of the exit to the inlet area) of 2.78. Grumman's projections of wind tunnel test data of this configuration to their optimum turbine load factors and operating conditions result in power coefficient levels over eight times those of the best conventional wind turbine. Grumman has also supplied a parametric cost breakdown of their ducted rotor system.

Planar Static Inducer

The Polytechnic Institute of New York Aerodynamic Laboratories has developed a vortex augmentor concept employing a low aspect ratio delta platform wing-like structure. Separated flow in the form of leading edge vortices concentrates the kinetic energy density of the wind from a large upstream area into a kinetic energy density flow in a small area within the vortices. The interaction between the vortex fluid stream and a suitably designed aerodynamic surface can provide regions of kinetic energy density up to nine times greater than that in the free stream. Sforza's predictions of rotor performance of a delta wing system suggest a four-fold increase in power over unaugmented operation. The vortex flow field produced by the wing has a swirling character; therefore, a turbine placed in the flow can be made to rotate in the same sense as the vortex. Rotation with the vortex allows turbine rotation at a much higher tip speed ratio. The planar surface is thereby viewed to act as a "pre-rotation vane."

This may be a misleading explanation of the flow augmentation mechanics. The additional component induced by the swirl of the vortex in the circumferential direction is secondary compared to the greatly increased axial flow velocity. Furthermore, the vortex cannot increase the net energy of the flow but, in fact, will generate irreversible energy losses due to viscous effects. It is an increase mass flow through the actuator which causes augmentation.

Dynamic Inducer

The duct behavior previously described has shown that a radially outward force exerted on the air near the actuator can have an advantageous effect. The radial force creates the increased mass flow through the disk and, consequently, the large diffusion. This required radial force can also be created by tip-vanes.

Since the tip-vanes are moving at turbine tip speed, their effective dynamic pressure is proportional to the square of the tip speed ratio, X. Thus, the tip-vanes can produce the same radial force as a static duct with a very much smaller surface area. In comparison, for the same diffusion and force coefficient, the ratio of tip-vane area to duct area varies as $1/X^2$, a very significant reduction, since X may be about 10.

Another important difference exists between the dynamic inducer (tip-vanes) and the static inducer (cylindrical duct). Tip-vanes are attached to the blades and thus drag forces on the tip-vanes represent power losses. The drag may be of two types -- induced and profile. The profile drag can be readily computed and converted to a viscous power coefficient loss.

The induced drag can be eliminated by properly sizing the tip-vane span so the upwind tip vortex is cancelled by the downwind tip vortex of the tip-vane. VanHolten has observed this "vortex synchronous state" even when the tip-vane span is greater than necessary for tip to tip cancellation, indicating that tip-vane sizing is not highly critical.

AeroVironment has been engaged in the development of the dynamic inducer rotor (DIR). The DIR concept has the theoretical potential of increasing the power output of wind turbines by a factor of 2. The key results of a complementary program conducted at the Delft Institute of Technology have been that substantial induction can be achieved from the tip-vanes. This has been determined by measuring the radius of a smoke filament striking at the tip-vane radius and comparing this with the case of no tip-vanes. Up to four times the normal mass flow has been achieved with the induction effect.

The NASA Mod-X 200 kW Wind Turbine

The NASA baseline Mod-X configuration was the result of an evaluation study of major components and subsystems. Selection of the baseline configuration was guided by the philosophy that those features of a wind turbine that were shown to be potentially cost-effective and to be technically feasible in earlier NASA work were to be incorporated into the Mod-X baseline configuration, and changed only if proven to be too costly or impractical during the design.

Efforts to reduce all component weights and costs were made, with special emphasis on the major subsystems; the rotor, drive train, yaw drive, tower and installation.

The pod assembly consists of all the equipment atop the tower (rotor, gearbox, pitch control, etc.). The pod assembly consists of a rotor mounted directly on the low-speed shaft of the gearbox and the generator bolted onto the gearbox casing at the high speed shaft. Compactness and cost savings are achievable because gearbox manufacturers routinely build combinations of gearboxes and generators for a variety of large industrial applications. It would be a straightforward matter to design and mass produce systems that would include a gearbox, a generator, a yaw bearing, and other needed auxiliary equipment in a single package at costs less than those of the individual components. With the gearbox functioning as the main supporting structure for the generator, pitch change mechanism and rotor, the bedplate is either eliminated or greatly reduced in size and weight. Such a single factory-assembled package reduces both fabrication and field assembly costs.

The hub structure carry the blade loads to the low speed shaft and be designed for adequate fatigue life. The hub allows the blades to teeter, and provides for passage and support of the pitch drive mechanism. The hub requires provision for a teeter damper, and extreme teeter angle stops.

In the NASA Mod-X study, the structure of the various blade concepts that were considered was sized using wind loads for a steady 150 mph wind at hub height. In addition, the blade structure was chosen so that the natural bending frequencies were above 2 per revolution and were not some integer multiple of the rotor rpm. NASA did not select a final blade design and material because there was no obvious choice of a blade design that would provide a significant cost reduction and would withstand the rigors of wind turbine operation. Several concepts were considered as candidates for the Mod-X. These include a wood blade, a steel spar and rib blade, a steel blade, and a transverse fiberglass tape (TFT) blade.

The basic pitch change mechanism (PCM) for the Mod-X would consist of a linear actuator that is located on the rotor axis with a push rod inside the rotor shaft, and a pair of straight links that connect the end of the rod to a bell crank at the root of each blade. This system converts the linear motion and force of the actuator to the rotary motion and torque needed to pitch the blades. Around the actuator rod is a large coil spring whose function is to supply power to quickly feather the blades during an emergency shutdown.

The gearbox functions include supporting the rotor on the input shaft, incorporating the generator as an integral structure on the high speed shaft side, and housing the yaw gear. To be able to carry the added loads, the gearbox casing, the input shaft and bearings would have to be heavier than usual. The added weight of the gearbox would be offset by a greater weight and cost reduction that resulted from elimination of the large bedplate and a separate rotor main shaft and its bearings.

The Mod-X tower would be made of cylindrical members, have vertical loads transmitted into three legs by a bearing at the 35-foot elevation level, and have the horizontal loads resisted by bearings at the 35-foot elevation and at ground level. The foundation would use precast concrete vaults backfilled with excavated earth. Tower sections would be fabricated with all the necessary electrical wiring, hydraulic lines, and other equipment preassembled at the factory. Placing the rotating/stationary interface at the tower base reduces the amount of equipment that must be on top of the tower and, therefore, decreases maintenance costs. The design provides for easy installation and eliminates the need for a large crane. Rotating the tower mass provides greater stability for possible yaw and access to the top of the tower is protected from the elements.

Using the weights of the major components for the Mod-X subsystems, costs were determined by NASA using a dollars-per-pound figure chosen from available data for mature mass-produced products.

AeroVironment Generalized Performance Analysis

The power coefficient, C_P, of any windmill is equal to the mass flow coefficient, C_M, times the head loss coefficient, C_H. According to inviscid theory, $C_H = 4\underline{a}\,(1 - \underline{a})$, where $\underline{a}$ is the axial interference factor. According to AeroVironment performance theory, $C_M = C_{M_o} - M_a \underline{a}$, where C_{M_o} is the no-load augmentation factor, and M_a is the axial interference multiplier. Both of these terms are dependent only upon system geometry. For a normal windmill they are both equal to one. For an augmented windmill, C_{M_o}

is greater than one, and M_a is one for a free turbine and increases toward two if the turbine is enclosed. Thus, the equation for C_P is $C_P = (C_{M_o} - M_a a)\ 4a\ (1-a)$. Figure 1 shows the optimum C_P for M_a equal to one and two, and various no-load augmentations.

According to inviscid theory, C_H cannot exceed one, as to do so would violate the law of conservation of energy. However, in a real viscous, flow windmills have achieved C_H's approaching two. When this much head is removed from the flow, the fluid has insufficient energy to leave the low pressure area at the rear of the turbine. If not for viscous effects, the fluid would simply stop and block further flow through the turbine. This de-energized wake material can be "scavenged" by turbulent mixing with the outer flow, thus reenergizing the wake flow sufficiently for it to continue downstream.

When a windmill is operated with a C_H greater than one, it is often referred to as operating in the windmill brake state. Such operation is characterized by wake turbulence and reverse flow regions. The power output is actually greater than the total kinetic energy flux of the mass flowing in the capture stream tube. This means that a windmill operating in the windmill brake state is actually able to utilizeenergy from flow that did not pass through the actuator disk. Even with this added energy, a normal windmill still has its best C_p when operating with C_H less than one. For an augmented windmill, however, the maximum output point may lie deep in the windmill brake state. In order to analyze the power output of a windmill operating in the brake state, it is necessary to find a relation between a and C_H that is good for C_H greater than one. At the present time, there is no such relation. So, for each case, an assumption was made for this relation in order to obtain an estimate for the brake state performance.

For each augmented configuration under consideration, a high confidence performance estimate that assumed a C_H less than one, and an extrapolated estimate assuming operating at about a C_H of 2.0 was made. Table 1 shows the C_P's thus found. Table 2 gives the rotor sizes necessary for these configurations in order to have each generate 200 kW when the wind speed at 9.1 meters altitude is 7.5 meters per second. Figure 2 shows sketches of the extrapolated systems drawn to scale. The following assumptions were made to obtain these estimates: Rotor efficiency, 71% of ideal; transmission efficiency, 94%; generator efficiency, 94%, and wind speed variation with height:

$$V_Z = U_r \frac{\ln (Z/Zo)}{\ln (Z_r/Z_o)}$$

where V_Z is the wind velocity at height Z, V_r is the reference wind speed at height Z_o, and Z_r is a roughness parameter assumed equal to 0.05.

The total kilowatt hours produced per year was found from the Justus equation, assuming an average wind speed of 5.4 m/sec at 9.1 meters. This gives a total of 697,950 kWh produced per year.

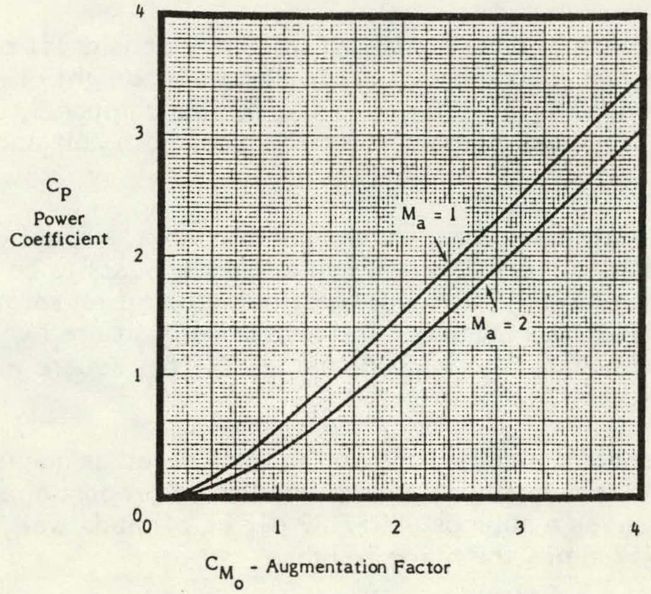

FIGURE 1. Ideal power coefficient of general augmented wind turbine.

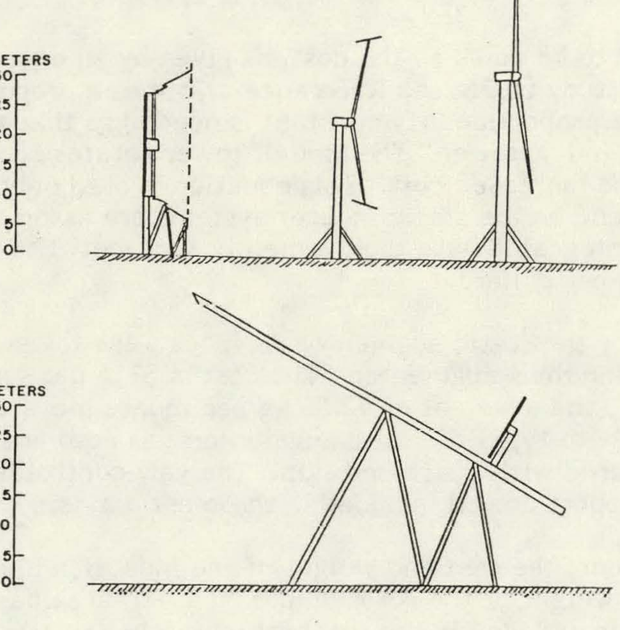

FIGURE 2. Sketches of wind turbines designed for the extrapolated level design.

Cost Analysis

In order to find the cost of each configuration under consideration, each is divided into a number of components. The cost and weight of each component is then scaled in an appropriate way to the similar component in the Mod-X. The costs discussed below are for the hundredth unit and estimated in 1978 dollars.

The rotor cost per unit blade area, weight per unit area, and solidity are all assumed to be constant for all rotor radii. This appears to be a conservative assumption, since the Mod-X has the largest diameter of all rotors considered, and it is expected that the rotor cost and weight per unit area will increase somewhat for larger radius rotors. The cost is $877 per square meter and the weight is 62.3 kg per square meter.

The hub and pitch control mechanisms are all considered as one unit. The weight and cost of this component are assumed to be proportional to the rotor weight. This gives a hub cost of $7.89 per kg of blade weight, and a hub weight of 0.957 times the blade weight.

The bedplate and gearbox are an integrated unit for the Mod-X. The primary cost driver for this unit is the power level that must be handled, not the gear ratio of the gearbox. This gives the same cost for all configurations for this component. The cost is $26,400 and the weight is 7,484 kg.

The electrical system (generator, power conditioning, transformer, circuit breakers, and controls) are assumed to have the same cost and weight for all systems. The cost is $11,700 and the weight is 2,495 kg.

The tower is assumed to be equal to the cost, as given by an equation from the General Electric study (1976, see Reference 1), times a proportionality constant of 1.38. The proportionality constant is needed so that the correct cost is given for the Mod-X tower. The Mod-X tower rotates for yaw control, which accounts for the increased cost. This equation is used only for the dynamic inducer system, as the static inducer systems are assumed to have the tower structure integrated with the augmentor surface. The weight of the tower is 0.4 kg per dollar.

The cost and weight of the static augmentor surfaces were taken from Grumman estimates for their augmentor. The cost is $314 per square meter of augmentor surface, and a weight of 42.86 kg per square meter. These values were used for both types of static augmentors, as both are space frame structures covered with a stressed skin. The yaw control, support tower, and nacelle support are all included in these estimates.

For the dynamic inducer, the cost and weight of the induction blades is equal to the cost and weight of the rotor blades on a per-area basis. The inducer blade weight is included in the total rotor weight for computing the hub costs.

The foundation which supports the entire structure costs \$0.1213 per kg of supported structure.

After all of the component costs are totaled, a 14.35% miscellaneous charge, followed by a 15% G&A charge, and a 15% profit charge are all tacked on. The maintenance cost is \$4,000 per year initially, growing to a levelized cost of \$7,500 over a 30-year lifetime.

The cost of electricity is computed from:

$$\text{cost per kWh} = \frac{\text{total cost x annual charge factor + yearly maintenance}}{\text{total kWh produced per year}}$$

Table 3 gives the total cost of each configuration, the cost of electricity for each system, and the ratio of these costs to that of the Mod-X.

OUTLINE OF PROGRAM PLAN FOR FURTHER DEVELOPMENT OF AUGMENTOR SYSTEMS

Summary of Augmentor Principles

All augmentors operate by inducing a larger mass flux through the actuator disk than would occur in the free actuator case. This can be accomplished only by increasing the axial velocity through the actuator, and no additional effect is achieved by inducing rotational components. There is no way of increasing the total head of the free stream flow except by doing additional work on it. However, acceleration of the axial flow, in effect, draws air from a greater cross-sectional area than that associated with the free actuator.

It is helpful to consider the no-load amplification, that is the ratio of the no-load mass flow through the actuator with augmentation, compared with that for a free actuator with no augmentation. This provides an upper bound on the maximum flux of air from which energy can be extracted, since the far downstream wake velocity theoretically should not be lower than about one-third free stream. Thus, the energy extraction can be computed from the mass flux and the wake head loss. Consequently, the augmentation potential should be based on the increase in mass flux which varies as the speed through the disk, and not on the cube of this speed. As power is drawn from the actuator disk, the resistance of the system will increase, so that the amplification will drop below that for the no-load case. The determination of the flux amplification with power production is a nontrivial problem, different for various types of augmentors, and has been treated by both analytical and experimental techniques.

The tower drag is independent of the inducer system for the inviscid flow. However, a real inducer produces drag under the no-load case, which occurs due to viscous drag effects in the dynamic inducer and the duct, and to both viscosity and lift-induced drag in the case of the planar static inducer. Thus, a price of increased tower load must be paid for all inducer systems compared with a free wind turbine.

For all inducer systems the efficiency of the rotor system itself becomes very significant, because the viscous losses are related to the local flow speed and are thus accentuated by induction. So, augmented systems will benefit more by increased rotor efficiency, just as a high-speed aircraft benefits more by viscous drag reduction.

Thus, the criteria by which an augmentor may be judged are the no-load mass flux amplification, the effects of power extraction on this amplification (that is, how much the amplification is reduced), the total system dragwise load created by the augmentor and power extraction system, and the surface area (or, more significantly, the cost) of the required augmentor.

A further important fluid mechanical issue arising here is that the augmentor makes it possible for the external flow to assist in scavenging the actuator flow. In an ideal inviscid system one can compute the actuator load for maximum power extraction. The limits are imposed by the condition that as head is extracted from the flow the mass flux through the actuator is reduced. Now, the power is the product of the head extraction and the mass flow, so that for extraction of a large amount of head the mass flow is necessarily reduced. In practice, this means that the far downstream slip stream will be found to have a speed close to zero with consequent reductions in the mass flux. However, if there is turbulent entrainment between the slip stream and the outer flow, then the slip stream velocity can be increased so that the mass flow in the wake is increased and the wake is scavenged and swept downstream. This presents an interesting situation where the wake flow is actually reenergized by the outer flow. This phenomenon seems most pronounced for augmented systems and we can explain this as follows: At the actuator, a certain proportion of the local kinetic head can be extracted kinematically, but far downstream the final wake velocity will be determined by the speed corresponding to the reduction of total head of the flow. Thus, if one could extract, say, 30% of the local kinetic head in a flow of twice free stream speed (due to an augmentor), then 120% of the free stream kinetic head would have actually been removed. Thus, it seems plausible that, with augmentors, the possibility of extracting a larger amount of the local dynamic head occurs, providing there is some turbulent mixing process in the wake of sufficient entrainment capacity to restore the wake speed to some positive value in the direction of the flow.

It is believed that the fundamental principles of the augmentor, described above, will make it possible to analyze the optimum requirements of an augmentor from the basic fluid mechanical ideas. Thus, application of the above concepts makes it possible to logically configure an optimal augmentor system, rather than analyzing various postulated good configurations. This morphological approach may make it possible to determine whether any augmentor configurations of high potential have been overlooked.

Comparison of Systems Analyzed

Using the ideas outlined above, and employing current structural cost estimates, we can calculate the plant cost and power cost of the various systems.

These results are shown in Table 3. It is noted that the standard propeller-type system (Mod-X) appears distinctly superior to both forms of static inducer, and marginally better than the dynamic inducer. It is seen that the disadvantage in the case of the static inducers is the high cost of the inducer itself, which constitutes about 85% of the cost of the system and is not cost-effective in the additional power it produces.

We conclude that the cost of the static inducer surfaces must be reduced by a factor of between 3 and 10 for the system to be cost-effective compared to the Mod-X. It appears unlikely that this is possible. It is noted here that rather optimstic estimates of the aerodynamic performance have been made, so that further effort to make these systems cost-effective should relate to structural cost-reduction. However, the static inducer systems may show more attractive cost figures when operating in high wind regimes, since the power output will increase but not the inducer cost, because it is already designed for high winds.

It is noted that for all the inducer systems improved rotor efficiencies will be very advantageous, because of the increased flow speeds at the rotor. The dynamic inducer will particularly benefit from increased rotor efficiency since this will reduce the viscous losses due to the tip-vanes or inducer blades compared to total rotor output. In addition, this increased efficiency will decrease the system drag, thus reducing the tower load and, consequently, its cost. It is believed that improved rotor viscous efficiency will make the dynamic inducer cost-effective.

Augmented systems should always be compared on an equal power output basis, as has been done here, not on an equal rotor area basis. The equal rotor comparison leads to the deceptive concept of "X times the power from the same rotor," which does not take into account the increased costs of tower, power train, and generator.

It is further noted that all the extrapolated "maximum power coefficient" systems are more effective than the high confidence systems. But these maximum power coefficient systems involve operation at very high rotor kinetic head extraction levels, involving situations close to, or in the windmill brake state, which are not possible in inviscid flow and involve turbulent entrainment scavenging. Various test data suggest that this scavenging does, in fact, occur even for free wind turbines. However, the fluid mechanics of this state are poorly understood and more research is required here.

Finally, it is noted that while none of the systems have been exhaustively analyzed structurally for cost estimation, it is likely that the structure estimates for the dynamic inducer are most reliable, since the tip-vanes are more similar to standard rotor blades than the static inducer surfaces. It is noted further that if the "blade-locked gale" case is taken as a design criterion, then the dynamic inducer is likely to be at an even greater advantage than the other systems because its surface area is much smaller and presents less drag surface normal to the wind.

TABLE 1. Configuration power coefficients.

Configuration	C_P Ideal	C_P Rotor	C_P System
Axisymmetric, static, high confidence	2.37	1.68	1.47
Axisymmetric, static, extrapolated	4.74	3.36	2.95
Planar, static, high confidence	1.36	0.96	0.85
Planar, static, extrapolated	2.99	2.12	1.86
Dynamic, high confidence	1.56	0.71	0.63
Dynamic, extrapolated	2.00	1.02	0.90
Mod-X	0.59	0.42	0.37

TABLE 2. Configuration rotor sizes.

Configuration	Rotor Radius (Meters)	Hub Height (Meters)	Area Ratio
Axisymmetric static, high confidence	10.73	23.61	3.15
Axisymmetric static, extrapolated	8.50	18.70	5.02
Planar static, high confidence	7.98	39.91	2.85
Planar static, extrapolated	6.05	30.23	4.96
Dynamic, high confidence	16.40	27.39	1.35
Dynamic, extrapolated	14.47	23.16	1.74
Mod-X	19.06	30.48	1.00

TABLE 3. Summary of configuration costs.

Configuration	Total Cost (Dollars)	Total Cost Ratioed to Mod-X	Cost of Electricity (¢ per kWh)	Cost of Electricity Ratioed to Mod-X
Mod-X	202,805	1.0	6.3	1.0
Axisymmetric static high confidence	600,450	3.0	16.6	2.6
Axisymmetric static, extrapolated	398,965	2.0	11.4	1.8
Planar static, high confidence	1,191,040	5.9	31.8	5.0
Planar static, extrapolated	710,150	3.5	19.4	3.0
Dynamic, high confidence	262,750	1.3	7.8	1.2
Dynamic, extrapolated	249,925	1.3	7.5	1.2

From the aerodynamic point of view, quite extensive work has been done on both types of static inducer, and the high confidence power augmentation has been proven. This is not the case with the dynamic inducer, where no actual power augmentation has been demonstrated. Experimental work on complete dynamic inducer systems is very limited and no comprehensive, systematic tests on the complete unit have ever been performed. However, the principles of flux amplification have been experimentally proven, and it has also been experimentally shown that the dynamic induction system can be driven at relatively low power level. Taking into account the fact that the analyses here show that the dynamic inducer is comparable to the baseline system, it is believed that further work is justified to refine the aerodynamic and structural analysis.

Recommendations for Research and Development on Augmentors

The current conclusions regarding augmentor devices have identified the areas of uncertainty, of high promise and of serious disadvantage. It is believed that in most of the technology, passable estimates can be made and that it is appropriate now to concentrate on certain types and to focus the scope of innovative research to major programs on the most promising systems, while still maintaining a low level funding in high risk fundamental exploratory research.

It is recommended that research in the following areas should be conducted:

High Power Output Rotors Operating in the Windmill Brake State

- It has been shown that augmentor rotors can benefit from operating in the brake state. This brake state apparently involves turbulent entrainment from the outer flow, thus making additional energy available to the actuator. Analytical and experimental work is appropriate here with special attention to turbulent effects. It is noted that this research would also have considerable bearing on the understanding of the development of wind turbine wakes, which is important in constructing models for the performance of arrays of wind turbines.

Increased Rotor Efficiency for Augmented Systems

- It has been noted that augmented systems are particularly benefitted by increased rotor efficiency, which will presumably come from using airfoil sections of lower profile drag and higher lift. This work can be performed on two-dimensional airfoils and should be both analytical and experimental. This research can be coupled with the development of airfoil sections for vertical axis machines.

Cost Estimates for Static Inducer Surfaces

- It has been shown that the Static Inducer surface represents a major cost element in those systems, but the precision of cost estimation is not known. However, a large amount of experience on wind-loaded surfaces does exist in the construction and aerospace industry. It is believed that a more comprehensive cost estimate of these inducer structures should be made, using both fundamental design principles to size the components and statistical data from comparable wings and ducts.

Aerodynamic Development of Dynamic Inducers

- It has been shown that the dynamic inducer represents the most potentially attractive inducer system, yet experimental test data is lacking and the aerodynamic performance has had to be estimated from a combination of various component performances. It is recommended that analytical, experimental, and field test research should be performed on developing inducer tip-vane geometry, of integrating the tip-vanes with the power blades, and of designing and operating the complete system.

Aeroelastic Analysis of Dynamic Inducers

- If the aerodynamic performance of the dynamic inducer proves attractive, then it will be necessary to determine if there will be any aeroelastic problems. At the present level, the aeroelastic study can be made prior to complete detailed definition of the dynamic inducer system, since the basic geometry can be specified now. An analytical study, using available aeroelastic computer models, modified for this geometry, should be performed.

Improved Cost Analysis of Dynamic Inducer Rotor

- The current method of cost estimating power blades and tip-vanes for dynamic inducer systems is based on ordinary horizontal axis rotor systems. However, the tip-vanes experience a complex load system due to inertial and aerodynamic effect and, in addition, introduce special dragwise and radially inwards loads on the power blades, which are not normally present for ordinary rotors. Thus, the blade loading will be different, and it is to be expected that this will have an effect in blade cost.

General Study of Potential of Inducer Systems

- The work already performed has shown that different types of inducers do, in fact, increase the power output of a rotor, although at an increased cost, associated with the inducer geometry. However, the systems studied to date have not been optimized for maximum efficiency. It is believed that sufficient basic understanding of the aerodynamics and structural cost is now available, so that a wide ranging morphological study of inducers can be made, with a view to identifying configurations having optimal characteristics, just as this can be done for lifting surfaces.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations are summarized below in abbreviated form. The reasons and detailed explanation of these statements are given in Reference 1.

1. Of the three systems analyzed, the dynamic inducer was the only one of cost-effectiveness comparable to the baseline Mod-X, an advanced horizontal axis conventional wind turbine. A dynamic inducer using high confidence performance figures has a power cost ratio of about 1.2 of the baseline. The power cost ratio of the static inducer systems was about two to five times that of the baseline unit.

2. For the static inducers, the aerodynamic performance is quite well understood, and test data is available. For the dynamic inducers, although theoretical performance estimates are promising, no test data is available for the complete system. However, test data for subsystems of the dynamic inducer is available, and has supported analytical estimates. It is noted that much less research has been performed on the dynamic inducer system than on the others.

3. Structural analysis and cost estimation of the various inducer systems is still quite imprecise and statistical cost data is lacking. However, it is believed that cost reduction by a factor of two or three, which is what is required to make some of the inducer systems cost-effective, will be very difficult to achieve.

4. An understanding of the general mechanisms of inducers has been obtained, and the importance of turbulent effects for highly loaded rotors has been identified.

5. It is recommended that research on innovative inducer systems should concentrate on the most cost-effective device, the dynamic inducer.

6. A short-term research program has been outlined, designed to investigate only those areas which show the most promise. These areas involve:

    a. dynamic inducer aerodynamics, aeroelasticity, and structural cost.

    b. Study of windmill brake states for heavily loaded rotors, and improvement of rotor efficiency.

    c. Structural cost estimates to study the very high apparent costs of static inducer surfaces.

    d. Limited high risk work on the identification of optimal inducer systems.

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Session IV

OPEN DISCUSSION 2

George Tennyson DOE: We are not really concerned with efficiency only but efficiency as it tends to reduce the cost of the energy and system cost.

Irwin Vas, SERI: The objective of the studies is to provide an assessment of the advanced and innovative concepts by impartial observers. That is not an easy task. We have listened to presentations for the last day and will continue to hear about these concepts today and tomorrow. We appreciate your technical expertise in this effort.

Oman: With regard to the Kornreich review of the Yen turbine, I would agree with just about everything that was said, with one very major exception. There is an implication, if not a statement, to the effect that the very best chance was given to innovative systems and conventional systems were penalized whenever there was a question or doubt. I have no doubt in my mind that the investigators believed they followed this idea. However, there are many ways that one could change the structural design and construction concepts that were used as the basis for their cost estimates. I think it would be irresponsible for us to attribute those numbers to anything but a state-of-the-art point design for the structure. That issue is clearly and vitally important in assessing the future potential. For instance, the vanes are solid. If you scale vanes, you find very quickly that the cost per kilowatt goes up linearly with characteristic dimensions of the device. That is obviously not the route to take. The number of stiffening rings was considered to be conservative. I think that is very pessimistic because efficient structures would have more stiffening rings, not fewer. There are many ways that structural cost estimating rules could be addressed, how successfully remains yet to be proven. The point I wish to make is that we must interpret these observations as today's guesses, not as the final conclusion on what may be delivered.

Theodore Kornreich, JBF Scientific Corp.: I agree with you that it is a point design. We had a professional structural engineer do the work. I would like to repeat my statement, that based on the best information we have, the statement that you made is perfectly valid. We did not include many costs in the tornado system as we could not get a good handle on them. We took what I consider to be relatively pessimistic costs for conventional systems, as compared to the data that were presented yesterday.

Gabriel Miller, NYU.: The difficulty of doing generic studies was pointed out in the last two papers: two different analyses of the same data for the same machines resulted in two completely different conclusions. The first paper indicated that the DAWT machine may be cost effective while the dynamic inducer was not whereas the second paper, using the same data, revealed the opposite. I would appreciate your comments.

Peter Lissaman, Aerovironment, Inc.: The results are not contradictory. Marcel Harper said that the dynamic inducer was about the same as the 200 kW, MOD-X, and I stated that it looked about 1.2 times more expensive. That is the same, within our accuracy limits. Harper had the DAWT being more expensive by a factor of about 70% if made of steel and cheaper if made of concrete. We indicated that it would be 1.8 times more expensive using steel. We are consistent.

Martin Hoffert, NYU.: I just would like to again make a brief observation with regard to the wind environment. I believe that there is an extreme sensitivity in terms of cost to the assumption of the 120 mph wind loading. The difference between a design specification of 120 versus 100 mph is about a factor of 1.4 in load which, with a linear relationship, corresponds to a 40% difference in cost. The probability of getting 120 mph for one second or more in the 30 year lifetime of the machine is something like 10^{-50}, and for 100 mph it is 10^{-30}. I do not think that anyone would want to accept those numbers as being realistic. They are basically extrapolations of the wind duration profile based on limited data at much lower wind speed. What is the probability of getting a 120 mph wind — or even a 100 mph wind? It's possible that if you are in the eye of a natural tornado you may get such extreme wind speeds. For certain types of machines the cost factors are weighed adversely in terms of high wind speed. I believe that the specifications under which these comparative evaluations have been made are an extremely important factor, particularly as policy implications may be drawn from them. Would Mr. Kornreich briefly comment on this?

Vas: One thing that I tried to do in these generic studies is to attempt to get consistency between studies. Studies are often made at different wind velocities and comparisons are difficult. In our studies we have specified the wind regime and shear. I realize that the wind velocity is different in various parts of the country, some people even designing machines rated at 40 mph. For my purpose, I require a method of comparison using reasonable wind characteristics. With regard to the possibility that there is a very small likelihood of wind speeds in the 90-120 mph range, you may wish to verify the conditions that have been recorded at the Rockwell site at Rocky Flats where several machines were destroyed due to high winds.

Peter Moretti, Oklahoma State University: In Stillwater we have never recorded more than 90 knots of wind, but several times all our anemometers blew away. Yesterday, we heard that we needed a clearance of 1500 ft in every direction for every windmill. We must examine the economic tradeoff of designing windmills that won't fail, and designing windmills that have to be put into desolate places because they may fail.

James Yen, Grumman Aerospace Corp. I would like to suggest that you continue to evaluate other options in the structural design of the tornado machine.

Robert McConnell, SERI: I would like Dr. Lissaman to comment on the performance of tip vanes on a rotor having airfoils.

Lissaman: Positive power augmentation has not been demonstrated, but I am certain that it can be, with augmentation as high as 100%.

Oman: Would each of the evaluators please give a quick answer as to whether they considered blade replacement in the cost of the conventional systems, and how they dealt with that in the unconventional systems? Did they need replacement of critical components through the 30 year life of the machine?

Marcel Harper, Tetra Tech., Inc.: We didn't address that directly.

Lissaman: No.

Kornreich: The answer is no, but I will qualify that. We did not consider replacement in any component of the tornado system. I believe that the energy costs that we have quoted for the conventional systems are sufficiently higher than one could expect (due to technological advancements and optimization) and therefore would include replacement.

LARGE HORIZONTAL-AXIS WIND TURBINE DEVELOPMENT

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ABSTRACT

One facet of the Federal Wind Energy Program, Large Horizontal Axis Wind Turbine Development, is being managed by the NASA Lewis Research Center. These activities consist of several ongoing wind system developments oriented primarily toward utility application. In addition, a comprehensive technology program supporting the wind turbine projects is being conducted. This paper presents an overview of the NASA activities.

First-generation-technology large wind turbines (Mod-0A and Mod-1) have been designed and are in operation at selected utility sites. Second-generation machines (Mod-2) are scheduled to begin operations on utility sites in 1980. These second-generation machines are estimated to generate electricity at less than 4¢ per kilowatt hour when manufactured at modest production rates. However, to make a significant energy impact, costs of 2 to 3¢ per kilowatt hour must be achieved. The federal program will continue to fund the development by industry of wind turbines which can meet the cost goals of 2 to 3¢ per kilowatt hour.

Lower costs will be achieved through the incorporation of new technology and innovative system design to reduce weight and increase energy capture. The national challenge, however, is associated with acceptance by the utilities of wind turbines as part of their energy generating capability and the creation of a competitive industry to produce wind turbines efficiently. The principals - government, industry, and the utilities - are currently involved in meeting this challenge.

INTRODUCTION

Since 1973, the Federal Government has sponsored an expanding research and development program in wind energy in order to make wind turbine generators a viable technological alternative to existing electrical generating capacity. The current Federal Wind Energy Program, under the sponsorship of the Department of Energy, is directed toward the development and production of safe, reliable, cost-effective machines which will generate significant amounts of electricity.

One element of the Federal Wind Energy Program is Large Horizontal Axis Wind Turbine Development, which is being managed by the NASA Lewis Research Center. This activity consists of several ongoing wind system developments oriented primarily toward utility application. In addition, a comprehensive technology program supporting the wind turbine projects is being conducted. This paper presents an overview of the NASA activities. More detailed descriptions of the projects are presented in references 1 to 3.

WIND TURBINE DESCRIPTION

A typical wind turbine that NASA is developing is shown in figure 1. The rotor and drive train are mounted on a tower 100 to 200 feet high. The axis of rotation is parallel to the ground - thus the name horizontal axis wind turbine. The rotor consists of two blades. Rotor diameters of the machines currently under development range from 125 to 300 feet. The rotor operates at a low rotational speed of 20 to 40 rpm, and its output terminates in a gearbox which is simply a speed increaser (fig. 2). The gearbox increases the rotational speed to 1800 rpm, as shown, and the high-speed shaft drives a standard synchronous alternator. The alternator output is connected to a utility network. There are two controls on the wind turbine: (1) a yaw control, consisting of an electric motor, a pinion shaft, and a bull gear, which orients the machine in the direction of the wind, and (2) a pitch control, which moves the blades and controls the power. The pitch control is very similar to that of an aircraft propeller.

ONGOING ACTIVITIES

The wind turbines, either operational as experimental machines or under development, are illustrated schematically in figure 3. Three machines are shown. The Mod-0 and Mod-0A machines have rotor diameters of 125 feet and power outputs of 100 to 200 kilowatts. The Mod-1 is a larger machine, 200 feet in diameter, which is rated at 2000 kilowatts. An even larger machine, the Mod-2, is 300 feet in diameter and generates 2500 kilowatts; it looks different from the Mod-0A and Mod-1. The Mod-2 was developed later than the Mod-0A and Mod-1, and it was designed with a new technology base.

The annual energy output of these machines is shown in figure 4. At a site with an annual mean wind speed of 15 mph, the annual energy output of the Mod-0A machine is approximately 1000 megawatt hours per year. The Mod-1 machine will produce approximately five times the annual energy of the Mod-0A machine, and the Mod-2 produces 10 000 megawatt hours, or enough electricity for 1000 average homes.

The Mod-0A, Mod-1, and Mod-2 machines are being used (or are planned to be used) as experimental machines at utility sites. The activation dates for these machines are shown in figure 5. Four Mod-0A wind turbines are planned. Two machines are already operationing at Clayton, New Mexico, and Culebra Island, Puerto Rico. A third machine will be placed at Block Island, Rhode Island, in 1979, and a fourth machine will be erected in Hawaii in 1980. The results of 1 year of successful operation at Clayton, New Mexico, have been published in reference 1.

The Mod-1 wind turbine is planned for initial operation at Boone, North Carolina, in mid-1979, and the Mod-2 development is currently planned as a three-machine program. The three machines may be placed at a single site in 1980 for a 7.5-megawatt demonstration.

All the wind turbines in operation or under development are automatically (microprocessor) controlled. Their operating map is shown in figure 6. The units start when the wind velocity reaches a range from 7 to 11 mph (at a 30-ft height). As the wind speed increases, the power output also increases until rated power is attained. The power is then held constant at the rated value until a wind velocity of approximately 35 mph (at 30 ft) is reached. At wind velocities exceeding 35 mph, the wind turbine is shut down. It simply does not pay to design the machines for very high wind speeds. The annual energy content of the wind is small at high velocities because the wind does not reach these velocities very often on an annual basis. In addition, if the machines were designed to operate in high winds, the machine cost and weight would be excessive.

Mod-0 (100 kW) Wind Turbine

Mod-0 was the first large wind turbine that was designed and built by NASA (fig. 1). It is located at the NASA Plum Brook Station at Sandusky, Ohio. Mod-0 has been in operation since 1975 as a research machine and is utilized to validate wind turbine design techniques (computer codes) and to demonstrate new concepts that have potential to increase reliability and lower machine capital cost. Mod-0 tests and operations are closely focused to the support of ongoing projects conducted by industry. In this way, Mod-0 has made major contributions to the electrical and structural design of the machines currently under development (Mod-0A, Mod-1, and Mod-2).

Mod-0A (200 kW) Wind Turbine

The objective of the Mod-0A program was to gain early experience with wind turbines at utility sites. As stated previously, two machines are currently operational (fig. 7). The Mod-0A machine was designed and built by NASA. Westinghouse Electric Corporation is supporting the program and was the installation and support contractor for the Clayton machine. Westinghouse is assuming increasing responsibility for the other Mod-0A machines. NASA and DOE have been pleased with the success of the Clayton machine over the past year. The electrical, structural, and performance aspects of the basic system design have been validated. There have been no problems with the interface between the wind turbine and the utility. The machine is routinely synchronized to the utility grid and has provided approximately 3 percent of the Clayton power over the past year. The utility personnel are capable of operating the machine without difficulty. As expected, we had early operational difficulties with some of the hardware, but overall the operation has been very successful. The weekly and monthly machine availability in 1979 is shown in figure 8. As can be seen, having overcome early operational difficulties, we expect to reach the goal of 90 percent in 1979.

Mod-1 (2000 kW) Wind Turbine

The objective of the Mod-1 program (similar to Mod-0A) is to gain early operational experience with a megawatt output wind turbine at a utility site. The Mod-1 machine except for the blade was designed and built by the General Electric Company; the blade was built by the Boeing Engineering and Construction Company. The Mod-1 is a scaled up version of the Mod-0A machine. The machine and blade are shown in figures 9 and 10. The machine fabrication and installation are complete, and the acceptance tests and final machine checkout are in process at Boone, North Carolina. The operational phase of the program is expected to begin in mid-1979.

Mod-2 (2500 kW) Wind Turbine

The objective of the Mod-2 development was to design a cost-competitive, safe, reliable megawatt wind turbine for utility application at moderate wind sites (14-mph annual average at 30 ft). A model of the machine is shown in figure 11. This was the first machine designed to cost. The goal is for the 100th machine to generate electricity at less than 4¢ per kilowatt hour. The Boeing Engineering and Construction Company is the prime contractor for Mod-2. To date, there is every reason to expect that the cost goal will be met. The Mod-2 design has benefited extensively from prior experience. Test results from the Mod-0 and Mod-0A programs have been used to validate computer codes and identify and validate new design concepts that have been applied to Mod-2. In addition, the design experience from the Mod-1 project has been used. The key to the Mod-2 success to date has been the flexible structural system design, which has led to a relatively lightweight low cost machine with high annual energy output. Long lead hardware has already been ordered for the machine, and operations are scheduled for 1980.

COST OF ELECTRICITY

The cost of electricity (COE) in cents per kilowatt hour is plotted as a function of mean wind speed in figure 12 for the NASA wind turbines either operational or under development. This COE plot reflects the machine capital costs for the second units that are built and assumes that the machines will operate and generate electricity 90 percent of the time that the wind is in the proper speed range. The cost of electricity is calculated by a formula for new technologies recommended by the Electric Power Research Institute:

$$\mathrm{COE} = \text{(machine capital cost)(fixed charge rate)} \\ + \text{(operation and maintenance cost)/annual energy}$$

The fixed charge rate used was 0.18.

Several conclusions can be drawn from figure 12. The COE is dramatically affected by the site mean wind speed, and the identification of attractive wind sites is important to the application of this technology. The Mod-0A (200-kW) machine is associated with relatively high cost of electricity, 30 to 50¢ per kilowatt hour. A significant improvement (approx. 2 to 1) has been made in the Mod-1 (2000-kW) COE. Keep in mind that these two wind turbines are the same basic design; however, Mod-1 is a much larger machine. There are definite economies of scale which result in a major reduction in the Mod-1 COE from the Mod-0A COE. With Mod-2, in turn, another large cost reduction (2 to 1 compared with Mod-1) is expected as a result of improved technology incorporated into the Mod-2 design. The Mod-2 machines that will be operational in 1980 are expected to produce electricity at 14-mph wind sites at costs below 8¢ per kilowatt hour.

The dotted curve shows the projected Mod-2 costs for production units. We anticipate that these units will be cost-competitive in certain areas with attractive wind sites where current fossil fuel costs are high. However, before there is broad market penetration, further reductions in COE must be achieved. We believe that these reductions can be made. New system developments currently planned will incorporate new technology which will result in lighter weight, lower cost systems.

The contribution of the wind turbine subsystem elements to the cost of electricity is shown in figure 13. When the Mod-0A and Mod-2 rotor costs are compared, it is apparent that Mod-2 design improvements have resulted in major rotor cost reductions (2 to 1). In addition, the rotating machinery on top of the tower (blades, gearbox, generator, etc.) now comprises approximately one-half of the wind turbine costs, which signifies an economically balanced design.

The cost contributions of the other elements are fairly evenly distributed. However, it is believed that further reductions in costs of all of the subsystems can be achieved, with the largest reductions still to be gained in the rotor and drive trains.

DEVELOPMENT ASSESSMENT

Technology

Major improvements have been made in wind turbine technology over the past 5 years. As a result, wind turbine system design is understood. The design tools are in an advanced state of development and are available to U.S. industry. Operational machines at utility sites have validated the basic system, electrical, structural, and mechanical designs. The compatibility of the single unit wind turbine with utility interfaces has been successfully demonstrated. Further operational experience is required to address long-term reliability. Additional blade development is required and is under way to reduce cost and weight. Metal, fiberglass, and wood blades are all currently attractive candidates. A 150-foot fiberglass blade built by Kaman is shown in figure 14. Planetary gearboxes in large sizes may also require some development.

Environment Issues

No serious environmental issues have been identified which would impede the development of large wind turbines. Experience to date has shown that wind turbines are safe, quiet, and clean; however, television interference is a siting consideration.

Economics and Market Potential

Large megawatt machines have the greatest potential for application in utility networks because of economies of scale and are the only machines that will generate significant amounts of electricity. In most applications, wind turbines must produce electricity at 2 to 3 per kilowatt hour to have wide application as a utility fuel saver at current fuel prices. The Mod-2 machine approaches these costs, and moderate COE reductions and/or higher fuel costs will result in substantial market potential.

CONCLUDING REMARKS

First-generation-technology large wind turbines (Mod-0A and Mod-1) have been designed and are in operation at selected utility sites. Second-generation machines (Mod-2) are scheduled to begin operations on a utility site in 1980. These second-generation machines are estimated to generate electricity at less than 4¢ per kilowatt hour when manufactured at modest production rates. However, to make a significant energy impact, costs of 2 to 3¢ per kilowatt hour must be achieved. The Federal program will continue to fund the development by industry of wind turbines which can meet the cost goals of 2 to 3¢ per kilowatt hour. These lower costs will be achieved through the incorporation of new technology and innovative system design to reduce weight and increase energy capture. The national challenge, however, is associated with acceptance by the utilities of wind turbines as part of their energy generating capability and the creation of a competitive industry to produce wind turbines efficiently. The principals - government, industry, and the utilities - are currently involved in meeting this challenge.

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2. Mod-1 Wind Turbine Generator Analysis and Design Report - Executive Summary. General Electric Co., Philadelphia, Pa., under NASA Contract NAS3-20058, Report No. DOE/NASA/0058-79/3, NASA CR-159497, Mar. 1979.

3. Lowe, J.: Status and Outlook of Megawatt Size Wind Turbines for Utility Applications. Paper Presented at Energy Technology VI Conference, Washington, D.C., Feb. 26-28, 1979.

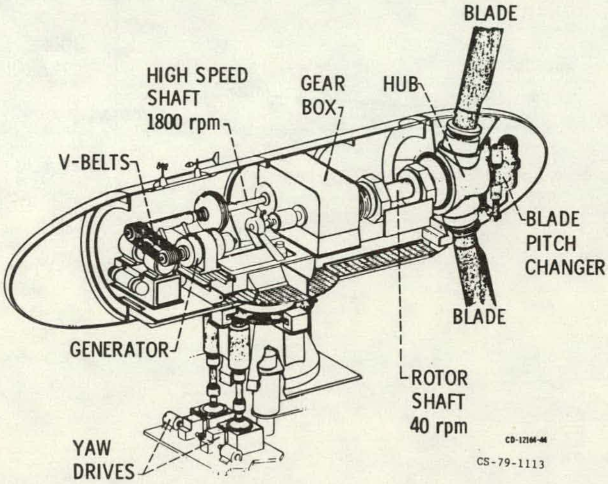

Figure 2. - 200 kW wind turbine nacelle interior.

Figure 1. - Horizontal axis wind turbine (Mod-0).

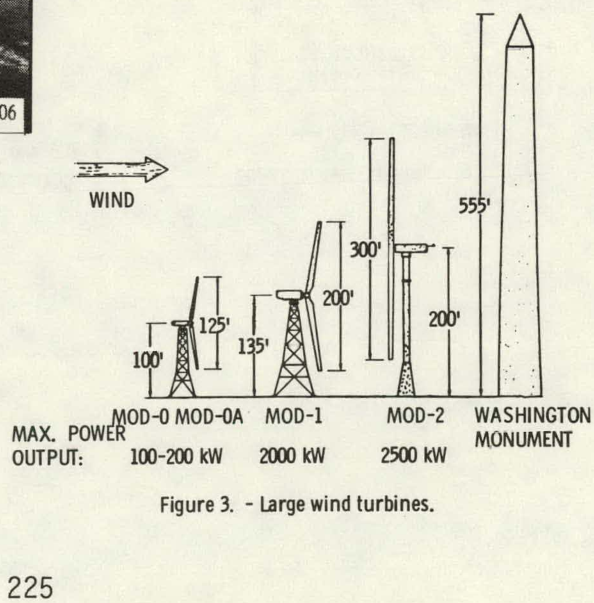

Figure 3. - Large wind turbines.

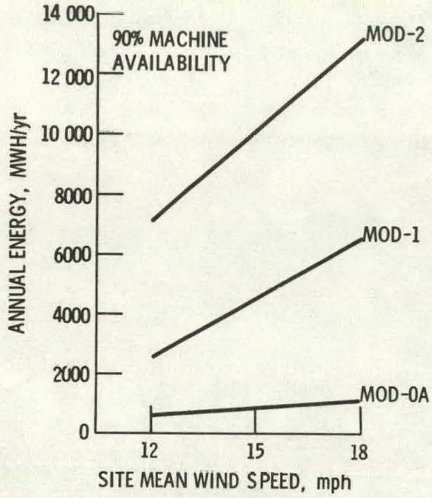

Figure 4. - Annual energy output.

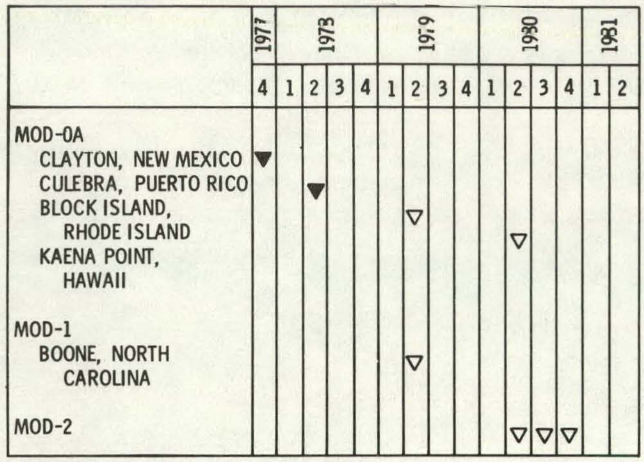

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Figure 5. - Actualor dates for large wind turbines.

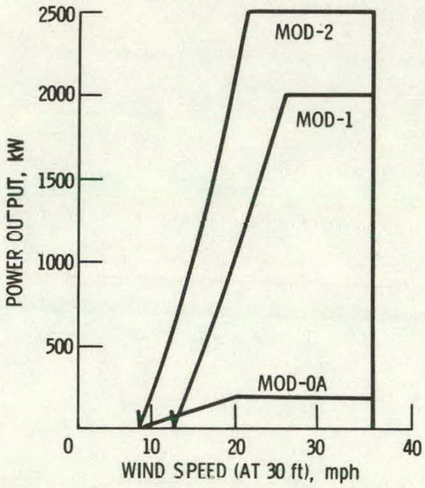
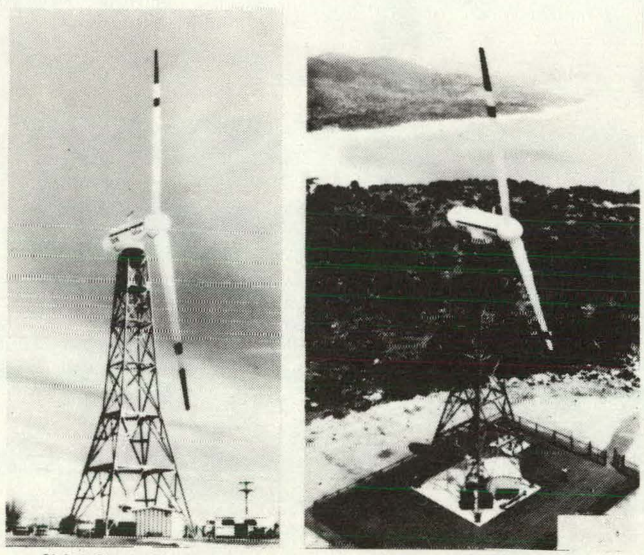


Figure 6. - Wind turbine operating range.



CLAYTON, NEW MEXICO CULEBRA, PUERTO RICO

Figure 7. - Clayton and Culebra machines.

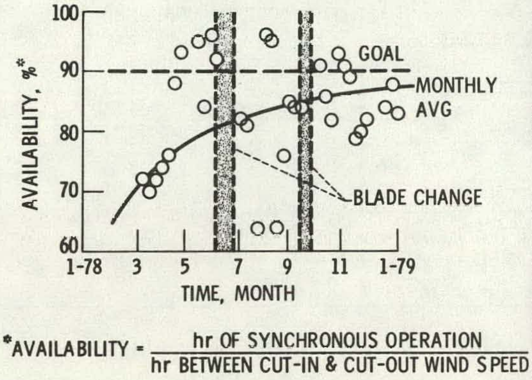


Figure 8. - Mod-0A availability.

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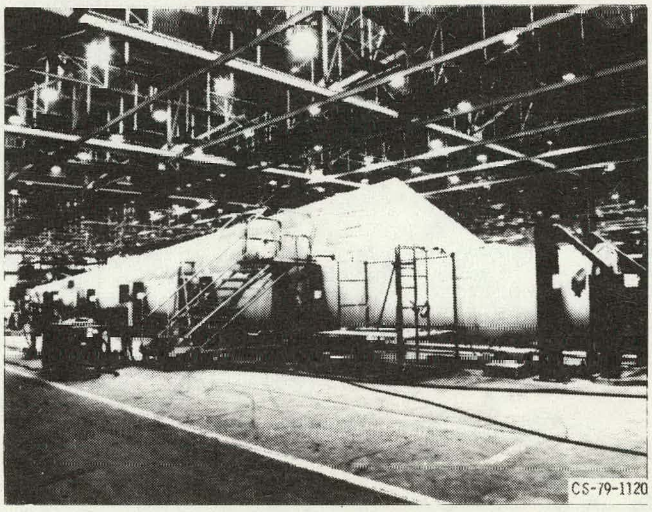

Figure 10. - Mod-1 blade.

Figure 9. - Mod-1 Machine.

Figure 11. - Mod-2 wind turbine.

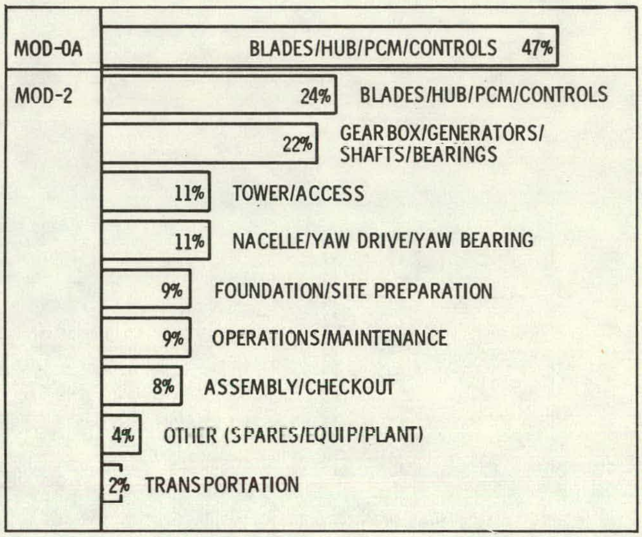

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Figure 13. - Contribution of design elements to COE.

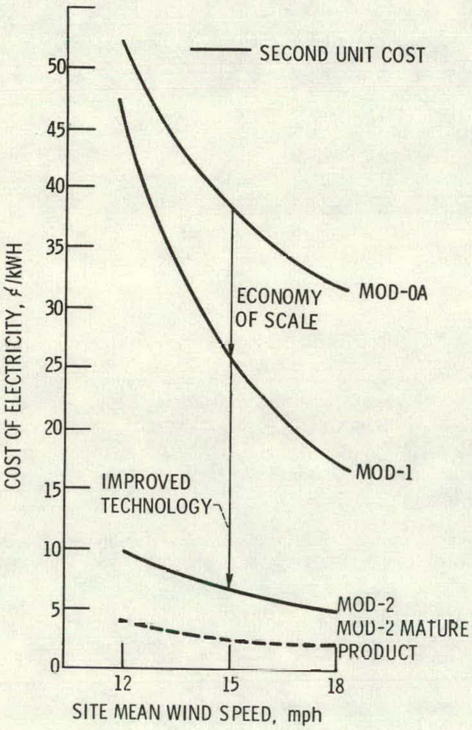

Figure 12. - Cost of electricity.

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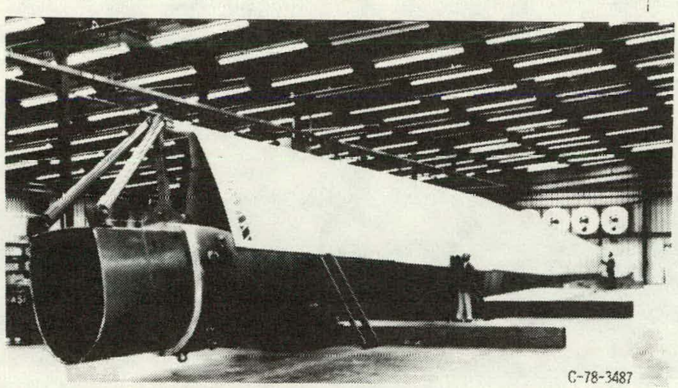

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Figure 14. - Kaman 150-ft fiberglass blade.

RESPONSES TO THE SPERA PRESENTATION

Marcel Harper, Tetra Tech., Inc.: The 9% for O&M is different from the number presented in February. At that time, you were talking about $15,000 for maintenance costs which is less than 1% of the initial cost.

Spera: This is the same chart that I used in February. It is 9% of the cost of electricity.

Jain-Ming Wu, Engineering Research & Consulting, Inc.: What kind of maintenance is needed for this type of machine?

Spera: The Mod-2 machine has a very detailed maintenance plan. With every potential failure there is associated a certain amount of time, manpower, and cost. These are the costs included in the 9%. Replacement of major subsystems is not included.

Richard Oman, Grumman Aerospace Corporation: Based upon your last statement, is it correct to say that your costs do not provide for the replacement of any of the blades or any of the other major subsystems during the life of the machine?

Spera: That is correct.

James Yen, Grumman Aerospace Corporation: What is a Mod-X?

Spera: It is a paper study which was performed by the Lewis Research Center. The purpose was to put together a design for a 200 kW machine which would reduce the cost of electricity to the 5-6¢/kWhr range.

Bill Clayman, American Wind Energy System Association: Was there additional damage to the structure of the fiberglass blade?

Spera: The test was a static test of a single blade, not a dynamic test. It was the manufacturing prototype.

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INNOVATIVE STRAIGHT BLADED VERTICAL AXIS WIND TURBINE

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ABSTRACT

Those theoretical and experimental studies of straight bladed Darrieus wind turbines which have been conducted at West Virginia University (WVU) since 1975 are reviewed in this paper. Emphasis is placed on the unusual aerodynamic effects which result from the orbital motion of the turbine blades, and the significance of these effects regarding turbine blade design is discussed. Blade test data from an outdoor turbine are compared to two dimensional wind tunnel tests of the same blades, and substantial differences in blade drag are noted. These differences are explained in terms of flow curvature, and the analytical techniques for investigation of this phenomenon are briefly mentioned. The authors point out that potential performance improvements may result from the application of variable camber and/or circulation control airfoils to turbine blade design. An indoor test facility, which will be used to systematically investigate blade aerodynamics, is described. Its use in comparing conventional to circulation control blades is discussed.

INTRODUCTION

Analytical and experimental studies of straight bladed vertical axis wind turbines have been underway at WVU since 1975. The primary objective has been the evaluation of circulation control airfoils, which exhibit higher lift to drag ratios than conventional airfoils, and should offer improved turbine performance[1]. Preliminary research revealed aerodynamic complexities beyond initial expectations. Therefore the circulation control design effort was somewhat delayed, so that the new information could be incorporated in configuration optimization studies. Theoretical analysis showed the extreme sensitivity of turbine performance to the assumed blade drag. To verify selection of the proper drag coefficients and to provide data for comparison to theoretical predictions, an experimental turbine was constructed and tested at WVU. A major finding of the test program was that flow curvature effects, previously thought to be insignificant, were in fact important determinants of turbine performance. It was also learned that blade drag characteristics could be determined quite simply from torque data taken at zero wind conditions. Thus, it was decided that systematic studies of fundamental aerodynamics could be conducted more cost effectively at an indoor test facility, and that this same facility could be used to evaluate the benefits of circulation control. Such a facility has been constructed; it is described in the text following a more detailed description of the research which preceeded it.

THEORETICAL STUDIES

Early theoretical studies conducted at WVU recognized the extremely complex aerodynamics of Darrieus turbines, particularly the unsteady nature of the flow and the interaction of turbine blades and wake. Therefore, a vortex model [2] was developed for the blades and the wake which, it was hoped, would be sensitive enough to reflect these flow complexities. Figure 1 shows a typical wake/blade interaction predicted by this method. Another interesting application of the method was to estimate C_p under the idealized assumption of zero blade and support structure drag. The result of these calculations, shown in Figure 2, suggest that the theoretical C_p limit for Darrieus turbines may exceed the theoretical Betz limit for propeller type machines.

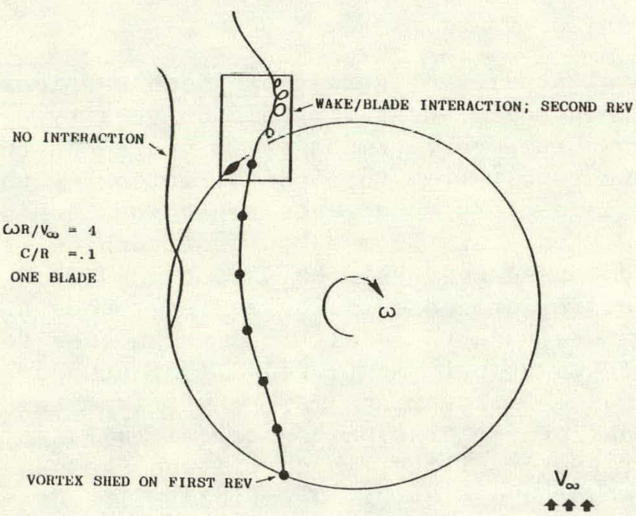

FIGURE 1. DYNAMIC INTERACTION OF THE TURBINE BLADE AND WAKE

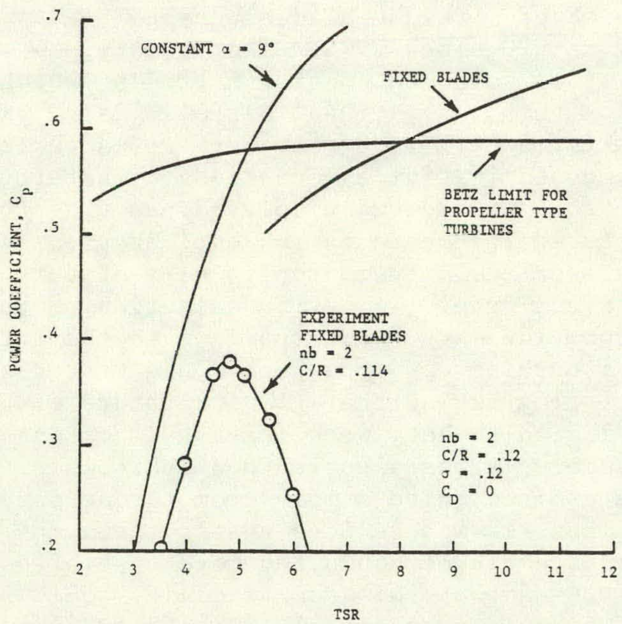

FIGURE 2. THEORETICAL VAWT PERFORMANCE LIMITS AND EXPERIMENTAL DATA

Darrieus turbine performance prediction methods are semi-empirical, requiring a priori knowledge of blade drag. Thus, the boundary layer characteristics are of considerable interest. A theoretical analysis [3] was conducted which showed that the orbital motion of the turbine blades resulted in extraordinary boundary layer radial pressure gradients that could appreciably influence both lift and drag.

The evidence of previous investigations and the WVU theoretical studies clearly pointed to the need for experimental data. For this reason an experimental Darrieus turbine was constructed at WVU as part of the continuing research.

EXPERIMENTAL TESTS

The outdoor test model shown in Figure 3 provided experimental data which were used to deduce turbine blade drag and power coefficients. The effects of tip speed ratio, solidity and Reynolds number were investigated by testing two sets of blades of differ-

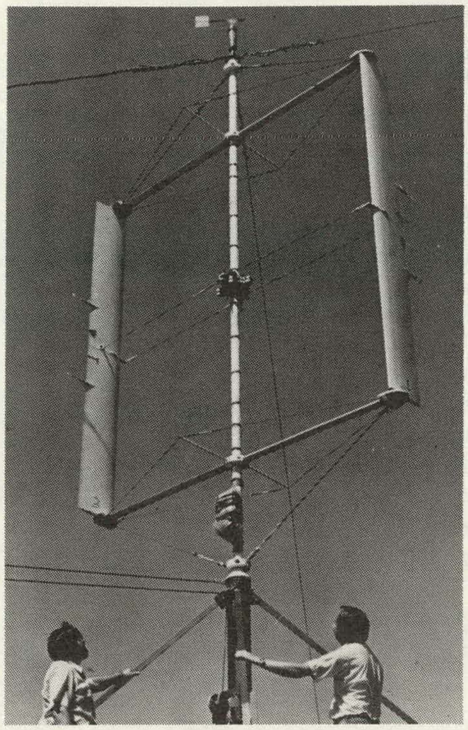

Figure 3. WVU OUTDOOR TEST MODEL VAWT

ent C/R at various rotor RPM's. The first set had a 17.4 cm chord (C/R = 0.114); the second set had a 39.7 cm chord (C/R = 0.260). Both had NACA 0015 airfoil sections and blade spans of 3.25 meters. Figure 2 shows some typical power coefficient data obtained from the free air tests. Details of machine design, test procedures, data reduction and analysis can be found in References 4, 5 and 6.

In analyzing the test results it became convenient to define an effective drag coefficient which reflected the combined effects of aerodynamic drag and moment. This coefficient is given by the equation,

$$C_{D_e} = C_D - C_M C/R. \qquad (1)$$

C_{D_e} will always be greater than C_D if the turbine blade produces a nose out pitching moment. For $C_M = 0$, which was originally presumed to be the case for the symmetrical airfoils mounted at their quarter chords, then $C_{D_e} = C_D$. Curves of C_{D_e} versus α_g were developed from torque measurements taken at different blade pitch settings and rotor RPM's. These plots produced some noteworthy results. First, $C_{D_{min}}$ increased with increasing Reynolds number, a result contrary to the normally observed trend associated with a laminar boundary layer at the low test Reynolds numbers. Secondly, $C_{D_{min}}$ apparently occured at negative values of α_g, a characteristic indicative of non zero airfoil incidence, camber, or both. These perplexing observations prompted efforts to more adequately interpret the phenomena.

Our studies [6] showed that the usual assumptions of constant V_R and α_g over the entire blade chord could introduce substantial error in blade aerodynamic analysis. These findings differed from those of previous studies [7], which concluded that the effects of orbital motion and the resulting flow curvature were negligible for small C/R. Fortunately, the outdoor test model offered the opportunity to substantiate the predicted overall detrimental effects of flow curvature.

FLOW CURVATURE CONSIDERATIONS

One of the simplifying assumptions in the analysis of Darrieus turbines has been that an average instantaneous blade relative inflow velocity and angle of attack could be accurately defined. These are assumed to be the values calculated at the point of attachment of the turbine blade to its support arm, a distance R from the turbine axis of rotation. Upon closer examination, however, it is found that this assumption may produce errors. The radial distance from the turbine axis of rotation to any point on the blade chord is unique. Taking this unique radius into proper consideration when defining the turbine geometry leads to mathematical expressions for the "local" angle of attack, α, and relative inflow velocity, V_R. While V_R changes along the chord by only a few percent, changes in α can be very large depending upon the blade location relative to the free stream wind, the tip speed ratio and C/R. It can be shown that the effect becomes more pronounced as C/R increases.

From the kinematic analysis [3] it is apparent that the orbital blade motion produces circular streamlines from the blade point of reference and that this flow curvature markedly alters the local relative velocity and angle of attack of the turbine blades. It is logical to conclude that the resulting aerodynamic properties will differ from those of blades in rectilinear flow. This observation led to speculation that perhaps the symmetrical airfoils in curvilinear flow would exhibit the aerodynamics of cambered airfoils in rectilinear flow. This phenomena had been noted by previous investigations [7,8] but was dismissed as insignificant for blades of small C/R. The authors were not similarly convinced, however, and so proceeded with the more detailed conformal mapping analysis outlined below.

The curvilinear flow field of Darrieus turbines may be examined with the aid of conformal mapping techniques. By this method [6] the actual geometric airfoil in the curved flow may be transformed to an equivalent airfoil in rectilinear flow. This process effects a change in camber; thus, the terminology "virtual camber" and "virtual incidence" is applied to the airfoils which have a particular camber and incidence is essence but not in fact. Defining the effective angle of incidence resulting from flow curvature as α_i and the geometric angle of attack at the reference point on the blade chord as α_g, the combination of the two is the virtual angle of attack, $\alpha_v = \alpha_g + \alpha_i$. α_v is the actual flow angle of attack experienced by the turbine blade. Through the transformation, local velocities and angles of attack are preserved, so that the virtual airfoil should exhibit similar aerodynamic behavior to that of the geometric airfoil in orbit. Sectional airfoil data is then applied to the virtual airfoil whose properties vary with the assumed C/R, θ and tip speed ratio.

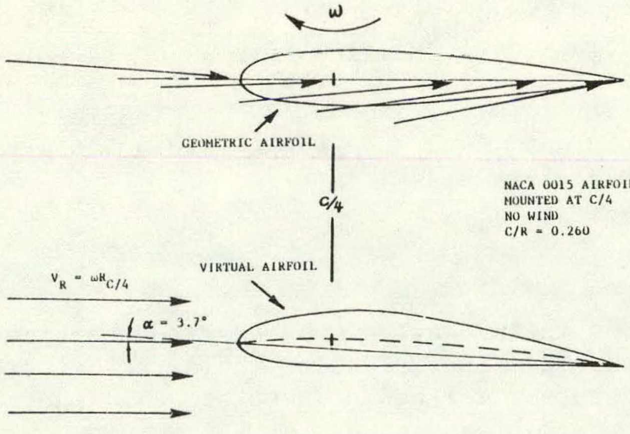

Figure 4. GEOMETRIC AIRFOIL IN CURVED FLOW AND EQUIVALENT VIRTUAL AIRFOIL IN RECTILINEAR FLOW

Figure 4 illustrates the transformation procedure for an NACA 0015 airfoil mounted at its quarter chord and having zero incidence to the rectilinear blade velocity vector. Zero free stream wind velocity, TSR = ∞, was assumed; thus, dependence on orbital position was removed. This assumption does not invalidate the qualitative illustration of virtual camber effects.

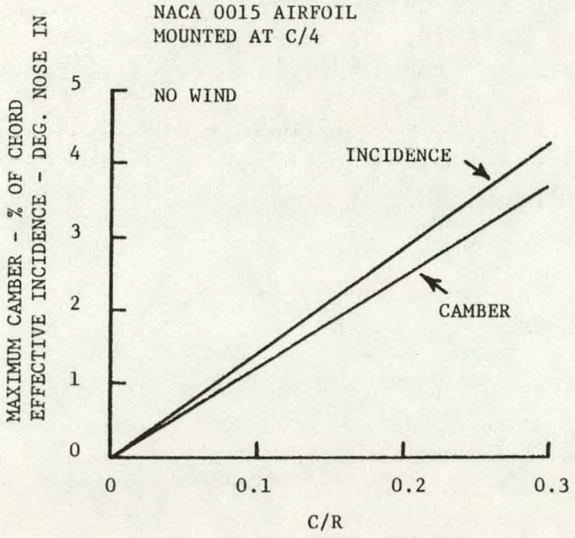

Figure 5. LINEAR VARIATION OF VIRTUAL CAMBER AND INCIDENCE WITH C/R

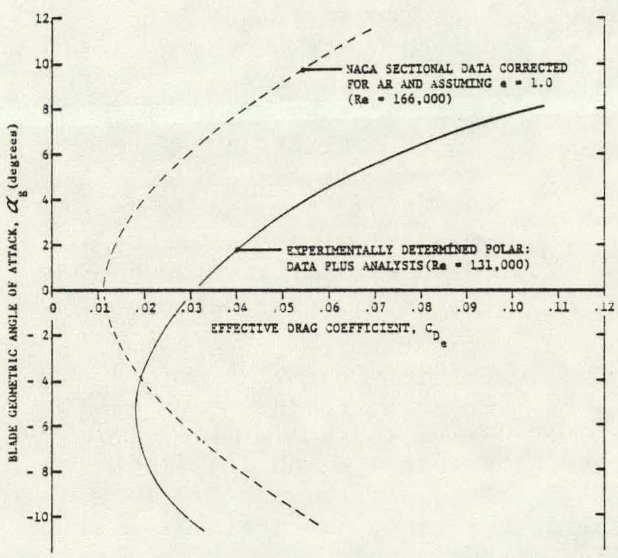

Figure 6. EXPERIMENTAL DRAG POLAR FOR LARGE BLADES AND NACA SECTIONAL DATA

Analysis shows that flow curvature introduces an effective angle of incidence in addition to the usual blade angle of attack. Furthermore airfoil camber is altered. The magnitude of both changes is strongly dependent on C/R as shown in Figure 5. Of particular interest are the results for the blades tested on the WVU turbine. It was found that the small blades transform to airfoils having 1.4% camber and 1.6° incidence, and that the large blades transform to airfoils having 3.2% camber and 3.7° incidence.

Figure 6 compares drag curves from test data to NACA 0015 airfoil sectional data [9] corrected for finite span effects. For the large blades, the experimental drag agrees poorly with the corrected sectional data. $C_{D_{min}}$ is approximately 75% greater than expected and it occurs at a large negative angle of attack, $\alpha_g \simeq -5°$. Recall that the conformal transformation procedure predicts an effective angle of incidence of 3.7° which would in large part account for the α_g shift. For the small blades, the drag compares well except at the large α_g corresponding to high lift coefficients. This could only be explained by the loss of planform efficiency in the noted range and may result from the aforementioned premature laminar boundary layer separation. As with the small blades, a much reduced planform efficiency is indicated for the large blades.

It was thought that the disparate drag characteristics of the large and small blades might result from airfoil shape or roughness differences, but sections of each blade were tested in the WVU low speed wind tunnel [3], and the test results, Figure 7, revealed only minor differences

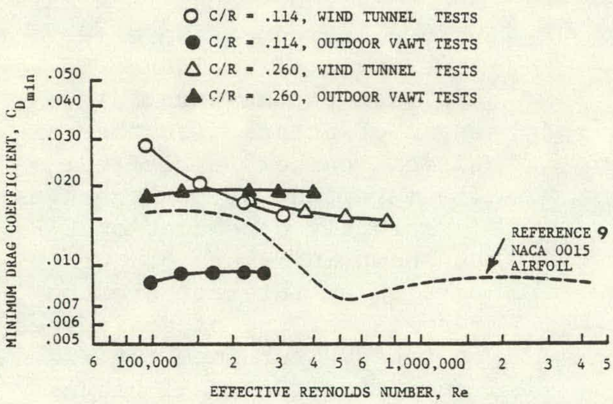

Figure 7. COMPARISON OF $C_{D_{MIN}}$ FROM WIND TUNNEL AND OUTDOOR TESTS

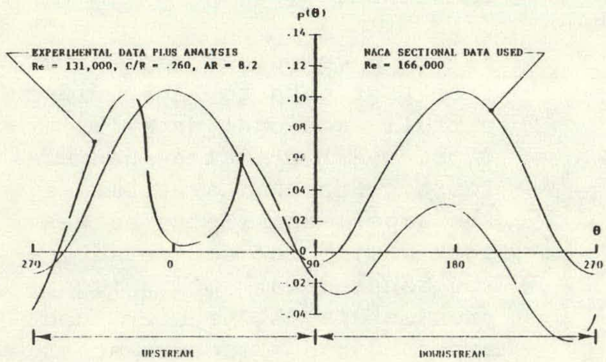

Figure 8. THE MERIT FUNCTION p(θ) CALCULATED FOR THE GEOMETRIC AND VIRTUAL AIRFOILS

in drag characteristics. Note also in Figure 7 that $C_{D_{min}}$ from the outdoor turbine tests does not decrease with increasing Re as is well documented in the literature and demonstrated by the wind tunnel data. It has been concluded that these unusual drag characteristics are attributable to flow curvature and its associated virtual camber and boundary layer effects.

Virtual camber influences airfoil aerodynamics in two important ways: first, it causes an upward shift in the lift curve, and second, it introduces a moment coefficient which produces countertorque over the entire blade orbit. Virtual incidence acts to shift the lift curve to the left on the α_g axis of the C_L - α_g curve. The effect of these features on power extraction may be observed with the aid of Figure 8. p(θ) is a non dimensional measure of merit which is proportionally related to C_p. Details of its derivation and significance can be found in Reference 10, but for the present discussion it will suffice to say that it is a convenient parameter which depends only upon turbine geometry and blade airfoil characteristics. It is useful for comparing airfoils which are candidates for Darrieus turbine blades. p(θ) is plotted in Figure 8 for both the virtual and geometric airfoils assuming the large chord blades mounted at their quarter chord in fixed pitch operation at TSR = 5.5. Note the sharp drop in p(θ) at approximately 50° and 330° for the virtual airfoil. This is due to blade stall in these regions. For the geometric airfoil, the maximum angle of attack reached at TSR = 5.5° is α_g = 10.5°. But virtual incidence causes an increase in this value to α_v = 13.8° and the stall angle is exceeded. Associated with blade stall are large drag increases which diminish torque production. On the downstream side of the turbine p(θ) is everywhere reduced since the virtual airfoil produces very little lift at negative angles of attack due to the virtual camber effect.

Integrating the p(θ) curves of Figure 8 shows that the net measure of merit for the virtual airfoil is only 22% of that expected of the geometric airfoil. This result would of course change at different TSR and C/R. In fact, analysis of the $p(\theta)$ plot for the small blades (not presented here) showed a net measure of merit decrease of only 1%. It was noted for these small blades that efficiency actually increased on the upstream side of the turbine, but that losses on the downstream side more than offset the front side gain. The situation suggests that some combination of virtual camber and incidence may actually produce a net gain in C_p.

The importance of flow blockage and unsteadiness cannot be neglected in considering turbine performance. Both depend on rotor solidity, and so a choice of C/R cannot be made solely on the basis of flow curvature considerations. However, the preceeding analysis, which is based on the properties of the virtual airfoils, should still be valid for evaluating competing airfoils and pitch schedules. That is to say, if one airfoil has better aerodynamic properties than another, it should still show an advantage regardless of the specific influence of other flow phenomena (blockage, unsteadiness, and to a large extent, boundary layer effects). The $p(\theta)$ method is therefore a means of evaluating airfoils and their performance relative to each other; it cannot be used to accurately predict C_p.

FLOW CURVATURE TURBINE DESIGN IMPLICATIONS

Large C/R's produce significant detrimental aerodynamic changes and one might assume that they should be avoided. This is not necessarily true since by understanding and using to advantage the mechanisms of virtual aerodynamics, large C/R blades remain viable choices. They may in fact be preferred because the desired rotor solidity can be achieved with fewer blades, obviously at lower cost. Furthermore, large blade chords imply high Reynolds numbers, and therefore improved lift and drag characteristics. So the choice of airfoil section, C/R and blade pitch schedule can only be made intelligently upon proper consideration of flow curvature. The material which follows discusses several possibilities.

Symmetrical airfoils have historically been chosen for Darrieus turbines because $C_L - C_D$ characteristics are identical at positive and negative α_g corresponding to upstream and downstream orbital positions, and because C_M is zero and contributes no countertorque. However, virtual camber and incidence destroy the premise upon which the choice of these airfoils is based. For a given α_g more lift is produced upstream than downstream, and the additional α_i may even cause blade stall at certain TSR's. The simplest way to alleviate this problem is to fabricate geometric airfoils whose virtual equivalents are the symmetrical airfoils originally chosen. The inverse conformal transformations of Reference 3 would be used to design the geometric airfoil for the assumed TSR, C/R and blade mounting point. Since this can be accomplished for any C/R, the objection to large C/R is obviated. The concept may be extended to the consideration of airfoils whose virtual equivalents really are cambered. These airfoils would experience increased power extraction on the upstream side of the turbine due to increased C_L, and the diminished efficiency on the downstream side might be more than offset by the upstream improvements. This seems particularly plausible since power extraction is asymmetric with respect to the cross wind axis as a result of flow blockage. At the present time it is not certain whether net power extraction will be increased by designing for front side or back side optimization. But the option remains to explore this possibility by judicious choice of camber and initial blade pitch setting. Such a study can only be pursued experimentally or with the aid of an accurate model of the flow blockage.

Under certain conditions power extraction on the upstream portion of the turbine may be greatly improved as a result of virtual camber. This results from higher C_L at a given α_g. Note in Figure 8, for example, that had the large blades not stalled at $\theta \simeq 50°$ and $\theta \simeq 330°$, $p(\theta)$ would have remained greater than expected over the entire upstream side. For variable pitch machines the stall problem can be avoided by adjusting the blade pitch schedule. But the severe power loss on the downstream side resulting from virtual camber and incidence must also be considered. If the favorable effects noted on the front side could somehow be extended to the back side, overall efficiency would be greatly improved. This situation recommends serious consideration of electromechanically implemented variable camber.

Variable camber has been used extensively on fixed wing aircraft in the form of leading and/or trailing edge devices and all manner of boundary layer control devices. It should certainly be possible to apply these same principles to Darrieus turbine blades. Cyclic manipulation of plain or split flaps should be no more difficult than cyclic manipulation of blade pitch. Combined with judiciously chosen virtual camber and control of blade pitch, performance enhancement should be substantial. It is of course questionable whether the greatly increased aerodynamic drag and moments of flapped airfoils could be overcome by the increased lift to yield a net improvement. But the potential can be demonstrated simply by considering $p(\theta)$ at the optimum operating point of the blades. Figure 9 illustrates the situation by comparing drag polars of a symmetrical NACA 0012 and a cambered NACA 4412 airfoil. In this example, a lift/drag ratio improvement of 34% at the operating point produces an estimated 38% $p(\theta)$ increase for blades of $C/R = 0.10$.

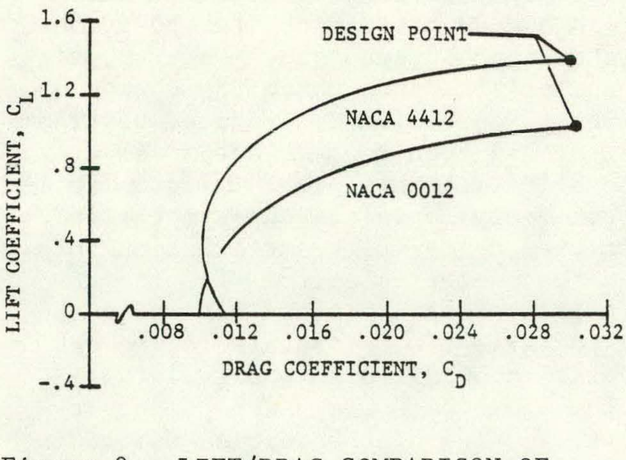

Figure 9. LIFT/DRAG COMPARISON OF CAMBERED AND SYMMETRICAL AIRFOILS

The potential of cyclically manipulated leading edge devices is similarly impressive whether used alone or in concert with trailing edge devices. Leading edge devices have the effect of extending the linear range of the lift curve and delaying stall. Thus, higher C_L's are achieved at higher angles of attack. C_L increases of 35% and stall angle increases of 60% are typical. The combined effect of a 35% C_L increase and a 60% increase in blade stall angle is to more than double the positive torque produced by the lift. Undoubtably, countertorque will also increase as a result of C_D increases. Nevertheless, the potential net performance improvements associated with leading edge devices are quite promising. Furthermore, it may be possible to design a passive system which requires little or no power for leading edge device actuation.

Aerodynamic improvements associated with variable camber may also be achieved by boundary layer and/or circulation control. The concept being investigated at WVU involves circulation control by blowing over a round trailing edge. Extremely large lift coefficients are developed at virtually all angles of attack. Preliminary analysis shows than even when the power requirements of blowing are deducted, C_p improvements result. The original concept applied to Darrieus turbines involved alternate upper and lower surface blowing as the blades passed through $\theta = 90°$ and $\theta = 270°$. Another interesting possibility is to tailor the blade camber to optimize power extraction either upstream or downstream and then to apply blowing on the alternate side. This would simplify mechanical implementation while at the same time reducing the power requirements for the supply air.

Regardless of how the effects of variable camber are produced a secondary benefit is a reduction of the TSR at which maximum C_p is achieved, presumably the turbine operating point. Lower TSR's are permitted when blade stall angle increases, and lower TSR's are dictated when blade drag increases. Reducing the operating TSR implies a reduction in blade angular velocity, ω. Much of the turbine structural design is dictated by the centrifugal forces which are proportional to $(\omega)^2$. Thus, reduced operating TSR makes the structural design criteria less stringent and will certainly reduce costs.

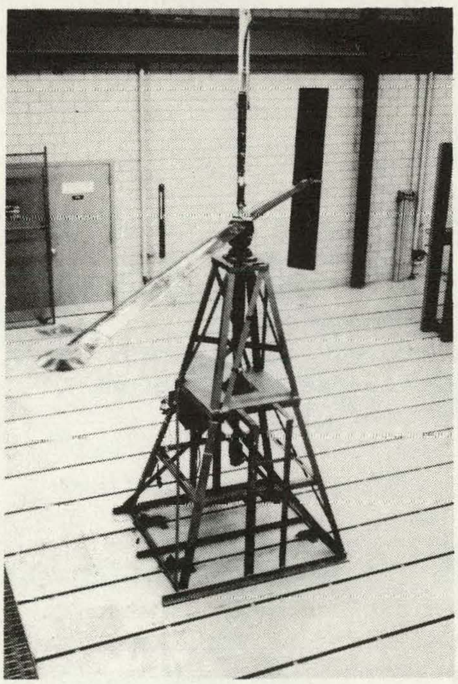

Figure 10. WVU INDOOR VAWT BLADE TEST MACHINE

INDOOR BLADE TEST FACILITY

Experience with the outdoor test turbine showed that a great deal of fundamental aerodynamic information could be deduced from tests at zero wind conditions. It was decided therefore, to construct an indoor test facility which could be used to systematically investigate parameters of aerodynamic significance. The philosophy behind this approach is analogous to that which leads to the use of wind tunnels prior to flight test of prototype aircraft. An important distinction between the blade test facility and wind tunnels is the simulation of curvilinear flow by rotating the test blades about a central shaft as shown in Figure 10. Testing in the benign indoor environment facilitates maintenance and model changes, while delays resulting from adverse weather are obviated. Furthermore, the blade support structure and the entire instrumentation system are permanent reusable components. Virtually any blade configuration can be tested on this machine. Reynolds number and C/R are changed by systematically varying the rotor RPM and by using various combinations of interchangeable support arm sections. Provisions for changing the blade angle of attack are also incorporated. To test different airfoil shapes only a single blade must be constructed. Modifications of a particular blade permit investigation of aspect ratio effects, end plating and lift enhancement devices. The facility is also designed for testing boundary layer and circulation control by either suction or blowing. Blade aerodynamic lift, drag and pitching moment are measured by a three component internal strain gage balance. A torque cell on the shaft provides data which can be used to cross check the effective drag resulting from aerodynamic drag and pitching moment. Precision slip rings mounted atop the shaft have sufficient capacity to monitor blade stresses, internal pressures, balance fouling or other parameters of internest. Data is continually sampled and fed through an analog to digital converter to an on line mini computer which processes in real time and/or stores information for subsequent analysis.

An unusual feature of the test machine is the use of a single blade cantilevered at mid span on a central support arm. There are no guy wires or ancillary supports. The centrifugal forces resulting from blade rotational motion are balanced by a counterweight located on the support arm equidistant from the central shaft. This configuration presented some challenging structural design problems, but was chosen for several important reasons. First, overall costs are minimized and configuration changes are simplified when only one blade is used. Secondly, this choice allowed us to demonstrate the feasibility of this configuration as a viable candidate for production machines. If future developments prove the workability of this configuration, Darrieus turbine net power extraction should be enhanced as a result of reduced support structure drag.

BLADE TEST OBJECTIVES

The primary goal of the indoor blade tests is to demonstrate that the aerodynamic improvements associated with circulation control will materialize in the unique curvilinear flow field of Darrieus turbines. Concurrently, the high pressure air delivery system is being developed and tested on the indoor facility. Tests of conventional blades, shown in Figure 11, are also being pursued so that their aerodynamic characteristics can be directly compared to those of the circulation control blades shown in Figure 12. A test matrix of Re, C/R and α_g has been established which will also allow comparison of test data to published NACA sectional data, to the WVU free air tests of a similar blade and to the WVU two dimensional wind tunnel tests. Furthermore, the conventional blade test data will be used to verify the flow curvature effects predicted by the conformal mapping analysis and demonstrated in the outdocr tests. In this manner it is hoped that analytical procedures can be developed which can be used to perform blade optimization studies. Assuming that the circulation control blade tests show promising results, these procedures will be used to design a circulation control blade for free air testing.

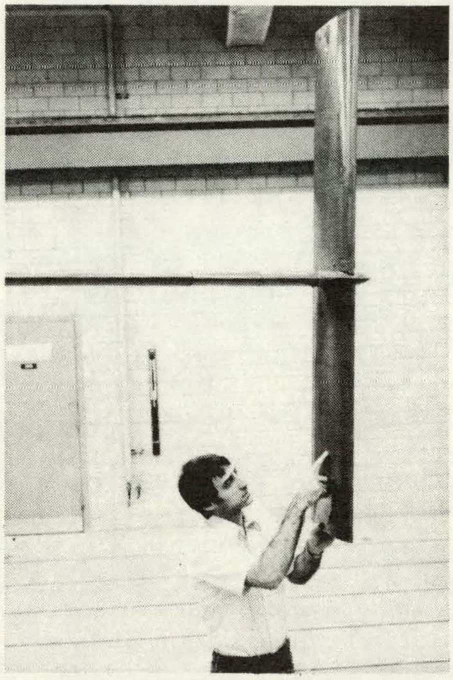

Figure 11. NACA 0015 AIR-FOIL BLADE ON INDOOR TEST MACHINE

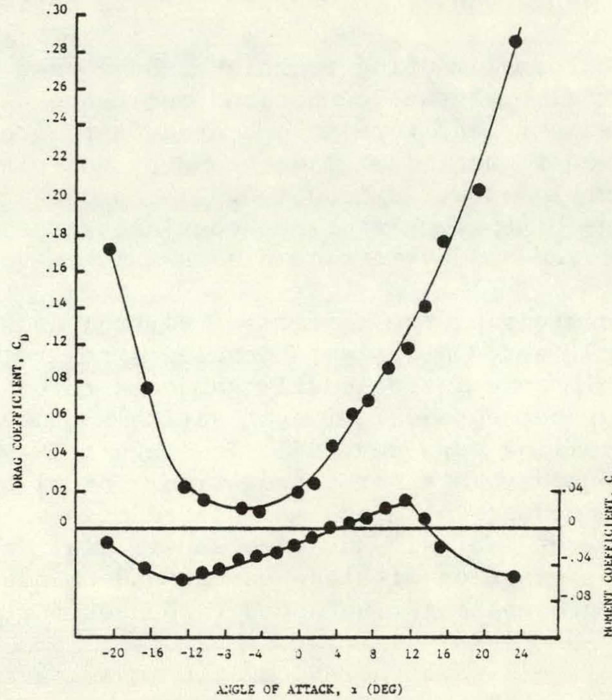

Figure 13. TYPICAL DATA FROM INDOOR TESTS

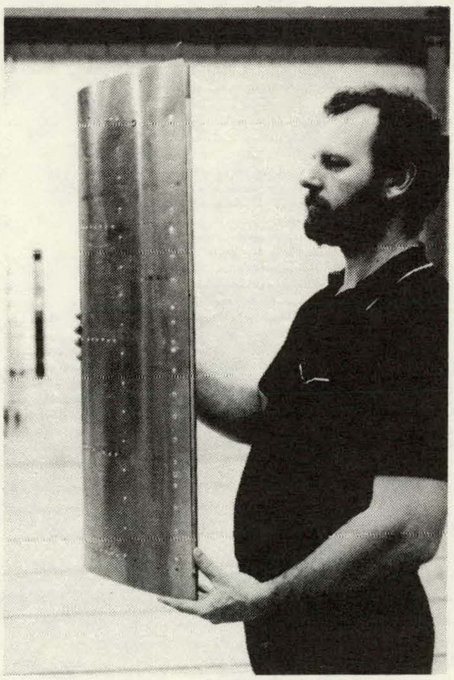

Figure 12. CIRCULATION CONTROLLED BLADE FOR IN-DOOR TEST MACHINE

Most of the tests conducted thus far have been directed toward verifying structural integrity, checking the instrumentation, developing software and determining tare characteristics. However, some preliminary aerodynamic results have been obtained from the indoor test facility and are shown in Figure 13 for illustration.

CONCLUDING REMARKS

The theoretical and experimental research conducted at WVU have attested to the complex aerodynamics associated with Darrieus turbines. It has been shown that airfoils in curvilinear flow exhibit characteristics much different than they would in rectilinear flow. In addition to virtual camber and incidence, large boundary layer pressure gradients result from flow curvature and act to alter the airfoil characteristics. Under most circumstances flow curvature has a detrimental influence on blade aerodynamic efficiency. However, when properly considered, virtual aerodynamics may be used advantageously to enhance turbine performance.

Conformal mapping techniques have been developed which can be used to predict virtual camber and incidence as a function of basic airfoil geometry and turbine operating parameters. These methods can then be used to optimize blade geometry and pitch schedule, thus improving turbine power extraction. The procedure is as yet untried, but it is one of the goals of the continuing research to verify performance improvements by testing blades which have been designed as described.

In studying the effects of virtual camber on Darrieus blade aerodynamics, certain insights developed regarding the possible use of blades which are intentionally cambered to enhance performance. This led to further consideration of variable camber in the form of leading and/or trailing edge devices. The result is similar to that achieved through boundary layer or circulation control by blowing, namely, substantial increases in C_p and modest reductions in the optimum TSR. Though much of the analysis has been superficial, the authors are convinced that optimization of blade camber and boundary layer/circulation control represent major untapped resources for performance improvement.

To facilitate the systematic investigation of blade aerodynamics and to assess the aerodynamic improvements of circulation control, an indoor test facility has been developed. Virtually any blade configuration can be tested(only a single blade must be fabricated) by manipulating its radial position, angle of attack and rotational speed. The facility is to be used in a fashion analogous to wind tunnel testing. That is to say, the fundamental aerodynamics of potential blade configurations will be investigated and designs will be optimized using the test results. Subsequently, these designs may be tested outdoors. The scope of the research to be conducted using this facility is currently quite limited. But the facility offers exciting possibilities for future studies. These include boundary layer pressure surveys, leading/trailing edge device testing and systematic studies of important blade geometric parameters.

ACKNOWLEDGEMENTS

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NOMENCLATURE

C	Turbine blade chord
C_D, C_L, C_M	Drag, lift, and moment coefficients, respectively
$C_{D_{min}}$	Minimum drag cofficient
C_P	Blade power coefficient
R	Turbine rotor radius
Re	Reynolds number
TSR	Tip speed ratio: ratio of ωR to free stream wind
V_R	Blade relative inflow velocity
α	Angle of attack with respect to the local velocity
α_g	Angle of attack at the blade mounting point
θ	Angle between free stream wind vector and radius arm

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AUTHORS' NOTES

1. The acronym VAWT refers to Vertical Axis Wind Turbine.
2. Rotor <u>solidity</u>, $\sigma = (nb)(C)/2R$.
3. nb is the symbol for the number of turbine blades.

RESPONSES TO THE MIGLIORE PRESENTATION

Peter Moretti, Oklahoma State University: You explained very clearly the curved field and the conformal transformation in order to get a straight flow for the ideal flow field. This is an important point. You also said that whereas the conformal transformation takes care of the ideal flow there are also effects on the boundary layer due to the rotating coordinate system which affects performance of the airfoil. This has also been pointed out by Lissaman and in the rotating machinery work of Johnston at Stanford. Kindly comment on the possible consequences and implications that this might have on rotating machinery as well as the dynamic inducer.

Migliore: We did conduct an analysis which showed that you get an order of magnitude difference in the boundary layer pressure gradients. In fact, we find that this effect is proportional to the tip speed ratio squared, so it is rather important. If you look at the blade rotation, there is a certain portion of the orbit where that may in fact help because the suction side of the airfoil changes with orbit. It is a complicated phenomenon to analyze in terms of its impact on performance. I might add that the indoor test machine we designed has the capability of doing boundary layer studies by actually pressure tapping the airfoil.

Melvin Snyder, Wichita State University: In addition to the difference in angle of attack due to the virtual field, there is in fact a difference because the upwind blade experiences a wind velocity which is different from the downwind blade as a result of the energy which has been extracted so that the apparent angle of the attack of the two blades at the same phase angle is different. Did you consider this in your analysis?

Migliore: We did present an oversimplified version of this phenomenon. In fact, the angle of attack varies with orbital position, with blade mounting point, with chord to radius ratio, etc. We refer to this as a blockage effect. There is no good model of blockage effects but it is absolutely certain the downstream blades experience a different velocity field. We know of no way to analyze this problem except perhaps by using vortex methods to show the changes in velocity. Theoretically, these methods work. The most concise reference that I can give you at this point is AIAA paper No. 79-0112. Our final contract report contains an entire volume on this flow curvature.

George Tennyson, DOE: I would like to thank Peter Lissaman for illustrating that the Dutch windmills have shown that windmills can last more than 30 years. One of the main purposes of this gathering is to determine how we should screen innovative techniques so that we can devote the funding to the most worthy concepts. I would like you people to think about that and to be able to provide your input in the windup session. I am very interested to see if constant mass flow coefficient rates for circulation control are used in a changing situation or whether the flow rate is varied around the circuit.

AUGMENTED VERTICAL AXIS
WIND ENERGY SYSTEM EVALUATION

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ABSTRACT

Performance and cost characteristics of wind energy conversion systems employing both a vertical axis of rotation and some form of augmentation beyond a "stand-alone" rotor are assessed, with emphasis on two systems currently approaching commercial feasibility: (1) the Tornado-Vortex Yen Wind Turbine (YWT) and (2) the diffusor-augmented Lebost Wind Turbine (LWT). Both technological and cost-effectiveness considerations are discussed for these systems with emphasis on developing appropriate economic measures for their respective applications, i.e. electric power generation for the YWT and residential and commercial space heating for the LWT. A cost-effectiveness analysis is developed for target costs per unit frontal area for such systems showing the influence of annual mean windspeed, tower height, atmospheric boundary layer stability, capital-cost financing rates and the inflation rate of the fossil fuel displaced. The latter two parameters are particularly sensitive ones in assessing both lifetime cost-effectiveness and payback time. Although allowable costs vary by several orders of magnitude, depending on assumptions, for cost-effectiveness, initial target costs of the order of \$90 to \$400/m^2 of frontal area seem feasible and fairly realistic at this time. It should be noted that the cost effectiveness analysis presented can be used for all wind machines, not only vertical axis augmentors.

INTRODUCTION

The economic premise underlying any augmented wind energy system is that incorporation of low-cost "external" structures can provide a given amount of wind power at lower overall cost than a rotor-only configuration. Implied here is that the rotor-bearing-shaft assembly is a relatively high cost item, whereas an augmentor structure with few moving parts, less precision machining, etc. is relatively low in cost.

The present study deals with augmented machines with a vertical axis of rotation which have certain additional advantages in comparison with large propeller-type horizontal axis machines under development by DOE, NASA and others; namely

- Ease of coupling shaft output to ground-level loads without bevel gears, etc.
- Elimination of gyroscopic loads induced by horizontal-axis yaw
- Elimination of periodic bending-moment load cycles on horizontal-axis blades as they sweep the atmospheric boundary layer vertical shear flow which leads to blade fatigue.

Whereas a large number of concepts fitting the "augmented-vertical axis" category are possible in principle, we are aware of only two which have progressed sufficiently in their development and testing cycles to permit reasonable assessment of performance and cost-effectiveness at this time. These are the Yen Wind Turbine (YWT) documented in the papers by Yen (1975, 1976, 1977, 1978a, 1979), Hsu et al. (1978) and Loth (1978), and, the Patent by Yen (1978b); and the Lebost Wind Turbine documented in the papers by Hoffert et al. (1978) and Rugg et al. (1979) and the Patent by Lebost (1977). These machines will be discussed in some detail here. A possible third candidate is the Toroidal Accelerator Rotor Platform (TARP) described by Weisbrich (1977) which conceptually is a toroidal groove around a cylindrical structure in which a wind turbine is inserted. If a vertical axis rotor of, say, the Darrieus type is used, the concept qualifies technically as "augmented-vertical axis"; but TARP systems proposed thus far are primarily in the horizontal-axis context and in any event no data on vertical axis TARP's is available for objective analysis at present.

The Yen Wind Turbine (YWT)

The YWT system under development by James Yen and the Grumman Aerospace Corporation incorporates a confined vortex generated in a vaned tower by admitting atmospheric wind into a vertically extending structure; where the low pressure vortex core acts like a pump into which flow through a vertical-axis turbine discharges. An embodiment of this concept is shown in Fig. 1. Note that in addition to the vortical core flow which leaves the tower top by virtue of outflow induced by airflow over the structure, there is an additional flow through the turbine into the central vortex from the bellmouth at the bottom. The vortical flow suggests an analogy with a natural tornado where an outer (laminar) potential vortex with tangential velocity inversely proportional to radial distance surrounds a turbulent potential vortex where the tangential velocity is approximately proportional to radial distance (Hsu et al.,1978), and a high axial velocity (low static pressure) condition exists. The intersection of these zones defines the radius of the turbulent vortex core. The reduction of core pressure is not due to the turbulence but rather to the high Reynolds number which allows the potential vortex structure to be closer to the center where velocity increases sharply and which also inevitably results in turbulence at the core (Yen, 1978b).

The early papers by Yen envisioned servo-actuated louvres or vanes on the tower structure which would open on the windward side and close on the leeward to create the external tangential velocity field surrounding the core. A more recent concept is to fit the collecting tower with permanently fixed vanes so the tower has no active controls and no moving parts, Yen (1979).

In addition to the Reynolds number dependence of the vortex structure, there is a strong Reynolds number effect on the efficiency of the aerogenerator turbine which spins by virtue of the high (upward) axial velocity along the core. For this reason, tests on the small wind tunnel models in the early part of the YWT program measured the pressure field in the vicinity of, and across, a screen-simulated turbine. Fig. 2 shows the radial pressure field measured in such tests using a spiral cross-section tower and indicates the pronounced pressure drop at the core. In the absence of an actual turbine, an effective power coefficient for the model tests is used by Yen (1977) based on the work done on the screen,

$$C_{p,eff} = \frac{(\Delta p)_t \, U_t A_t}{1/2 \, \rho U_\infty^3 A_F},$$

where Δp_t is the pressure drop across the screen, U_t is the velocity into the screen, A_t is the screen area, and A_F = HD is the tower frontal area. Fig. 3 shows some early wind tunnels values for this power coefficient plotted against the disk loading coefficient $C_T \equiv (\Delta p)_t / [(1/2)\rho U_t^2]$. The low values of $C_{p,eff}$ in the vicinity of 0.04 - 0.06 are probably unrealistically small by virtue of the vortex core Reynolds number effect; more recent measurements by Grumman have yielded values up to 0.18 with spiral cross-section or active-vaned towers and 0.10 for fixed vane towers (Yen, 1979).

The efficiency of the turbine must be folded into the power coefficient for a realistic assessment. Preliminary data from Igra (1979) with a 0.4 m diameter 8-bladed shrouded (to reduce tip losses) aerogenerator indicate a mean efficiency $\bar{\eta}_t$ of some 75% is attainable in the velocity parameter $(\bar{U}_t/\omega r_t)$ range of 1.8 to 4.0 (Fig. 4), where the rated and actual values of this parameter, or equivalently the tip speed ratio $X \equiv \omega r_t / U_\infty$, are determined by the load match of the system (see later discussion).

It seems reasonable in view of this data, and allowing for a possible increase in performance in large, high-Reynolds number machines to take the power coefficient of the YWT fixed vane system based on frontal area as $\bar{C}_p \simeq 0.1$. By definition the Cp (annualized) is a function of the true $\eta_t(U)$ which must be used in an annualized power equation (see below).

A major characteristic of the YWT bearing on applications is the probable high turbine speed associated with high axial velocity along the core. It is emphasized by Yen (1978a) that the tornado vortex machine can be further augmented by situating such a facility above a fossil fuel or garbage burning combustor, or other hot zone perhaps heated by solar collectors, so as to induced convective updrafts through the turbine, especially when U_∞ is low. If these effects were properly regulated, the entire system might operate at very nearly constant turbine speed, an ideal condition for electric power generation from the viewpoint of system efficiency. Indeed, the YWT concept is primarily geared to electrical power generation and its cost effectiveness will be addressed in that context. Recent work on the YWT at Grumman includes the testing of aerogenerators for use with the YWT to maximize $\eta_t(U)$ and the construction of fixed-vane towers several meters in height for testing at a large NASA Langley Wind Tunnel facility.

THE LEBOST WIND TURBINE (LWT)

The LWT system under development by Barry Lebost of Spaceage Windmills, Inc., and currently being tested at the NYU Department of Applied Science is a very different machine from the YWT, although it shares the vertical axis and a type of augmenting structure. Fluid dynamically, it may be defined as a vertical-axis mixed flow turbine surrounded by a dome-like housing rotating independently, but on a common axis with the rotor, where the housing has vertical fins to yaw the dome into the wind. This exposes the retreating rotor blade to the ambient wind which enters through a cut-away dome section. The advancing blade is blocked from the wind however, and there is a flow deflecting skirt which runs halfway around the dome front (in place of a lower dome half) which acts as a diffusor in the sense Oman and Foreman (1973, 1975) have employed for shrouded horizontal axis machines. A current embodiment of the LWT system is shown in Fig. 1 where it may be compared with the YWT. A simplified analysis of the theoretical power coefficient based on a modification of impulse turbine theory to include the effect of decreased exit pressure associated with the diffusor skirt was developed by Hoffert et al. (1978) indicating linear torque-rotation rate characteristics with peak torque under static conditions. This differs markedly from the Darrieus and Darrieus-Savonius systems discussed by Banas and Sullivan (1977) which have zero or low starting torques, respectively; a factor which can greatly influence system performance for certain load types.

Initial wind tunnel tests at NYU were aimed at establishing power coefficients versus rotation rate for small models using actual dynamometry techniques (as opposed to the YWT test based on $(\Delta p)_t$ across a screen-simulated turbine). The test set-up is illustrated in Fig. 5. It was found that the torque coefficient varies linearly with rotation rate and the power coefficient based on <u>rotor</u> projected frontal area varied parabolically with the tip-speed ratio $X \equiv \omega r_t/U_\infty$ according to

$$C_{p,r} = 2.4\, X_0^{5/2} \left(\frac{X}{X_0}\right)\left(1 - \frac{X}{X_0}\right)$$

where $X_0 \equiv \omega_0 r_t/U_\infty$ is the tip speed ratio under zero load (see Fig.6 for actual data). This correlation is useful for scaling because the Reynolds number dependence of the power coefficient is contained in the Reynolds number dependence of X_0. The peak power coefficient occurs at 1/2 the no-load rotation rate ($X = X_0/2$), so the expected power coefficient base on augmentor <u>frontal</u> area (where $A_F/A_T \simeq 2.7$) is $\bar{C}_p \simeq 0.2 X_0^{5/2}$; where the value of X_0 was found to be Reynolds number dependent but approaching a value near 1.0 after boundary layer transition (see dashed curve of Fig. 7). Subsequent wind-tunnel tests with an improved configuration gave values up to 1.2 corresponding to a $\bar{C}_p \simeq 0.3$.

This led to the decision to build a full-scale LWT for installation atop the Barney Building of NYU (Rugg, et al., 1979).

An important consideration from an applications point of view is that the LWT is a relatively low rotation-rate, high-torque machine with a peak power available which scales with the cube of the rotation rate; $P_{avail} \propto \omega^3$ (with X_0 fixed, this is equivalent to peak power scaling with $U_\infty{}^3$). For a hydraulic pump, for example, the power required also scales with the cube of ω (Daugherty and Franzini, 1977) so it should be possible to attain an almost perfect load match at all windspeeds for this type of load. This consideration leads immediately to a search for loads of $P \propto \omega^3$ in the context of appropriate energy technologies for such wind turbines. Whereas a number of experimentalists have considered the space heating potential of wind power in the context of electric resistance heating (e.g.,Cromack and Heronomus, 1977), it was recognized early in the LWT program that direct dissipative heating by paddle wheels immersed in circulating water stored in a conventional hot water tank would afford an excellent opportunity to exploit the high $\bar{C}_p$ potential of the LWT. For example, Fig. 8 shows that the wind-shaft mechanical energy and the BTU/hr output in circulating water of a 0.3 meter All American Engineering dissipative water brake both scale very nearly with ω^3 (Heronomus, 1977). Although the possibility of using a heat pump (inverse refrigeration cycle) powered by a wind turbine has been considered, the drop-off in heat pump efficiencies for the high temperature differences needed to store heat (as for example, hot water) have mitigated in favor of dissipative heating in a system like that shown in Fig. 9. Relationships between the dimensions of paddles, water brake diameter, weight, etc.,and heat output of water brake have been correlated from numerous model tests by Neyeloff, et al., (1978) It should be recognized that over 30% of domestic energy consumption is for space heating, which suggests that cost-effective production of heat by wind power could well make a comparable or greater contribution to the national energy picture than electric power generation.

Insofar as the LWT is geared to space heating applications it is worth comparing the available windpower resource with the solar flux resource. (See,e.g. the analysis in Duffie and Beckman, 1974.) In the Northeastern USA where home heating costs are particularly high, the wind intensity is lower in winter than summer, whereas the windspeed is appreciably higher, precisely at the time when thermal energy is needed. Furthermore, the heating requirement for building increases (about linearly) with windspeed because of convective cooling (the "wind chill factor"), while the heat output of an LWT-water brake system would increase with the windspeed cubed. Another application of potential importance is the utilization of the LWT for pumped storage although the cost effectiveness analysis presented below focuses on space heating.

These factors, together with the good load-matching and high $\bar{C}p$ of the system suggest that the LWT concept, as well as the YWT concept, should be pursued, bearing in mind the different applications of these systems.

On 15 February 1979 a 6 m (20 ft) rotor diameter LWT was installed atop a 12 m (40 ft) tower on the rooftop of the NYU Barney Building (Fig. 10) for purposes of testing this concept. Preliminary data on X_0 for the full scale prototype (Fig. 7) suggests that values of $\bar{C}p \simeq 0.3$ may well be obtained, although dynamometer tests have not yet been completed. A system similar to that of Fig. 9 is being installed and preliminary results should be available in the coming months.

PERFORMANCE AND COST-EFFECTIVENESS ASSESSMENT: METHOD AND ASSUMPTIONS

A rational assessment of the cost-effectiveness of any wind energy system must account for the energy generated over some appropriate payment period in terms of the economic value of that energy over the system lifetime. It will be assumed that both the YWT electrical power generating system and the LWT space heating system have operating lifetimes of ℓ = 30 years.

The total energy (heat or work) generated in any given year depends on the spectrum of windspeed available at the site, taking into account the vertical profile of fluid velocity in the environment associated with the atmospheric boundary layer, as well as the fluid dynamic and mechanical efficiency of the turbine system plus load, and the annual capacity or plant operating factor OF. The power generated over an annual period, $T_0 \approx 1$ yr $\simeq$ 8766 hr $\simeq 3.16 \times 10^7$ s, is related to the windspeed duration profile $\tau(U)$; that is, the amount of time in any given year that the windspeed exceeds some specified value U. The present analysis employs the SERI specified wind duration profile,

$$\tau(U) = T_o e^{-aU^{\alpha}}$$

where $a \equiv \pi/(4.06\bar{U}^{\alpha})$ is a coefficient involving the annual mean wind at the effective inlet height to the turbine system $\bar{U}$, and α is an empirically-defined exponent ($\simeq$ 2.27). Its differential,

$$d\tau = \frac{\partial\tau}{\partial U} \cdot dU = - \alpha a T_o U^{\alpha-1} e^{-aU^{\alpha}} dU,$$

when integrated over all possible windspeeds has the anticipated property of recovering the annual period,

$$\int_{\infty}^{0} \frac{\partial\tau}{\partial U} \cdot dU = - \alpha a T_0 \int_{\infty}^{0} U^{\alpha-1} e^{-aU} dU = - aT_0 \int_{\infty}^{0} e^{-a\nu} d\nu = T_0,$$

where $\nu \equiv U^{\alpha}$, $U = \nu^{1/\alpha}$ and $dU = (1/\alpha)\nu^{(1-\alpha)/\alpha} d\nu$. Notice that the integration extends from a lower limit of arbitrarily large (infinite) windspeed to a dead calm (zero windspeed) because the duration profile is defined as the time the wind <u>exceeds</u> some arbitrary value U during the annual period.

For cost estimates, it is convenient to work with the turbine system power coefficient $\bar{C}p \equiv P_{out}/ [(1/2)\rho U^3 A_F]$ referred to the augmentor frontal area A_F. The output power of interest P_{out} is W of electricity delivered to a distribution grid or BTU/hr available for space heating so the $\bar{C}p$ should be understood to contain internal system efficiencies such as the aerogenerator and electrical conversion efficiencies in the YWT, and the losses associated with transmission systems, heat leakage and imperfect load matching in the LWT system. It does not include the influence of downtime due to system repairs, outside breakdowns, etc. This latter effect, important for electric power generation, is accounted for by multiplying by the plant operating factor OF†. Assuming the operating factor, or fraction of time the system is operative, is independent of windspeed, we can write the mechanical or electrical work done over a year as

$$W = \int_0^{T_o} OF \times P_{out}\, d\tau = OF \times \int_\infty^0 P_{out} \cdot \frac{\partial \tau}{\partial U} \cdot dU = -b\int_\infty^0 \nu^{3/\alpha} e^{-a\nu} d\nu,$$

where $b \equiv (1/2)\rho\alpha T_o A_F \bar{C}p \times OF$ is a coefficient proportional to the product of the frontal area, the power coefficient and the operating factor. The integral can be readily evaluated in terms of the gamma function, $\Gamma(n+1) = n\Gamma(n)$, where $\Gamma(n)$ is tabulated by Abramowitz and Stegun (1970) for $1 \leq n \leq 2$; that is,

$$W = \frac{b\Gamma[(3/\alpha)+1]}{a^{(3/\alpha)+1}} = \Gamma[(3/\alpha)+1]\left[\frac{4.06}{\pi}\right]^{3/\alpha} 1/2\rho\bar{U}^3 T_o A_F \bar{C}p \times OF$$

Evaluating the gamma function numerically for $\alpha = 2.27$, i.e., $\Gamma(2.32) = 1.18$, gives $W \approx (1.66)(1/2)\rho\,\bar{U}^3 T_o A_F \bar{C}p \times OF$, which implies that from a power output point of view the effective windspeed over an annual cycle is greater by a factor of $\sqrt[3]{1.66} \simeq 1.17$ than the annual mean windspeed $\bar{U}$. This expression can be used to derive an expression for the factor PF* used by other investigators. The equation is $PF = (1.183\,\bar{U}/U_r)^3$ where $\bar{U}$ is the mean and U_r the rated speed. Note that if the mean wind is 12 mph and a machine is rated at 25 mph, the PF = .18. The foregoing can be used to obtain a simple relation for the number of kW-hr generated annually per unit frontal area of augmentor structure,

$$W/A_F = 138(U/U_r)^3 \cdot \frac{\bar{C}_p \times OF}{(\bar{C}_p \times OF)_r}, \quad (AKWH/m^2)$$

for a local air density of $\rho = 1.23$ kg/m³ based on a reference annual mean windspeed of $U_r = 5.36$ m/s (12 mph) and a reference power coefficient and operating factor product of $(\bar{C}p \times OF)_r = 0.1$, a reasonable, and probably somewhat conservative value (see earlier discussion; note also that 1 kW-hr = 3.6 MJ). The corresponding heat available in the LWT dissipative heating system is found by multiplying the above by the thermal equivalent of work,

$$Q/A_F = W/A_F \times \frac{3412\ BTU}{1\ kW\text{-}hr}. \quad (ABTU/m^2)$$

The variation of annual kilowatt-hours per unit frontal area and of annual BTUs per unit frontal area is shown on the logarithmic scales (a) and (b) of Fig. 11 as a function of the annual mean windspeed U for $\bar{C}p \times OF = 0.1$, 0.2 and 0.3. The cubic dependence of annual energy on annual mean windspeed appears as a series of straight lines of slope 3

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† OF = fraction of time system is in operation [(1-(down time/total time)]

* PF = fraction of time the wind is available to produce rated power or cumulative equivalent during a year.

because of the log-log plot. Of course, the available energy is quite sensitive to the available wind because of the cubic dependence, a fact which has led to the "rating" of some commercial wind turbines at unrepresentatively high speeds. For example, a factor of three increase in power coefficient is equivalent to an annual mean wind only a factor of 1.44 higher than the reference speed.

On the other hand, variations of this magnitude are routinely available by locating the turbine higher in the atmospheric boundary layer, by employing a tower, or in the case of the YWT system, by using an augmentor tower which penetrates higher into the atmosphere. Under appropriate conditions this could be a cost-effective, yet realistic, approach to exposing the turbine to a more energetic wind than the SERI standard of U_r = 5.36 m/s at a reference height of z_r = 9.14 m (30 ft).

Under conditions of horizontally homogeneous terrain, the velocity profile in the lower part of the atmospheric boundary layer -- the so-called constant flux surface layer extending some 10 - 100 meters upward from the ground -- can be written (Hoffert and Storch, 1979)

$$U(z) = (u^*/\kappa)\ [\ell n\ (z/z_0) - \psi(z/L)],$$

where $u^* \equiv (-\overline{u'w'})^{\frac{1}{2}}$ is the turbulent "friction velocity" at the earth's surface, z_0 is the aerodynamic roughness parameter which depends on the roughness of the underlying terrain, and $\psi(z/L)$ is a boundary layer similarity function depending on the ratio of height above the surface z to the Monin-Obukhov buoyant stability lengthscale L. The Monin-Obukhov length is the ratio of turbulence generated by shear to that generated (or suppressed) by buoyancy associated with radiative heating (or cooling) of the earth's surface; it may be defined as $L \equiv T_s u^{*2}/(\kappa g T^*)$, where T_s is the surface temperature, κ is von Karman's constant ($\simeq$0.35), g is the gravitational acceleration and $T^* = (\overline{T'w'})/u^*$ is the turbulent buoyancy flux scale with the units of temperature.

Ordinarily, z/L is negative under buoyantly unstable conditions (surface warmer than air above, typical of daytime conditions), positive for stable conditions (surface colder than air above, typical of nocturnal conditions) and zero for neutral conditions (generally present only near sunrise and sunset when air and surface are in thermal equilibrium and buoyancy flux vanishes). Under stable conditions the profile function has the form $\psi = -\beta z/L$ leading to the log-linear profile

$$U(z) = (u^*/\kappa)\ (\ell n\ (z/z_0) + \beta z/L);$$

where $\beta \simeq 4.7$ for conditions ranging from slight to moderate stability, and decreases rather suddenly to about 0.8 under strongly stable conditions (this is associated physically with momentum decoupling between the surface layer and the well-mixed atmospheric boundary layer above). The result is that under sufficiently stable conditions the second (linear) term dominates the velocity profile leading to much more intense winds than would be calculated for neutral (z/L = 0) conditions. Such an elevated high velocity region occurring under stable conditions is well-known in boundary layer meteorology where it is termed the <u>nocturnal jet</u>.

Recent measurements by Sisterson and Frenzen (1978) at high resolution of wind profiles collected over Central Illinois indicate that nocturnal, low-level wind maxima occur more frequently than previously supposed. Speculating on the implications of their results for wind energy conversion systems, these authors observe that in the case of propeller-type horizontal axis machines for which rotors as large as 100 m have been proposed, the long blades would probably experience severe mechanical strains as the alternately sweep through regions of higher and lower wind speed at the top and bottom of each rotation (The implications of such bending moment cycles on horizontal-axis fatigue strength and costs are discussed by Yen, 1979). On the other hand, *small, vertical axis machines mounted on tall towers could tap an appreciable portion of the additional energy in the lower portion of nocturnal wind maxima aloft* (italics ours). In view of the potential economic impact such regions of high velocity may have for the vertical-axis augmented systems under study here, we have assumed that the inlet velocity to the system U at some height z above the surface can be scaled from the SERI reference conditions by

$$U(z) = U_r \left\{\frac{\ln(z/z_0) + \beta z/L}{\ln(z_r/z_0) + \beta z_r/L}\right\},$$

where we shall take the aerodynamic roughness at the moderate value $z_0 = 0.005$ m and set $\beta = 4.7$. Two cases are considered; a neutrally-stable atmospheric boundary ($L \to \infty$) corresponding to the averaging out of the stable and unstable parts of the diurnal cycles over the annual cycle, and a slightly stable case ($L \simeq 27$ m) corresponding to a weighting of the annual average atmospheric boundary layer toward the stable side by virtue of the strong nocturnal jet effect found by Sisterson and Frenzen. In view of the lack of data on the structure of the annual mean profile weighted by such jets, the calculation should be viewed as illustrative at this time.

Thus the scales labeled (c) and (d) on the right-hand-side of Fig. 11 show the influence of tower height for the $\bar{C}_p \times OF = 0.1$ case. For example, a factor of three increase in power coefficient is equivalent to moving the turbine up from its reference height of 9.14 meters to about 300 meters up in a neutrally-stable layer, but the same effect (equivalent to an annual mean windspeed of 17.3 rather than 12 mph) is obtained for the stable profile at only 23 meters. Because of the great potential of such profiles it seems prudent to investigate such phenomena more deeply. It must be borne in mind however, that an upper bound windspeed generally available in the environment is the geostrophic wind $U_g \equiv (\rho f)^{-1}\partial p/\partial n$, where f is the Coriolis parameter (typically 10^{-4} s^{-1} in middle latitudes) and $\partial p/\partial n$ is the local horizontal pressure gradient of the synoptic surface pressure. (Holton, 1972). Typical values of the surface pressure gradient are $\simeq$ 1 mb/100 km $\simeq 10^{-3}$ Pa/m which means the winds aloft will generally be of the order of 10 m/s except during the passage of strong low pressure fronts, etc.

The cost implications of these results depend on the economic value of the energy generated by the system. At present, the retail rate of electricity purchased from a utility runs from $0.05 to 0.10/kW-hr with the latter rate characterizing power generated by burning low-sulfur oil generally imported from the OPEC states. For our cost-benefit analysis we set the cost of generating electricity at \$0.04/kW-hr, close to the present reality, and with a convenient property in the present context that will become evident momentarily. The current retail price of #2 home heating oil in the Northeastern USA with a heating value of about 140,000 BTU/gal is some \$0.62/gal. Taking into account the typical efficiency of 40% in home heating oil burners gives 54,000 BTU/gal available for heating at a cost of 1.15×10^{-5} \$/BTU which is equivalent to \$0.04/kW-hr; that is the cost of producing electricity at the utility level adopted here is equal to the cost of buying an equivalent amount of energy in the form of heating oil at the retail level. The fact that retail electrical rates are 2-1/2 times the \$0.04/kW-hr value has resulted in the well-documented cost catastrophy in electrical-resistance-heated homes in the Northeastern USA.

SERI has specified that for cost-effectiveness of electrical power generation the following formula, commonly used in the utility industry, be employed:

$$\overline{COE} = \frac{(IC)\ (FCR) + (AOM)}{(AKWH)},$$

where $\overline{COE}$ is the average cost of operation, IC is the initial or "turn key" cost of the turbine system, FCR is the fixed charge rate equal to $0.18\ yr^{-1}$, AOM is the annual operation and maintenance cost and AKWH = $(W/A_F)A_F$ is the annual energy output of the turbine discussed previously. In nuclear and fossil fuel power plants the AOM is not constant, but depends on the inflation rate in the cost of these nonrenewable energy sources. Indeed, the fuel cost tends to dominate the COE in contemporary fossil energy plants, and rate increases tend to scale very nearly with the fuel inflation rate. To account for this effect, the COE against which the wind turbine is compared costwise, should be allowed to increase over the facility lifetime. If COE is the initial cost of operation, the mean cost of operation over the lifetime ℓ = 30 yrs is (Ford et al., 1975),

$$\overline{COE} = \left\{\frac{(f + 1)^{\ell} - 1}{\ell f}\right\} COE,$$

where f is the fuel inflation rate.

This relation, as well as the initial rate of COE = \$0.04/kW-hr is used for the cost effectiveness estimates for both electrical power generation and space heating below. Note that the mean and initial values are identical for a fuel inflation rate of f = 0 %.

If a fuel inflation allowance seems optimistic for wind turbine cost-effectiveness, it should be noted that we are accepting the utility fixed charge rate of 18%. This is related to an interest rate r repaying a loan (or bond) financing the initial cost over the lifetime ℓ by (Ford et al., 1975),

$$FCR = \frac{(r + 1)^{\ell} r}{(r + 1)^{\ell} + 1},$$

or $FCR \simeq r$ for long times. For ℓ = 30 yr, an FCR of 18%/yr corresponds to a financing rate of 17.9%, which seems rather high. If, for example, the government were to wish to support the development of renewable energy resources, it should be possible to provide lower interest rate loans for financing such facilities. The Federal Tax Credit of up to $2200 to homeowners using solar and/or wind power is a step in that direction. Finally, we assume that the annual maintenance cost is a constant fraction of the capital cost (2%), that is AOM = 0.02 (IC).

Based on the foregoing assumptions the initial cost per unit frontal area of the augmentor structure from the standard equation is simply,

$$(IC^*)/A_F = (0.2)\{\frac{(f+1)^{30}-1}{30\,f}\}\,(W/A_F). \qquad (\$/m^2)$$

According to this analysis, a WECS for either electric power generation or space heating will be cost-effective over the lifetime of the machine so long as it can be marketed at some price $IC \leq IC^*$. Scales (e), (f) and (g) of Fig. 11 can be used to estimate the maximum allowable costs per unit frontal area by this criteria for fuel inflation rates of f = 0%, 7% and 15%, respectively. For example, a turbine at the SERI standard conditions of 5.36 m/s annual mean windspeed at a height of 9.14 m with a CpxOF = 0.1 will be cost-effective at $\$28/m^2$ or less at f = 0%, $\$100/m^2$ or less at f = 7% and $400 or less at f = 15%. Of course, exploration of the properties of the various scales of Fig. 11 will reveal other combinations of power coefficient, tower height for neutral or stable conditions and fuel inflation rate for cost effectiveness at some specified value of cost per unit frontal area achievable at current and projected structural methods and production economies.

While cost effectiveness over plant lifetime as defined here is the rational parameter to be used in the assessment of whether a machine meets utility guidelines with respect to costs, a measure which is commonly used to assess solar and wind energy devices (particularly by home-owners or commercial enterprises) is pay-back time. This parameter is certainly not a proper one for cost assessment, since after the pay-back time the power produced is free while fossil fuels would continue to incur costs. On the other hand since it is an often quoted one calculations for pay-back time have been accomplished.

For a 40% efficient boiler, oil will cost $(0.107) x \tau [e^{\bar{t}/\tau} - 1]$ \$/BTU in $\bar{t}$ years if it presently costs approximately 0.62 \$/gal for oil, where τ is related to the doubling time (i.e., for a 10% annual oil increase τ = 10.49 yrs).

The Lebost Wind Turbine, rated at 1.7 kW in a 15 mph wind for a 6.1 m diameter machine will produce approximately 4930 annualized BTU/hr in a region where the mean wind speed is 12 mph. If such a machine can be sold for $8200 installed and if a 10% interest rate is assumed (with a $2200 tax credit) it can be shown that the pay-back time is 5 yrs. On the other hand if the machine costs $10,200 installed the pay back time is 10 yrs. If the oil inflation rate is 15%, the $8200 figure translates into a pay back time of 3 yrs. One can thus see that the quantity pay-back time can be an easily manipulated figure depending on fuel inflation rate and installed machine cost.

CONCLUSIONS

At present two vertical axis augmented machines are actively under study, one (YWT) which is designed to produce electricity, the other (LWT) to produce heat. Both seem well suited for their intended purposes, but definitive statements with respect to system performance and costs of the machines are still not possible, although a substantial body of information about these systems at high Reynolds numbers is becoming available.

However, it is possible using the accepted cost of operation equations to determine a cost effective initial machine cost per unit frontal area of augmenting structure once the power coefficient is known. The analyses presented holds for all machines, not only vertical axis augmentors, except with respect to tower height required when large horizontal axis machines are considered, since for such machines the velocity profile intercepting the machine must be folded into the determination of tower height.

The analysis uses a fixed charge rate for money of 18%/ year to determine the cost effective initial cost of an installed machine. Lower interest rates (particularly for homeowners) would yield higher initial cost bounds for cost effectiveness. Of course, the cost benefits from positive social and environmental effects derived from not using fossil fuels, as well as the national benefits associated with our balance of payments, are not included in the final cost equation.

Even under the most stringent assumptions presented though, it appears that cost effective wind energy systems are indeed possible. For example, if a machine with a $\bar{C}p = .1$ in a 7% fuel inflation economy,can be built on a 9.14 m tower in a 12 mph mean wind for $\$90/m^2$, it is cost effective. Thus, a wind energy farm, rated at 100 Mw in a 12 mph mean wind would have a frontal area of $10^7 m^2$ and to be cost effective would have to cost less than $\$9 \times 10^8$ installed. Note that a 15% inflation rate would yield a cost effective price four times as high. These values seem feasible even with current technologies and materials costs.

While shaft power measurements of the LWT are available and indicate a $\bar{C}_p$ on the order of 0.2 to 0.3,no such numbers are available for the YWT. Power available to the turbine measurements indicate that the YWT would have maximum $\bar{C}_p$ on the order of 0.1, but turbine efficiency curves, however flat in the rated power region, will eventually fall off at velocities much larger (or smaller) than the peak point as can be seen in even the best data of Igra (1974). In order to use Fig. 11 to assess the capabilities of the YWT it will be necessary to see data for the actual $\bar{C}_p$, since it is possible that the integrated power equation presented above for W/A_F might yield an effective Cp somewhat below the power available to the turbine. This could be possible since the turbine efficiency η is a function of velocity U and the overall curve must be used in the final integration for W/A_F. On the other hand the possibilities of using the YWT with a solid waste burning system could help in the cost effectiveness of the machine.

The importance of atmospheric stability effects at site locations has been pointed out and could greatly effect cost effectiveness. Locating either the YWT or the LWT in a nocturnal jet, for example, could greatly effect cost effectiveness as can be seen from axis (d) in Fig. 11.

In conclusion, curves are presented to accurately assess cost effectiveness of vertical axis augmentors (or other machines) in terms of the maximum installed cost of such machines, as a function of power coefficient, mean windspeed,tower height, atmospheric stability and fuel inflation rate. Even conservative estimates indicate that efficient wind energy systems can be cost effective, particularly if the inflation rate of the displaced fuel is accounted for.

ACKNOWLEDGEMENTS

This work was supported in part under SERI Grant No. AH-9-8003-4 and NYSERDA Grant No. ER-205-78/79. We thank James Yen, Barry Lebost, Barry Rugg, Rudolf Wiley, Irvin Vas, Dean Corren and Helen Jones for their valuable contributions to this effort.

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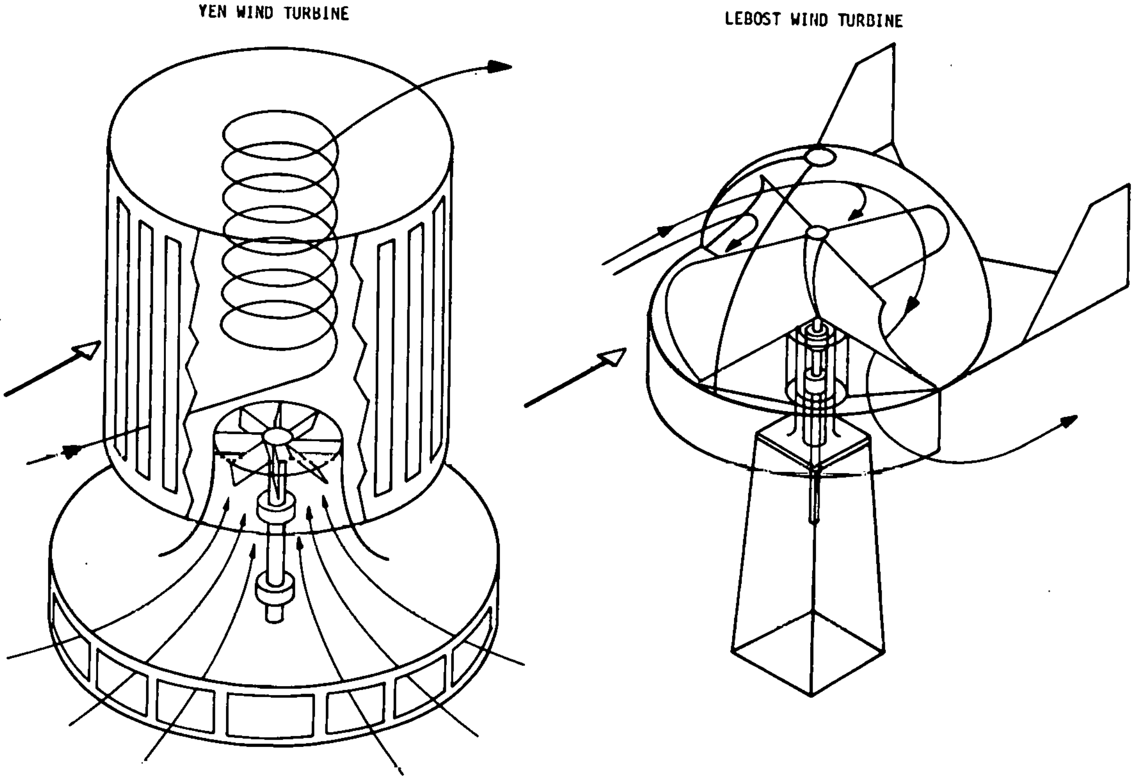

Fig. 1. Schematic Diagram of Yen Wind Turbine (YWT) and Lebost Wind Turbine (LWT) systems.

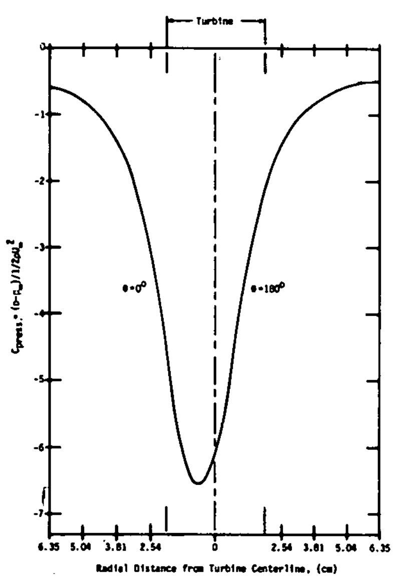

Fig. 2. Pressure coefficient profile along θ = 0^{0} and 180^{0} from Yen (1977) wind tunnel tests.

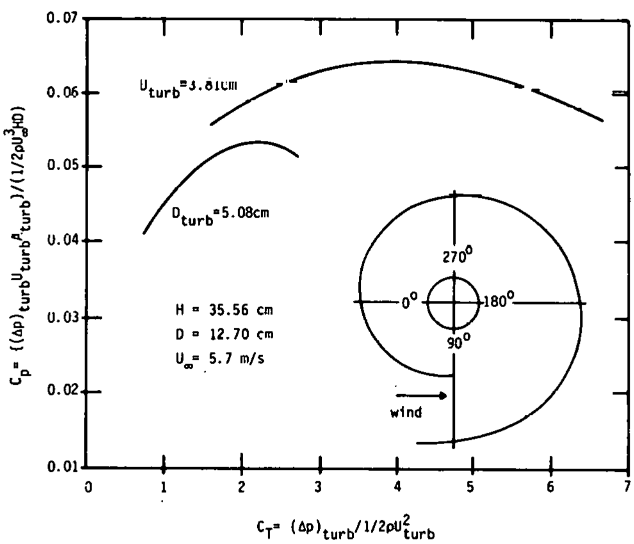

Fig. 3. YWT low Reynolds number wind tunnel data for screen-simulated turbine in spiral cross-section tower.

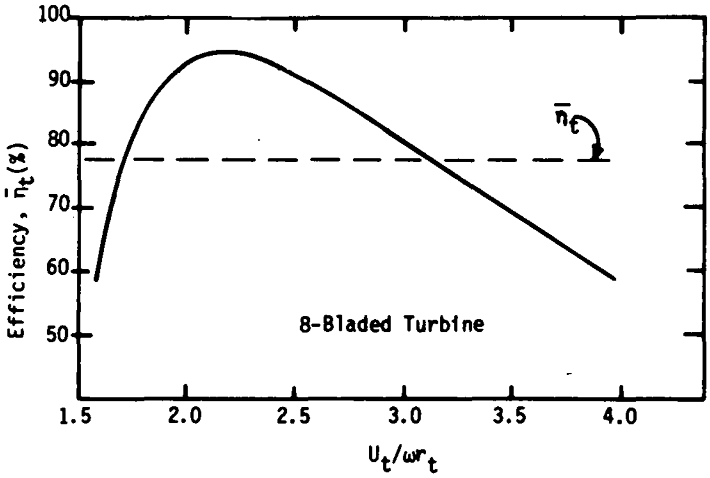

Fig. 4. Aerogenerator turbine efficiency versus $U_t/\omega r_t$ for 8-bladed design from Igra's (1974) Test data.

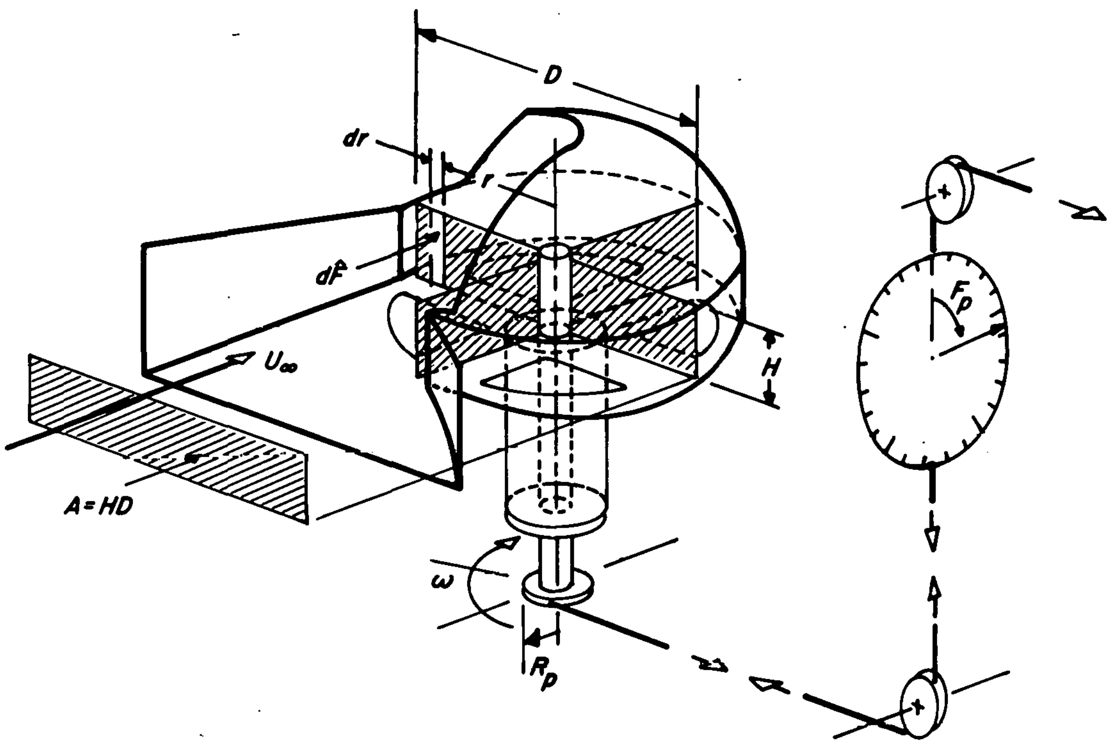

Fig. 5. LWT Wind Tunnel test set-up.

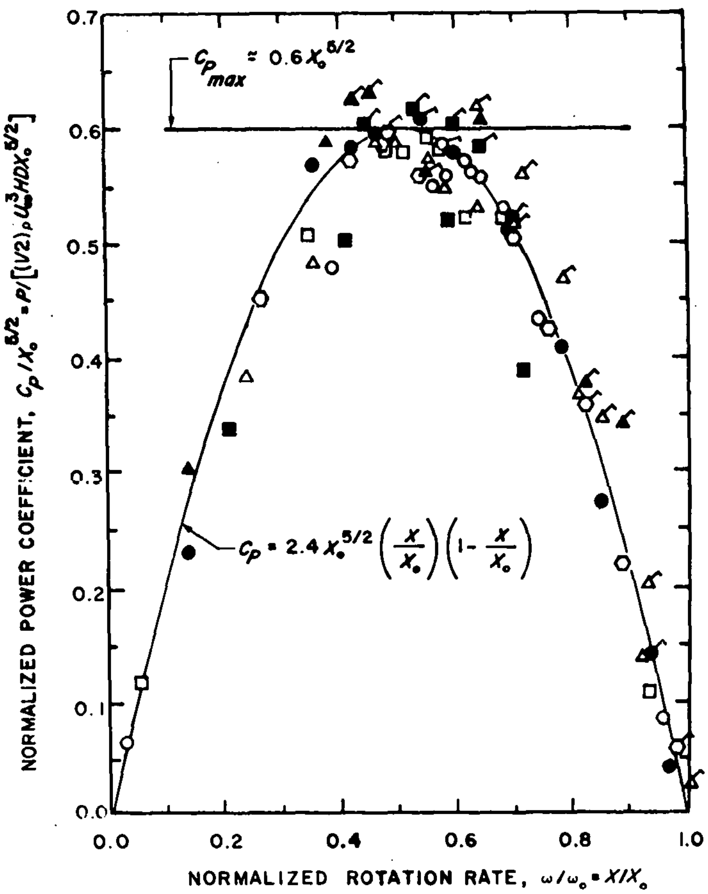

Fig. 6. LWT Wind-tunnel dynamometer power coefficient based on rotor frontal area HD (see Fig. 5).

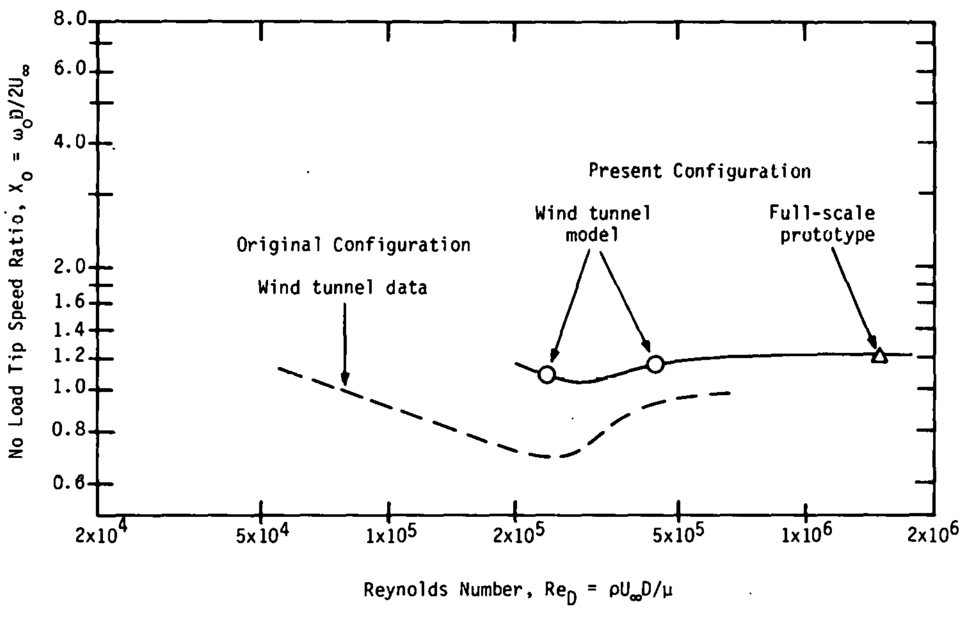

Fig. 7. Variation of LWT no-load tip speed ratio X_0 versus Reynolds number.

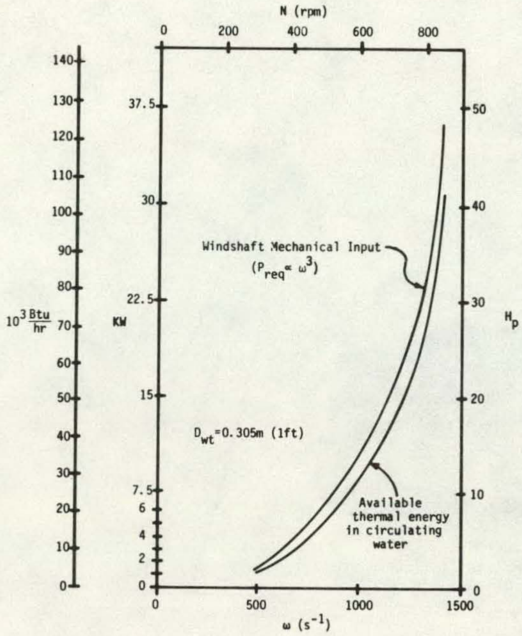

Fig. 8. Shaft power required and heat output to circulating water versus rotation rate for an All American Engineering water twister from Heronomous' (1977) data.

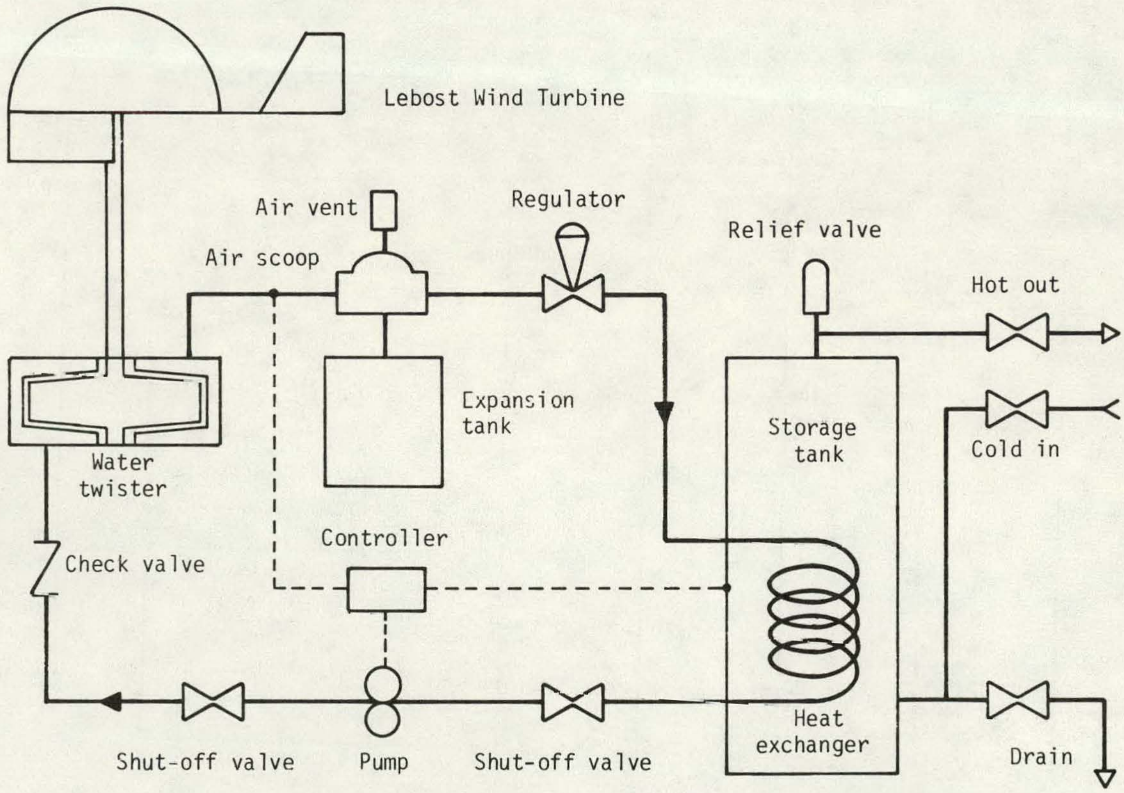

Fig. 9. LWT - water twister space heating system concept.

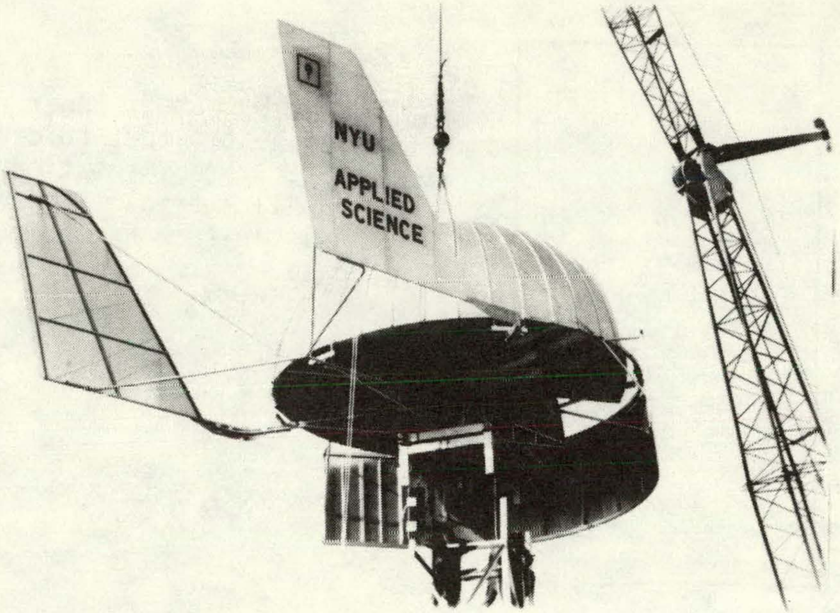

Fig. 10. Installation of LWT atop 12 m (40 ft) tower on rooftop of NYU Barney Building on 15 February 1979.

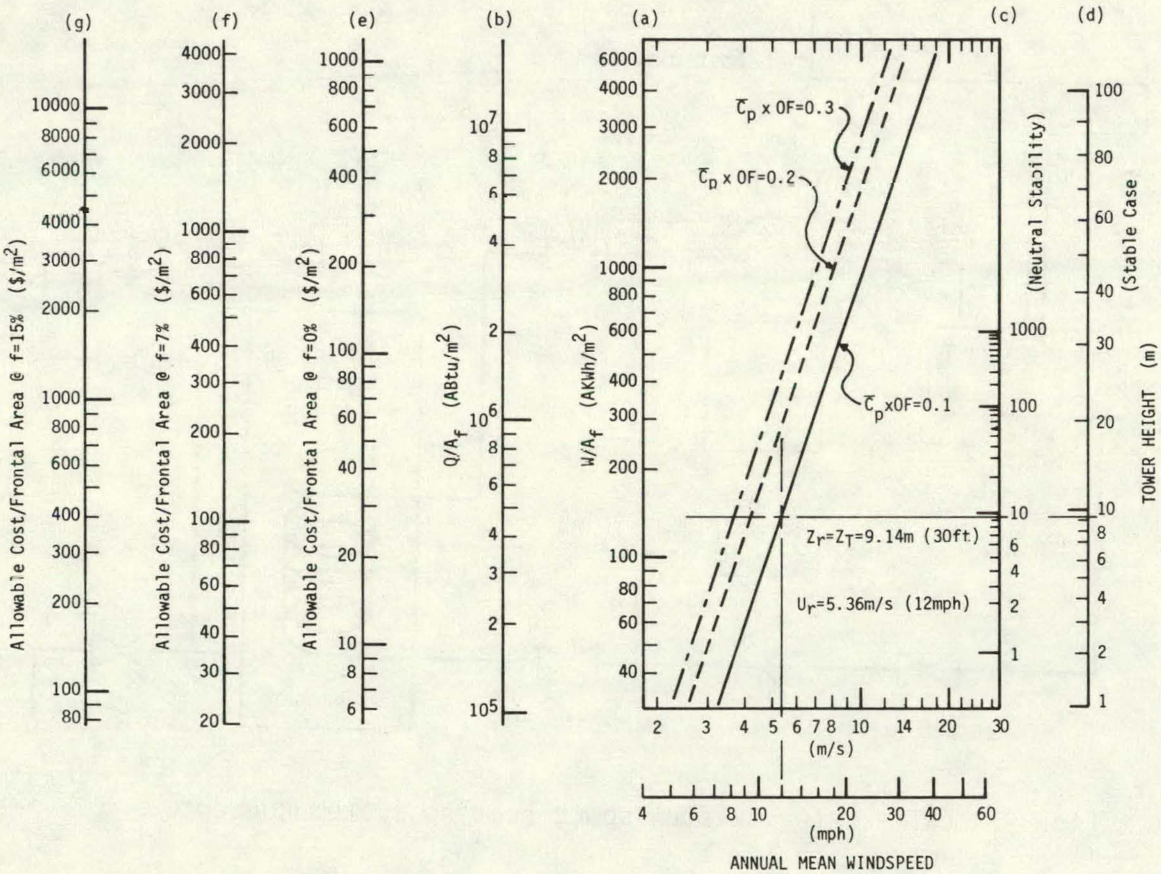

Fig. 11. WECS annual energy output per unit frontal area, equivalent tower height and cost/frontal area under various assumptions.

RESPONSES TO THE HOFFERT PRESENTATION

Question: Have you considered a simpler structure and, if so, do you have comments?

Hoffert: One of the things that Barry Lebost has been very concerned abut is reducing the structural cost of the domelike housing. The dome and the roof rotate on a common axis. One of the configurations that is being considered allows the dome to swivel around because it is open at one end. That conceivably could be cheaper than a tower.

George Tennyson, DOE: I was under the impression that what we were going to see was an evaluation of augmented axis wind machines. Will that be forthcoming in your report?

Hoffert: From our investigation of the literature there are only three systems that can be evaluated. We did not discuss at this meeting the torroidal acceleration platform which might technically be considered as a vertical axis augmented machine. From the literature the only machines that had been developed sufficiently in terms of test data to permit an evaluation were the two devices that we have presented today. Are you aware of additional configurations that would qualify as augmented vertical axis machines?

Question: Have you corrected for blockage and pressure gradient effects?

Hoffert: We believe that we have corrected for the influence of the wind tunnel wall by measuring the velocity immediately in front of the turbine and referring our power coefficient to the actual inlet velocity.

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ENERGY FROM HUMID AIR

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ABSTRACT

This is a summary of results to date of a research project which is in progress at the South Dakota School of Mines and Technology. The goal of the research is to find a cost-effective process to convert the energy in humid air into mechanical work, which will be used to drive an electrical generator. The research is being carried out by computer modeling.

Results for a natural draft tower show that it is not a cost-effective way to get energy from humid air. Parametric studies are presented for expansion-compression cycles. With suitable conditions, including large amounts of cooling during compression, this cycle has an attractive net work output. To avoid using all the output power to overcome machine losses, it appears necessary to use a one-machine mechanization. The most promising uses vortex flow to achieve the necessary expansion and subsequent compression with cooling. Power output and costs have been estimated for a vortex plant located in Puerto Rico.

INTRODUCTION

A vast amount of energy is contained in the latent heat of vaporization of the water vapor in humid air. If the water vapor is made to condense, the latent heat is released into the surrounding air. The mechanizations for converting the energy in humid air which are being considered in this project can be thought of as heat engines in which the air itself serves as the working fluid.

The attractiveness of the concept of converting energy from humid air has been published [1] and will not be developed in this paper.

NATURAL DRAFT TOWER

The simplest mechanization to extract energy from humid air is a vertical natural-draft, condensation tower (see Fig. 1). The efficiency of such a tower is dependent upon (1)

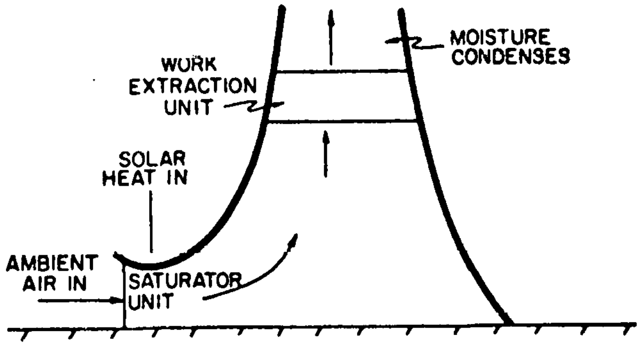


FIG. 1. NATURAL DRAFT TOWER

the degree of saturation of the ambient air at the inlet; (2) tower height; and (3) the prevailing atmospheric temperature lapse rate. As the air rises in the tower, its temperature and pressure follow the moist adiabat. The air inside the tower is then at a higher temperature than outside ambient air, and it rises because of natural buoyancy. The process is similar to that which nature uses in a thunderstorm.

Computer models have been developed for the natural draft tower, and extensive studies have been made using the computer. The power output naturally increases proportional to mass flow rate of air through the tower, expressed in kilograms of air per second. Hence various configurations are analyzed in terms of power output per kg/sec of air processed. Air at the tower inlet was assumed to be saturated (100% relative humidity) by means of a solar saturator unit.

Several shapes for a natural draft tower were studied. Power output was found to be essentially independent of tower shape. Power output as a function of tower height has been examined. (See Fig. 2.) It was discovered that power output is approximately proportional to the 1.4 power of tower height or:

$$\text{Power out} = K\ (\text{Tower Height})^{1.4}$$

Hence, to get a large power output there is a strong incentive to build a very high tower.

The natural draft tower was tested for power output at each of 5 geographical locations (San Juan, P.R.; Tampa, Fl.;

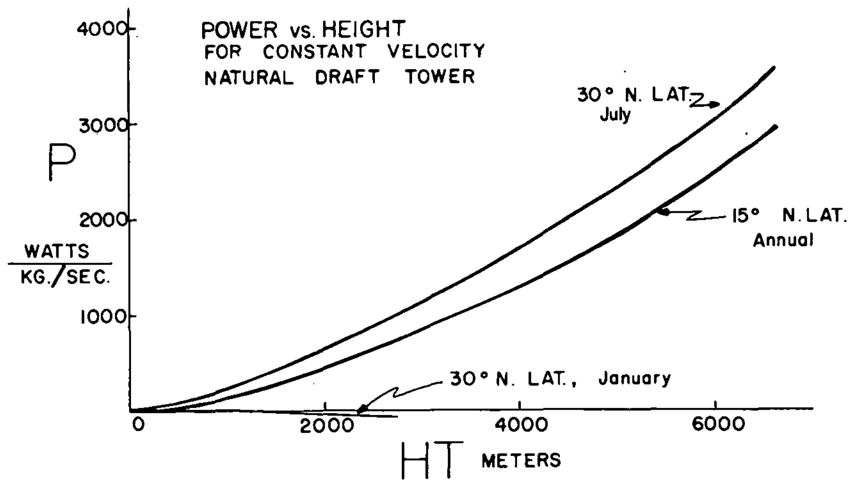


FIG. 2. POWER OUT VS HEIGHT.

Boothville, LA.; Lake Charles, LA.; and Hilo, HA.) for each day of the year 1975 and at two times each day. These correspond to the times when upper air meteorological observations were recorded. At the most favorable location, Hilo, HA, the overall average power output from a tower averaging 586 meters in height was found to be 52 watts per kg/sec of air processed. This falls far short of a goal we have set of 1600 watts per kg/sec.

Our conclusion based on all of the computer results is that the natural draft tower does not appear to be a cost-effective way to get useful energy from humid air. However, the natural draft tower was a logical first step in the computer modeling process.

EXPANSION-COMPRESSION CYCLE ANALYSES

It appears that to enhance power output it is desirable to expand to lower temperatures in order to obtain more condensation than can be obtained with the natural draft tower. A possible mechanization for such a process is an expansion-compression cycle. In this cycle moist ambient air is first expanded adiabatically to a low pressure and work is extracted from this process. During the expansion moisture condenses and falls out at its dew-point and is removed from the system. Now if the air, plus the remaining water vapor, is compressed adiabatically back to atmospheric pressure, work has to be supplied. For this case the compression work expended will have to be greater than the expansion work. However, if we accomplish the compression with cooling through a polytropic process, the work expended will be less than with the corresponding adiabatic compression process. With enough cooling, positive work output is possible from an expansion-compression cycle. In addition, the other parameters such as the inlet conditions and the degree of expansion can be adjusted to provide maximum power output. A possible modification is to let the expanded air rise through the natural draft tower before compressing it back to the prevailing ambient pressure at the top of the tower. Since the ambient pressure at higher altitude is smaller than the surface pressure, it appears that the compression work required might be less. (See Fig. 3.)

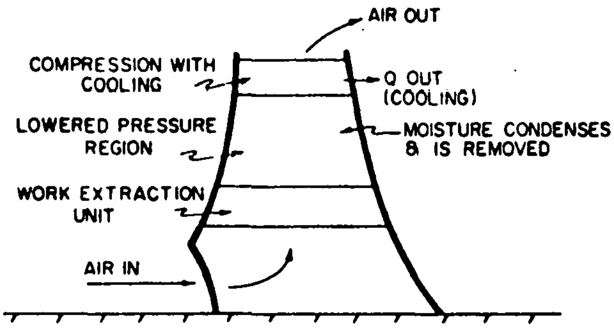


FIG. 3. EXPANSION-COMPRESSION TOWER.

In general, then, the performance of an expansion-compression cycle machine should depend on:

1) Amount of cooling and cooling water temperature available.
2) The degree of expansion the inlet air will undergo.
3) The degree of saturation of the inlet air.
4) Height of the tower.
5) Efficiencies of the expansion, compression machines, and the heat exchanger.

Assumptions Used in Parametric Studies

The following assumptions are used in the analyses throughout this section.

1. The expansion process is assumed to be isentropic. Moisture condensed is removed at the end of the process.

2. The compression process is assumed to consist of two stages. The first stage is an isentropic compression from the existing low pressure back to a fixed temperature, corresponding to the available cooling water temperature. The second stage of the compression process is assumed to be isothermal at the given water

temperature. This two-stage compression is necessary because the available cooling water temperature T_c is fixed, which means that no cooling is possible when the air temperature is below T_c.

3. Work done in the isentropic expansion process is determined from the energy equation. The changes in kinetic and potential energy are neglected and the work expression is given by

$$W_e = -m_a Cp_a \Delta T - m_{1w} h_{fg} - m_{wv} \Delta h_{wv} \tag{1}$$

4. The isothermal work expended is obtained by assuming the air mixture is ideal and follows a polytropic process curve (Pv^n = constant). When $n \neq 1$ the work is expressed as

$$W_c = - \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \tag{2}$$

For the special case where n=1 representing isothermal process, the work is given by

$$W_c = -P_1 V_1 \ln \frac{P_2}{P_1} \tag{3}$$

The cooling required in this process can be calculated from the energy equation as

$$Q_c = m_a Cp_a \Delta T + m_{wv} \Delta h_{wv} + W_c \tag{4}$$

5. A constant velocity tower is used in the study of tower height effect.

6. Machine losses are ignored in the calculations. What is being calculated is the work output of an ideal cycle. Definitions of symbols used:

W_e work done by humid air in an expansion process

W_c work of a compression process

Q_c cooling required in a compression process

n polytropic process exponent

m_a mass of air

m_{lw} mass of liquid water

m_{wv} mass of water vapor

Cp_a specific heat of air at constant pressure

h_{fg} evaporation enthalpy for water

Δh_{wv} enthalpy change of water vapor

Parametric Studies

Parametric studies have been made of the expansion-compression cycle looking at:

1) Power output vs cooling temperature. (Fig. 4.)
2) Power output vs degree of expansion. (Fig. 5.)
3) Power output vs degree of saturation. (Fig. 6.)
4) Power output vs tower height. (Fig. 7.)

As might be expected, power output increases as cooling temperature becomes lower. Power output increases with degree of expansion; however, it is not profitable to expand to a temperature that is more than about 10°C lower than the available cooling temperature. Power output increases with degree of saturation. The output decreases slightly with tower height; hence, a structure with negligible vertical height appears best for the expansion-compression cycle. This has the effect of tending to hold down structural costs.

Single-Machine Mechanization of Expansion-Compression Cycle using Vortex Flow

The greatest problem in obtaining useful power from an expansion-compression cycle is one involving machine efficiencies. A large amount of power is extracted during the expansion. A large but slightly less amount of power is put back into the air during compression. The difference is the useful output we are trying to obtain. With the two-machine mechanization, unless machine efficiencies are extremely high (in excess of 95%), the output hoped for is all consumed in machine losses, and no useful output is obtained.

An attractive approach is a mechanization of an expansion-compression cycle which requires only one machine. The one machine in effect sees only the difference between the expansion power out and the compression power going back into the system; hence, machine efficiency is less critical.

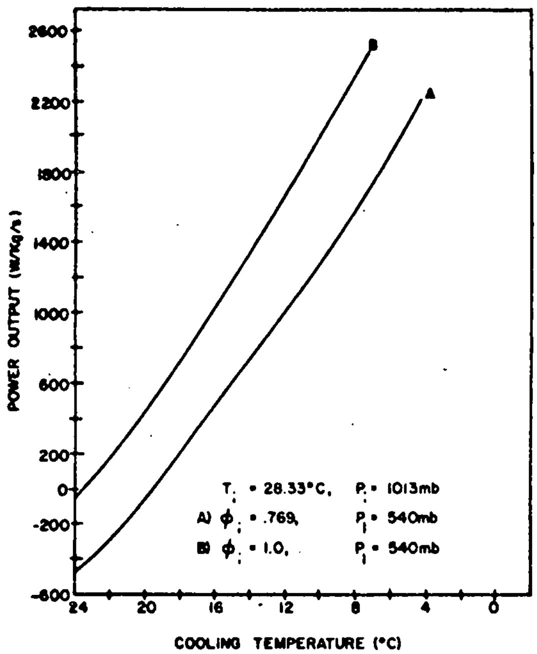


FIG. 4. POWER OUTPUT VS COOLING TEMPERATURE.

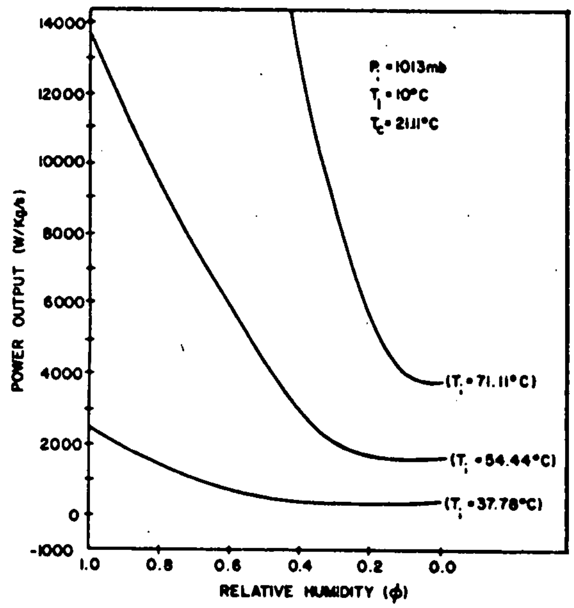


FIG. 6. POWER OUTPUT VS DEGREE OF SATURATION.

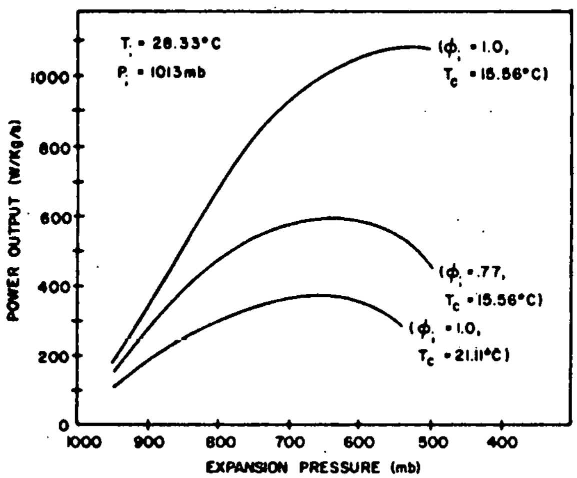


FIG. 5. POWER OUTPUT VS DEGREE OF EXPANSION.

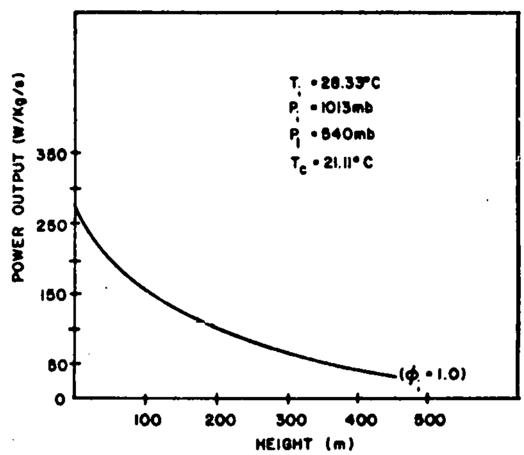


FIG. 7. POWER OUTPUT VS TOWER HEIGHT.

Symbols:

T - temperature

P - pressure

Ø - relative humidity

Subscripts:

i - inlet condition

l - low condition, after expansion

c - coolant

To illustrate the concept, one such mechanization would use a very high tower built as an inverted U-tube as in Fig. 8.

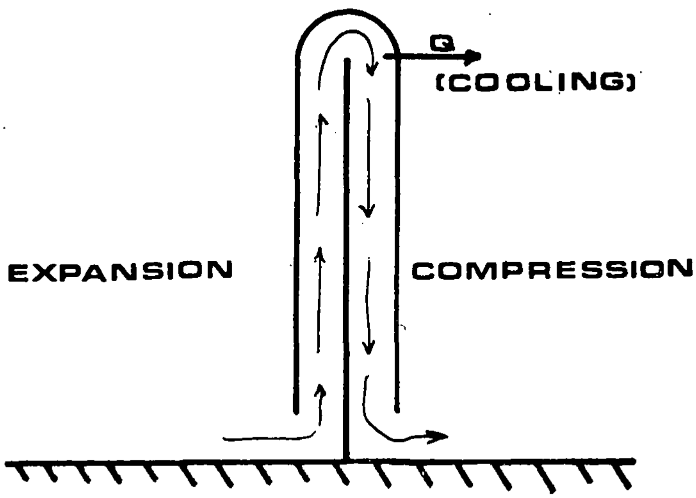


FIG. 8. INVERTED U-TUBE MECHANIZATION OF AN EXPANSION-COMPRESSION CYCLE.

The humid air rises on the left side of the tower and expands, with condensation of moisture. Just past the top of the tower, cooling is introduced. The result is that air on the right side is cooler and more dense than air on the left side. A flow of air through the inverted U-tube tower results. Compression takes place as the air descends on the right. An expansion-compression cycle has been realized via hydrostatics. Flow losses can be minimized by use of low velocities. One machine placed anywhere along the flow path can be used to extract power.

The above scheme is not economically practical because a very high tower would be required. It is presented only to illustrate the concept of a one-machine mechanization.

A more promising approach from the practical standpoint is to use vortex flow in a manner so as to get a one-machine realization of the expansion-compression cycle.

In Fig. 9 humid air enters through guide vanes on the upwind side of the upper or expansion chamber. Air spirals in toward the center of the chamber, where a low pressure prevails. Hence, the air is expanding as it approaches the center. While maintaining its vorticity and kinetic energy the air passes to the lower or compression chamber. Here it spirals outward and is compressed in the process. Cooling is introduced during the compression. The air exits through vanes on the downwind side. Since this cycle is a net power producer, the vortex will sustain itself and one machine, placed anywhere along the flow path, can be

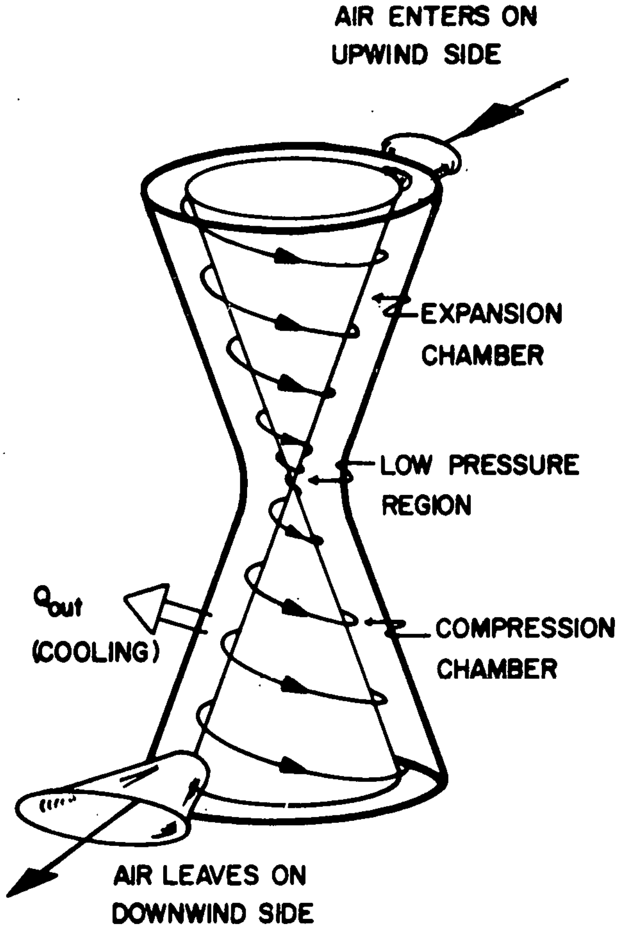


FIG. 9. VORTEX MECHANIZATION OF AN EXPANSION-COMPRESSION CYCLE.

used to extract power.

The above is intended only to serve as an outline of the essentials of the process. The diagram is intended to be only schematic in nature. Exact shapes and dimensions must be determined after modeling of the desired flow pattern.

POWER GENERATION POTENTIAL AND COST ESTIMATES FOR A LARGE HUMID AIR PROCESSING PLANT

Power Generation Potential

The computer analysis was employed to predict the hourly and monthly power generation for the year 1975 at a site on the island of Puerto Rico near Punta Tuna. At this location cooling water at a temperature of 6°C can be obtained about a mile and a half off-shore. The plant is assumed to be on land, with a large concrete pipe placed on the ocean bottom going out to the location of the 6°C cooling water. The plant size was chosen somewhat arbitrarily, so that it can process 10,000 kg/sec of air. To provide the cooling water required, the concrete pipe has a length of 2773 meters and a diameter of 2.917 meters.

To calculate the power output from the plant surface weather data for San Juan, PR were used. (Detailed surface data are not available for Punta Tuna.) In calculating power output from the plant, power necessary to pump the cooling water is subtracted from the power output from the turbine. We start with the theoretical power output from the expansion-compression cycle. A turbine is used to extract the net output power and is assumed to be 90% efficient. Flow losses in the vortex itself have been neglected. The research we are now undertaking will include calculation of these losses.

On the suction side of the pumps, fluid friction in the pipe was calculated for a hydraulic smooth, insulated pipe with a water velocity of 1.5 m/sec. A well-rounded bell mouth entrance was assumed. The equivalent pipe length was increased by 32 pipe diameters to allow for pump inlet connections. On the discharge side of the pumps, a constant head of 3 meters was assumed to account for lifting and spraying the water into the vortex chamber.

For the plant described above, Fig. 10 shows the variation in output power as a function of time of day for an average day in January and for an average day in August. The output power reaches its maximum at 2:00 p.m., the hottest time for the average day. Hence, power output is greatest just when it is most needed to supply electrical air conditioning loads.

Figure 11 shows variation of power versus month of the year for 1975 data. The center curve is average power for each month. The top curve is the maximum for each month, calculated for the most favorable weather condition during the month. The bottom curve is the minimum calculated at the least favorable time. Overall average power output for this plant is 6.73 megawatts. It is noteworthy that even in the winter months a respectable average power output is maintained. Furthermore, the minimum power out always exceeds one megawatt, indicating that the plant could theoretically operate all year on a continuous basis. No unfavorable condition of temperature or relative humidity at the inlet would close it down.

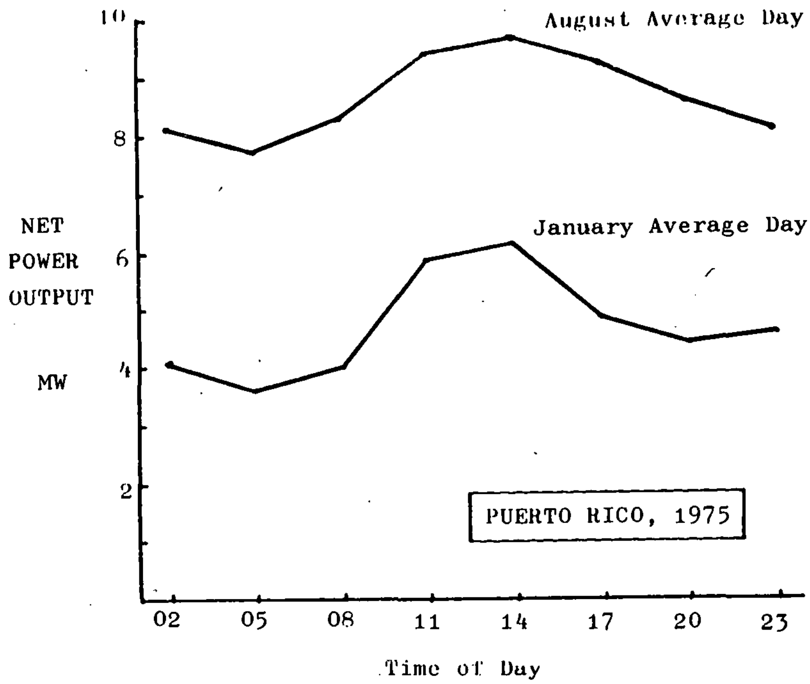


FIG. 10. NET POWER OUTPUT VS TIME OF DAY.

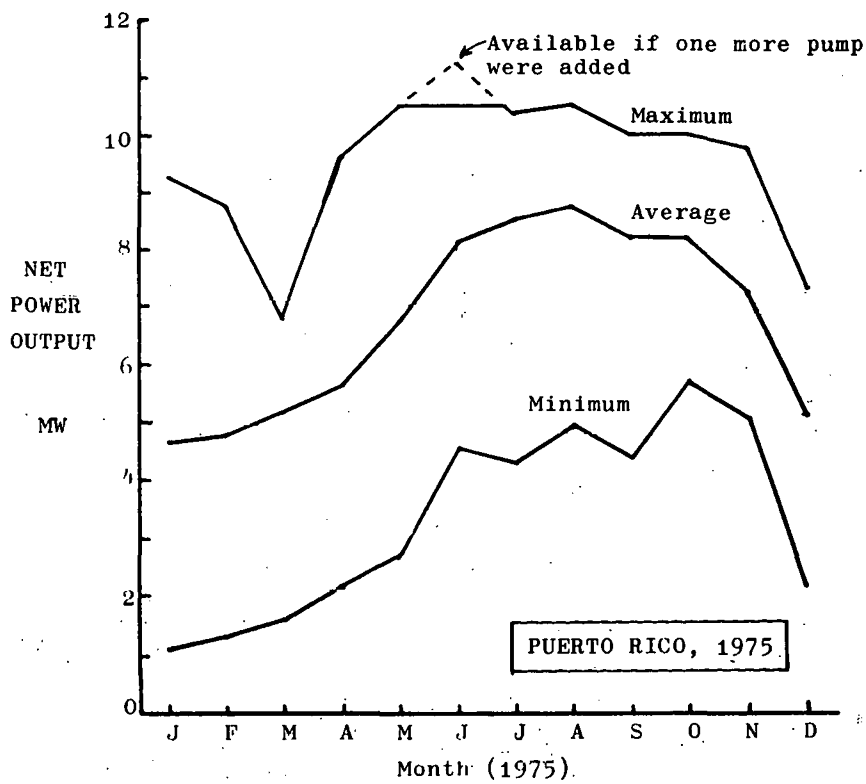


FIG. 11. NET POWER OUTPUT VS MONTH OF YEAR.

Cost Estimates

A capital cost has been computed for a vortex expansion-compression plant of the type shown in Fig. 9. Since the detailed flow analysis necessary for a complete vortex-design has yet to be done, a number of assumptions were used in lay-out of a rough preliminary design for cost estimation purposes. The assumptions are:

1. The plant has an air flow rate of 10,000 kg/s except when the air flow must be reduced because of cooling water pump limitations. Plant rating is 10.5 megawatts.

2. The plant site and electric power transmission lines are not included in the capital cost estimate.

3. Expansion and compression are ideal, frictionless processes.

4. Cooling of the air during compression is by direct contact between the air and a spray of cold water. No heat exchanger is necessary. A heat transfer effectiveness for the parallel flow is assumed at 0.9.

5. The structure for the vortex chamber is very large in diameter in order to accelerate the air from 5 m/s at inlet to 150 m/s at the center. The construction design and cost are similar to an airplane hangar.

6. The turbine is located at the orifice between the expansion and compression chambers. The turbine drives a synchronous generator.

7. The circulation of water for coolant is by twelve large turbine type pumps of 20,000 gallon/minute capacity each. These pumps are connected to a large diameter (2.917 m) concrete pipe. Water velocity in the pipe is limited to 1.5 m/s in order to minimize flow losses.

8. The plant has an automatic control system capable of controlling the air inlet doors in order to limit maximum power rating to 10.5 mw. Also, it selects the optimum number of pumps to operate as required by the ambient air conditions. If the air conditions are not favorable for operations, the control system will shut the plant down until favorable air conditions occur.

For the plant of 10.5 mw rated net power, the estimated capital cost is 15.91 million dollars, or about $1500 per rated kilowatt. Figure 12 shows a breakdown of the cost. The rather large structure selected in this design accounts for the major portion of the cost. It must be emphasized that these are preliminary design figures based on a configuration that would be workable, but has in no way been optimized. Figure 13 is a schematic diagram of the same plant.

Since the humid air power plant operates without fuel, the annual fixed cost is a figure which will come close to the total annual cost. Computing the annual fixed cost at 15% of the capital investment for the plant, and using the total kw-hr generated if the plant operates 12 months per year, the cost per kw-hr is 4.0 cents/kw hr. This appears to be an attractive cost figure for a non-energy consuming power plant.

Capital Cost Relationships

Structure cost was developed on a dollars per square foot basis for a structure similar to an airplane hangar. Cost data from [2] were used. Data from this same reference were used for estimating cost of the cooling water pipe.

Electrical machinery costs were estimated for a 9 mw generator using published data from reference [3].

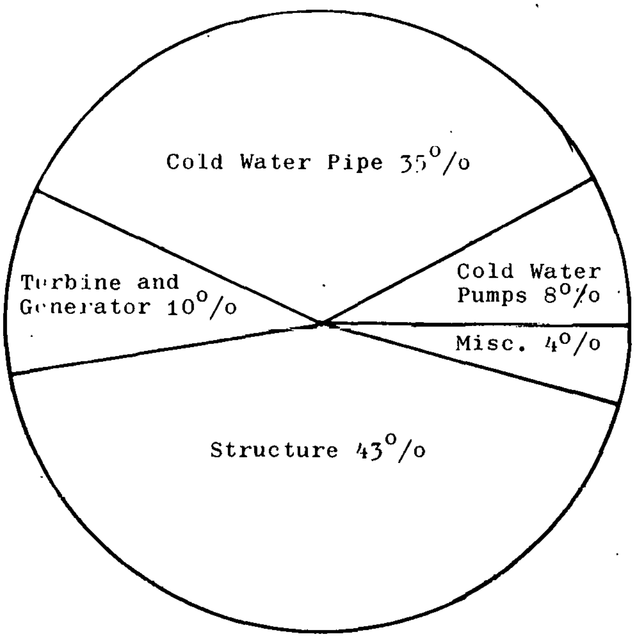
Pump costs were based on off-the-shelf prices for large pumps of the type used in waste water treatment plants. [4]

Installed costs of machinery were estimated on the basis of multiplying factors recommended in [5]. These factors include overhead and direct labor, transportation, and installation costs.

All costs were updated for price escalation for the time interval from the date of the cost quote up to 1977. Data in reference [6] were used for 1969 to 1975 and an escalation of 10%/year was estimated for 1976 and 1977.

Conclusions Regarding Cost Estimates

It must be emphasized that the preceding cost estimates are made for a very rough preliminary design. Further research is necessary to prove that the vortex mechanization can really be made to operate successfully. There will be some power losses in the vortex, and we are not yet in a position to estimate these losses. On the other hand, the



Total Cost: $15,900,000 (exclusive of site)
Design Rating: 10.5 MW at T = 32.2°C, RH = 63°/o, 6°C cooling water.

FIG. 12. CAPITAL COST OF HUMID AIR POWER PLANT.

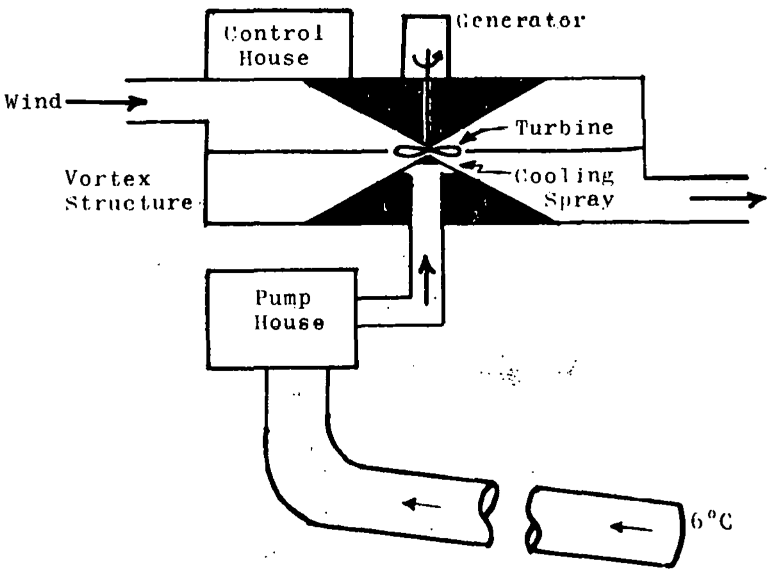


FIG. 13. SCHEMATIC DIAGRAM OF A HUMID AIR POWER PLANT.

estimates are based on a design for a plant which has not in any way been optimized. It is our belief that the cost estimates look sufficiently attractive that further research in this area is warranted.

ACKNOWLEDGEMENT

This paper is a report on research which was sponsored by the Wind Systems Branch, Solar Energy Division of the U.S. Department of Energy.

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4. "Verti-Line Pumps and Pump Systems," Layne and Bowler, La Puenta CA.

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6. "Capital Cost Estimating," Chemical Engineering, March 24, 1969.

RESPONSES TO THE OLIVER PRESENTATION

Carl Aspliden, DOE: I agree with you that the latent energy is two to three orders of magnitude larger than the kinetic energy in the boundary layer. If you look at the internal energy of a particle in the atmosphere (latent energy, potential energy, and kinetic energy) the kinetic energy is so small that even in a hurricane it is two to three orders of magnitude smaller than the other forms of energy. Your system has both an expansion and compression cycle. In the expansion cycle you release latent heat. As you release latent heat the air becomes more buoyant and works against the downdraft to the minimum pressure point. In the next cycle you compress air, the temperature is then adiabatically increasing and that is again working against your cycle. Can you elaborate a little further?

Oliver: There may be a difference in what we are considering. I said that the solar energy that reaches the surface of the earth is different from the solar energy that impinges on the earth's atmosphere from outside. In the final vortex mechanism I think buoyancy plays a very little part. Cooling is required during the compression cycle so that the air remains at a constant temperature during the recompression. If there is no cooling then the cycle is not a work producer.

Al Miller, PNL.: I found your tutorial to be very interesting and enlightening, but I have a question concerning the tornado which you are trying to generate. Calculations of atmospheric tornadoes, those that destroy barns and towns, indicate that a typical superstorm produces a pressure reduction on the order of 100-150 millibars at the center. You are talking about producing a pressure of half an atmosphere, 500 millibars. Could you please explain.

Oliver: We may have to get velocities that actually exceed those in a natural tornado in order for the system to work. You get more energy out of the system as the pressure decreases. The main restriction is that of the cooling water.

J. Ramstetter, Solar & Wind Energy Systems: Have you ever thought of using a mine shaft? Many exist which are 3 or 4,000 ft deep.

Oliver: We had thought of a mine shaft if a great vertical dimension was needed. For the vortex mechanization and structure, vertical height is not really important. Anything that uses significant vertical height is probably not cost effective.

SAILWING WIND ENERGY SYSTEMS ASSESSMENT

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MO

ABSTRACT

The sailwing windmill was conceived by T.E. Sweeney at Princeton University. Performance measurements were made with sailwing wind rotor models on a moving test bed. A 7.6 meter (25 ft.) diameter machine was built by Grumman Energy Systems and is presently turning essentially without power extraction at a site administered by Princeton University. It is estimated that the cost of energy from this windmill is comparable to that of good conventional wind machines of its size, namely 0.09 to 0.12 $/KWh for low quantity production and 0.06 to 0.07 $/KWh for advanced versions in high quantity production. The sailwing rotor has four times the blade area of a conventional windmill with fiberglass blades without an increase in blade weight or blade cost. The unresolved question is whether this high blade planform area is really needed to obtain good performance. It is recommended that the government sponsor a wind rotor model test series including sailwing rotors to experimentally study the effects of widely varying blade parameters.

INTRODUCTION

This report gives the highlights of the results of a three month study* on the technical development, performance characteristics and cost projections of wind energy conversion systems (WECS) using sailwings. The sailwing structure consists of a nose spar, two end ribs, and fabric wrapped around nose spar and trailing edge cable to form an airfoil section (Figures 1 and 2). The sailwing concept originated and was researched at Princeton University by T.E. Sweeney and his associates. The airfoil contour changes under the influence of the surface pressure forces. The sailwing rotor concept should be distinguished from the sail wind rotor that uses rotating sails rather than rotating wings. The sails need to be furled in high winds and in contrast to rotary sailwings the sail wind rotor cannot be left unattended.

The major purpose of the study was to determine, by critical evaluation, whether wind energy conversion systems using sailwings have the potential of being cost effective energy resources. The task required a system comparison with conventional unaugmented wind systems. For the purpose of such comparisons a standard wind speed duration function with exponent 2.27 and a mean wind velocity distribution vs. height above ground based on a surface roughness length of 0.05 meter will be used in this report.

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*Coinvestigator, A. Swift; Technical Advisors, D.A. Peters, W.A. Strutman.

The cost of energy will be based on the initial or "turn key" cost, on a fixed charge rate of 18% per annum, on uniform annual estimated operation and maintenance costs, and on the total annual KWh produced using the given wind speed duration function and estimated outages. The system is assumed to operate at a site with a yearly mean wind speed of 5.4 m/s (12 mph). The system should survive, without damage, wind speeds to 53.6 m/s (120 mph), assuming zero gust factor.

Very little documentation exists on rotary sailwings. The documentation is limited to some incomplete performance measurements on sailwing rotor models. Due to this lack of documented data the following assessment of sailwing wind energy systems involved a great deal of engineering judgement.

STATE OF ROTARY SAILWING DEVELOPMENT

To our knowledge sailwing rotors have been, or are, in development at five different organizations:

- <u>Princeton University</u>, where T.E. Sweeney originated the concept and owns the basic U.S. patents;
- <u>Grumman Energy Systems</u> holds an exclusive six year license from T.E. Sweeney;
- <u>Niels Borre</u> of Denmark is experimenting with sailwing rotors and is said to have been granted European patents;
- <u>Lund Enterprises</u> of California is apparently licensed by Niels Borre;
- <u>Flanagan</u> of New York is developing plans for home built sailwing rotors, using the Princeton design for the three-bladed, 11 foot diameter test rotor.

The Princeton sailwing rotor development is described in [1 to 4]. The bulk of the development at Princeton University was undertaken in 1974-76 under a NSF-RANN grant. This development was terminated in 1976 with the completion of the grant. No further sponsorship of rotary sailwing research or development has been obtained since then. The sailwing rotor development at Grumman Energy Systems also took place in 1974/75 and was apparently terminated in 1975. Documentation for any aspects of this development could not be obtained. Grumman Energy Systems decision to switch from rotary sailwings to rotary metal wings was not based on economic considerations. Rather, the refurbishing of the sailwings every few years was considered undesirable for the type of wind machine Grumman wished to market. Grumman designed and constructed a 25 foot diameter sailwing wind machine based on T.E. Sweeney's preliminary design. This wind machine was later given to T.E. Sweeney. Under a Lawrence Rockefeller grant to Princeton University, the windmill was refurbished with new sailwing fabric, somewhat modified by adding two fences at 1/3 and 2/3 blade span, and was installed at a Princeton University operated camp near Blairstown, New Jersey. Since June, 1978 this wind machine is turning at the camp site practically without power extraction. The alternator charges an automobile battery which is only used to light a bulb. There is no tachometer connected to the rotor, thus rotor speed is unknown.

Neither is wind speed measured. The machine has a manually operated rotor brake that is applied when hurricane winds are expected. Apparently the machine has survived winds up to 60 miles per hour with the rotor in autorotation, and winds up to 80 miles per hour when the rotor was stopped.

Information concerning the Niels Borre sailwing rotor development in Denmark could not be obtained. Lund Enterprises distributes a sales sheet* of a sailwing rotor machine called the "Windflower". It has a 24 to 28 feet diameter rotor and is mounted on a 38 foot high tower. The sales sheet refers to Niels Borre in Denmark as the inventer without mentioning the Princeton Development. The rated power is listed as 18 KW at 27 mph wind speed. The price of the machine less site preparation and installment is given as $10,000 to $10,500. Monthly output at 10 mph average wind speed is given as 3360 KWh, at a price of 2.8¢ per KWh assuming a 10% 30 year loan. These numbers appear in error by a large margin as even a superficial assessment will show. Apparently one machine was constructed in 1977 but was damaged in a storm. A second machine is presently being constructed. Our repeated efforts to obtain information on the "Windflower" in addition to that printed in the sales sheet failed. From a photograph of the machine [5] the blade geometry appears to be similar to that of the Grumman-built sailwing machine.

Flanagan's plans for a home built sailwing rotor are described in [6]. Upon contacting Mr. Flanegan we learned that the machine has not been built to date.

AERODYNAMICS OF SAILWINGS

An aerodynamic theory of the sailwing, substantiated by wind tunnel model tests, is presented in [7]. A sailwing configuration, according to Figure 1, is assumed, and thin airfoil analysis is applied. For zero wind velocity the airfoil has the shape as indicated by the dashed lines. The airfoil is symmetrical and consists of straight lines tangential to the round spar. When subjected to a relative wind velocity V with a geometric angle of attack α the aerodynamic pressure forces transform the airfoil into a shape indicated by the solid lines. Due to the up-motion of the trailing edge, the angle of attack is decreased by the amount $\Delta\alpha$, as compared to the geometric angle of attack of the undeformed airfoil. Due to the curvature of the contour there is a substantial camber of the deformed airfoil. The planform of the sailwing is shown in Figure 2.

A particularly significant variable for the sailwing is the trailing edge pretension coefficient defined by $c_{TO} = T_O/q\ S_W$ where T_O is the trailing edge pretension force, q the dynamic pressure, and S_W the sailwing surface area. The most important analytical result of [7] is the finding that there exists a critical value of c_{TO}, designated by c_{TOD}, below which the sailwing contour becomes unstable for low geometric angles of attack. This finding has been verified by experiment.

*Lund Enterprises, Inc., 1180 Industrial Ave., Escondido, California, 92025, Phone: (714) 746-1211.

The divergence tension coefficient c_{TOD} for aspect ratio 5 ranges from about 0.5 to 0.7. As the tension coefficient c_{TO} approaches its critical value, the initial lift slope $c_{L\alpha}$ for $\alpha \to 0$ approaches infinity as indicated in Figure 3 which gives analytical results of the $c_L - \alpha$ relationship for various ratios of tension coefficient over its critical value. For a tension coefficient below this critical value the lift for a small angle of attack is no longer unique and there is an unstable range where the sailwing contour will flip from one shape to another.

Test results for full scale sailwings of various aspect ratios are given in [8 and 9]. The airfoil is shown in Figure 4. Based on [7 to 9] the aerodynamic characteristics of sailwings can be summarized as follows:

(a) Sailwings have inherently high camber with a quarter chord moment coefficient of about -0.25 (nose down moment).

(b) For medium lift coefficients sailwings have $c_L - \alpha$ curves similar to a rigid airfoil with a 20° deflected 20% chord trailing edge flap.

(c) For low lift coefficient the lift curve slope becomes steep. To avoid an excessively steep slope, the trailing edge tension coefficient $T_O/q\ S_W$ must be sufficiently high. Low aspect ratio helps to prevent excessive lift slopes.

(d) For medium lift coefficients the profile drag of a sailwing with 12 to 14% thickness is comparable to that of a good rigid airfoil. Lift to profile drag ratios of about 100 can be easily attained at c_L values near 1.0.

(e) For low lift coefficients the sailwing profile drag is very much higher (2 to 4 times) than that of a comparable rigid wing.

One can conclude that sailwings have acceptable aerodynamic characteristics provided that 1) the high quarter chord negative moment coefficient is not bothersome, 2) that the low lift coefficient region is not important, 3) that the trailing edge wire tension force can be made sufficiently high, and 4) that the aspect ratio and wing area between ribs can be made sufficiently low to prevent excessive lift slope.

TESTS WITH SAILWING MODEL ROTORS

The usual performance measure for a wind rotor is the power coefficient defined by

$$c_p = \text{shaft power}/0.5\rho\pi\ R^2\ V^3 \tag{1}$$

where ρ is the air density, R is the rotor radius and V is the wind velocity. Using Goldstein's theory, valid for a non-contracting non-expanding vortex wake (lightly loaded rotor), one can determine limits for c_p which depend on the number of rotor blades. Aerodynamic blade drag is neglected. The upper c_p limits for infinite number of blades and for two and three blades are shown in Figure 5 taken from [10].

The Princeton sailwing rotor tests were conducted with the rotor mounted on a jeep. To extract rotor power, a motorcycle disk brake was applied and the rotor torque was measured by strain gauges. The rotor speed was read from a tachometer so that c_p vs. $\lambda = \Omega R/V$ could be determined. It was found that even a slight natural wind velocity had a strong effect on the measured c_p values. Moving against the wind resulted in higher c_p values than moving with the wind. An averaging procedure for the two measurements was devised.

Tests with the three-bladed rotor are reported on in [2]. In its optimum configuration it had a two foot diameter center disk and a semicircular blade tip, giving it a diameter of 11 feet. The planview of a blade is shown in Figure 6 together with data on the chord, airfoil thickness ratio, and geometric pitch distribution.

The maximum value of $c_p = 0.45$ measured with the Princeton three-bladed sailwing rotor has frequently been quoted and stands out far above measured values of c_p for other wind rotors in this tip speed range. The point $c_p = 0.45$ at $\lambda = 3$ is plotted in Figure 5. It is above the upper limit for a three-bladed rotor though this limit ignores airfoil drag.

Tests with a two-bladed sailwing rotor are reported in [3 and 4]. The optimum configuration had a center disk of 1.2 foot diameter, 20° blade twist and a blade root setting of 10° pitch.

There is an unexplained feature of the Princeton sailwing rotor test results. It was found that the performance deteriorated appreciably with increasing vehicle speed from 19.6 to 31.1 ft/s. The autorotational tip speed ratio was reduced from eight to seven and the maximum c_p value was reduced from 0.40 to 0.36 for the two-bladed rotor in its optimum configuration (g).

In summary one can say of the performance measurements made with the sailwing rotors on a moving platform that the maximum value of $c_p = 0.45$ at $\lambda = 3$ for the three-bladed rotor is most likely in error. The measured maximum value of $c_p = 0.40$ for the two-bladed rotor may be correct. The deterioration of performance with increasing vehicle speed needs an explanation and may or may not be caused by the sailwing characteristics. There is some doubt concerning the validity of the measurements with a moving test bed. This question should be studied.

PERFORMANCE AND INITIAL COST OPTIMIZATION OF SAILWING WIND MACHINES

We will use the two $c_p - \lambda$ relationships shown in Figure 7 in order to cover various possible sailwing designs and in order to include the uncertainties found in the Princeton performance measurements. The upper curve with $c_{pmax} = 0.42$ at $\lambda = 4.2$ is the most optimistic assumption for a three-bladed sailwing rotor similar to the 25 foot diameter Grumman-built wind machine compatible with Figure 5. Since test data for the back side of the c_p - λ curve are missing, the left hand side of the curves was estimated.

Variable and constant speed operation of the sailwing rotor have been studied. Here we will limit the presentation to constant speed operation. The computation of the yearly energy output will be performed in a non-dimensional way, following essentially a concept described in [11]. The wind rotor is assumed to operate in a uniform flow field and to transmit all of the available power to an electric generator tied to a grid. The yearly mean wind velocity $\bar{v}$ is used as a reference velocity to non-dimensionalize all other velocities. The rated electric generator output P_r is written in the form

$$P_r = (\rho/2)\ \pi R^2\ (u\ \bar{v})^3, \quad \text{where} \tag{2}$$

u is the non-dimensional characteristic wind speed and is treated as a main design parameter for the wind machine.

The tip speed ratio is defined by

$$\lambda = \Omega R/v\ \bar{v} \tag{3}$$

We will define the characteristic tip speed ratio by

$$\lambda_r = \Omega R/u\ \bar{v} \tag{4}$$

Thus we have the two non-dimensional design parameters, u and λ_r, that can be determined in such a way that either the yearly electric generator output is maximized, or that the cost of energy is minimized.

The velocity duration function in non-dimensional form is defined by

$$\phi(v) = \exp - (\pi/4.06)\ v^{2.27} \tag{5}$$

$\phi(v)$ is the fraction of time that the non-dimensional wind velocity exceeds the value v.

The non-dimensional power output p of the electric generator is

$$p = P/P_r, \quad \text{where} \tag{6}$$

P is the generator power output and P_r its rated output. The average non-dimensional power output of the electric generator is

$$\bar{p} = \int_0^1 \phi(p)\ dp \tag{7}$$

This relation assumes that the energy loss from power cut-out at high wind speed is negligible. The quantity $\bar{p}$ is also called capacity factor or plant factor. In a strict sense, the down time of the plant for maintenance or repair should be included in the plant factor. We assume here that for mature wind power plants this down time can be neglected.

The energy equation for the wind rotor is

$$p + p_{Loss} = c_p(\rho\pi R^2/2P_r)\ (v\ \bar{v})^3 \tag{8}$$

Inserting P_r from Equation (2):

$$p + p_{Loss} = c_p(v/u)^3 \tag{9}$$

Equation (9) can also be written

$$p + p_{Loss} = \lambda_r{}^3(c_p/\lambda^3) \tag{10}$$

Finally, we define the mean power coefficient k for the electric generator output by

$$\bar{P} = k(\rho/2)\ \pi R^2\bar{v}^3 \tag{11}$$

With $\bar{P} = \bar{p}P_r$ and with Equation (2) one obtains

$$k = \bar{p}\ u^3 \tag{12}$$

We will assume a linear loss function for the power loss

$$p_{Loss} = f_0 + p(f_1 - f_0) \tag{13}$$

So that from Equation (10)

$$p = (\lambda_r{}^3(c_p/\lambda^3) - f_0)/(1 + f_1 - f_0) \tag{14}$$

whereby $p \leq 1.0$

For the numerical analysis it is here assumed that $f_0 = 0.13$ and $f_1 = 0.20$. The effects of assuming values of f_0 and f_1, different from 0.13 and 0.20 respectively, have been studied, but are omitted here.

Configurations A and B from Figure 7 have been studied together with windmills not using sailwings. Only selected data on Configuration A will be presented here.

At rated power, p = 1, Equation (14) defines for a given λ_r value the quantity c_p/λ^3 which for constant rotor speed is proportional to rotor torque. Figure 8 shows c_p/λ^3 vs. $1/\lambda$ with the lines of rated power for the three selected values of λ_r superimposed. For the smallest characteristic tip speed ratio λ_r, the line of rated power lies above the c_p/λ^3 maximum, i.e., above the torque maximum. In this case rotor torque control is not needed since the rotor will never reach rated torque. For the higher two λ_r values, rotor torque must be reduced, perhaps by blade feathering, as soon as the rated torque line is reached. λ_{rcrit} is the value of λ_r for which rated torque and maximum rotor torque coincide.

Figures 9 and 10 show k, $\bar{p}$ and the cost factor CF vs. u for $\lambda_r = 5$. The relation for CF will be explained later. For other λ_r values the minima of the cost factor CF occur at about the same u values. Thus it is possible to plot for this u value, the capacity factor $\bar{p}$ and cost factor CF vs. characteristic tip speed ratio λ_r (Figure 11,12). From Equation (12), $k = \bar{p}\, u^3$, so that a separate plot for k is not required.

Figure 11 shows, in addition to $\bar{p}$, the maximum non-dimensional generator power $p_{max} = P/P_r$ vs. λ_r. For $\lambda_r = \lambda_{rcrit}$ it reaches the value $p = 1$. For higher design rotor speeds power must be dumped so as not to exceed $p = 1$. The dashed line corresponds to the highest rotor speed for which power dumping - that is torque control - is not needed. From Figure 11 it is seen that the $\bar{p}$ value at the dashed line is somewhat below the maximum $\bar{p}$. One will lose some yearly energy output by not selecting the λ_r for maximum $\bar{p}$. However the cost of energy, represented by the initial cost factor of Figure 12, can be lower than for the maximum $\bar{p}$ design due to the cost savings of not needing torque control. This is indicated by the discontinuity of the CF curve.

TECHNICAL ASPECTS OF SAILWING WINDMILLS

The following technical aspects of sailwing wind machines were studied. Only brief summaries of the results are given here:

Structural Integrity and Durability of Rotary Sailwings

Rotary sailwings can be designed with the same structural integrity as rigid rotary wings. The major hazard is exposure to sun light. Sun light causes deterioration and only a few years lifetime of the sail cloth can be expected. Industrial silicone rubber coated fabric that would extend the lifetime may or may not be suitable.

Dynamics of Sailwing Wind Machines

It appears that the use of rotary sailwings will not cause any major new dynamic problems. The special characteristics of rotary sailwings like the high torsional blade moments from high camber, the far forward chordwise center of gravity location and the relatively low rotational inertia must, of course, be properly considered in a detailed dynamic design and analysis.

Operation and Maintenance

Frequent refurbishing of the sailwings at two to three year periods must be expected. For a 25 foot diameter rotor refurbishing could be accomplished in a day, so that the increase in downtime due to refurbishing is negligible.

Configurations of Sailwing Machines

Rotary sailwings can be expected to produce similar effects with respect to configuration alternatives as rigid rotary wings, except that downwind operation may cause smaller disturbances from mast wake and that no information is available on deep stall effects used in constant speed fixed pitch machines.

Potential Improvements of Rotary Sailwings

Desirable improvements of the 25 foot diameter Grumman-built sailwing machine are: Automatic rotor brake instead of the manual rotor brake to protect against overspeed, possibly lower blade solidity ratio to reduce torque and storm forces, more durable fabric, improved spar-hub connection and design for constant speed operation, preferably with fixed pitch if the sailwing can operate satisfactorily in deep stall.

Size Limitation

Size limitations are imposed mainly by the problem of rather frequent refurbishing of the blades with new fabric. This procedure gets more complex and more costly with larger size. A 50 foot diameter sailwing rotor appears to be a reasonable upper limit.

COST EFFECTIVENESS OF SAILWING WIND MACHINES

The cost of energy is

$$COE = 0.19\ (IC)/AKWh \tag{15}$$

Equation (15) assumes a yearly charge rate of 0.18 and a yearly operation and maintenance rate of 0.01, both based on the initial cost IC. Downtime for repairs and refurbishing of the blades is neglected. From Equation (11) the annual kilowatthours are

$$AKWH = k(\rho/2)\ \pi R^2\ \bar{v}^3\ 8.766 \tag{16}$$

The air density will be assumed for standard sea level, $\rho = 1.23\ kg/m^3$. The rotor radius R is measured in meters and the annual mean wind velocity $\bar{v}$ in m/s. The average power $\bar{P}$ from Equation (11) is then obtained in watts. For 8766 hours per year the annual number of kilowatthours is obtained by multiplying $\bar{P}$ by 8.766.

For the initial cost minimization we will apply two approximations. First, we will neglect the effect of rotor speed on the initial cost. Since rotor speed variation at given rated power affects only about 10% of the total cost, neglecting its effect will not substantially change the initial cost. Second, when varying rated wind speed and the associated rated power, we will assume that the average power remains constant. The wind machine is designed to operate at approximately maximum average power, that is at the maximum value of k. When varying the characteristic wind speed u from its value for maximum k the change of k is small while the capacity factor $\bar{p}$ changes rapidly, see Figure 9. Thus, only the effect of $\bar{p}$ on rated power will be considered.

In order to estimate the change of IC with capacity factor $\bar{p}$ it is assumed that for a reference design that maximizes k the initial cost is IC* and the associated capacity factor is $\bar{p}*$. The actual IC is then

$$IC = [(1-x) + x\bar{p}*/\bar{p}]IC* \tag{17}$$

x is the cost fraction for those components that vary with rated power, namely for the generator and for the power train. From limited information on 25 foot diameter windmills and on the 125 foot diameter NASA/DOE MOD-0A wind machine in [12] it was determined that one can assume x = 0.2 for a wide range of machines.

For $\bar{p} = \bar{p}^*$ the actual initial cost is equal to the reference cost, IC = IC*. As $\bar{p}$ varies the fraction x of the reference cost varies inversely with $\bar{p}$. Inserting Equation (16) and Equation (17) into Equation (15) one obtains

$$COE = 0.19[((1-x) + x\bar{p}^*/\bar{p})/k]\ IC^*/[8.76(\rho/2)\ \pi R^2\ \bar{v}^3] \tag{18}$$

Assuming x = 0.2 and denoting

$$CF = (0.8 + 0.2\bar{p}^*/\bar{p})/k \tag{19}$$

we have

$$COE = 0.19\ (CF)\ IC^*/[8.76(\rho/2)\ \pi R^2\ \bar{v}^3] \tag{20}$$

In Figure 12 a jump of the initial cost factor CF is shown at that rotor speed where rated power is equal to maximum rotor power. For this and lower rotor speeds rotor torque control is not needed. The size of the jump is based on the assumption that the variable pitch rotor torque control costs 8% of total. Using the preceding cost optimization method the Grumman-built 25 foot diameter sailwing machine in its two Configurations A and B defined by Figure 7 have been optimized together with the MOD-0A machine. A c_p – λ relation for this machine has been determined on the basis of data given in [13] for zero pitch setting. Cost data were taken from [12].

In the following tables column A refers to low quantity production, and column B to advanced versions in high quantity production. The initial cost IC* of the sailwing machine has been estimated as $10,000 for low quantity production and as $6,000 for advanced versions in high quantity production. This refers to 1000 units for a batch. 100 units for a batch of the 125 foot diameter advanced MOD-0A machines is assumed in [12].

TABLE 1: COST OF ENERGY OPTIMIZATION

Machine	$\bar{p}$	k	CF	$\bar{P}$ KW	P_r KW	$/KWh A	$/KWh B
Sailwing A	0.25	0.33	2.60	1.91	7.70	0.097	0.058
Sailwing B	0.25	0.29	3.24	1.68	6.70	0.121	0.073
MOD-0A	0.23	0.31	2.85	63.0	271.	0.523	0.062

It is seen that even the derated sailwing B machine has a cost of energy which is only a small fraction of that of the much larger MOD-0A wind machine operating in various locations in the United States. The extremely great reduction in the cost of energy for an advanced version of this machine with a high quantity production is given in [12]. Whether or not such a reduction can be achieved is questionable. Even if it can, the small sailwing windmill will remain competitive with the much larger MOD-OA machine.

A limited statistical study on fiberglass and aluminum blade weights resulted in the following weight equation which agrees with helicopter blade weight statistics

$$W_{bl} = 2200\ (D/125)^{2.5},\ \text{lbs.}$$

The diameter D is to be taken in feet. The sailwing blade is also covered by this weight equation. Blade costs per unit weight have been determined for four wind machines and are shown in Table 2.

TABLE 2: BLADE COSTS PER UNIT WEIGHT

Machine	D ft.	($/lb) A	($/lb) B
Grumman sailwing	25	8.2	7.7
Astral Wilcon (Fiberglass)	25	8.8	5.4
Millville (Aluminum)	25	8.1	4.9
MOD-OA (Fiberglass version)	125	14.1	6.4

The sailwing data are our estimates. The data for the two other 25 foot wind machines have been obtained from the manufacturers. The data for the MOD-OA are from [12]. It is surprising how close the blade cost per unit weight are from these various sources.

Finally, the initial cost increments for the sailwing machine vs. the Astral Wilcon windmill have been estimated and are shown in Table 3. Both machines have 25 foot diameter.

TABLE 3: SYSTEM INITIAL COST INCREMENTS FOR GRUMMAN-BUILT SAILWING MACHINE COMPARED TO ASTRAL WILCON WIND MACHINE

Blades for low quantity production	0%
Blades for high quantity production	+3%
Elimination of blade pitch variation	-6%
Heavier power train because of higher torque	+4%
Elimination of tail vane	-1%
Increased tower strength because of higher storm loads	+5%
Equivalent initial cost increment from blade refurbishing	+5%
Total for low quantity production	+7%
Total for high quantity production	+10%

According to Table 1, performance uncertainties led to COE differences of 18%; somewhat higher than the 7 to 10% cost increment in Table 3. Thus the initial cost increment could be compensated for or overcompensated for by a performance increment. If, for example, the sailwing rotor would actually have $c_{pmax} = 0.42$ vs. the estimated 0.38 of the Astral Wilcon machine, the COE of both machines would be almost identical.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The rotary sailwing concept provides a viable alternative to conventional rotary wings for wind machines in sizes up to about 50 foot diameter. The concept is more attractive the higher the rotor solidity ratio (blade planform area over rotor disk area). The initial cost of a sailwing wind machine like the Grumman-built 25 foot diameter windmill is somewhat higher than for a comparable wind machine with fiberglass blades. The performance may or may not be sufficiently higher to compensate for the higher initial cost. There is some question as to the validity of the Princeton sailwing rotor performance measurements obtained with a moving test bed. The performance deterioration with increasing test bed speed is not explained. The important deep stall region of the sailwing rotor has not been tested.

Because of the basic viability of the sailwing concept and because of the uncertainties of its characteristics the following recommendations are made with respect to further government support of rotary sailwing systems.

(a) Clarify the question whether measurements on a moving test bed are usable without correction. A combined analytical and test approach to this question appears appropriate. The question is also important for moving test bed measurements of other types of wind rotors which are increasingly tested in this manner.

(b) Monitor over extended periods of time the wind speed and the rotor speed for the Grumman-built 25 foot diameter sailwing rotor in order to obtain indications as to the sailwing characteristics at higher wind speeds.

(c) Conduct tests with rotary sailwings using heavier industrial cloth with silicone rubber protection in order to determine whether longer lasting fabrics are suitable for sailwing applications.

(d) The difficulty of judging the validity of the Princeton sailwing measurements with a moving test bed are caused by the absence of other test results to compare them with. To remedy this situation it is recommended that wind rotor model performance tests be conducted, either in a wind tunnel or with a moving test bed at a reasonably high Reynolds number and with a variety of rotor solidity ratios, blade planforms, twists and tip geometries. As compared to the propreller or rotorcraft development phase that was backed up and preceded by numerous model tests, systematic test data on wind rotor parameter effects are presently not available. Because of its low weight and cost per unit blade area, the sailwing rotor should be included in such systematic test series together with low solidity rotors of conventional design.

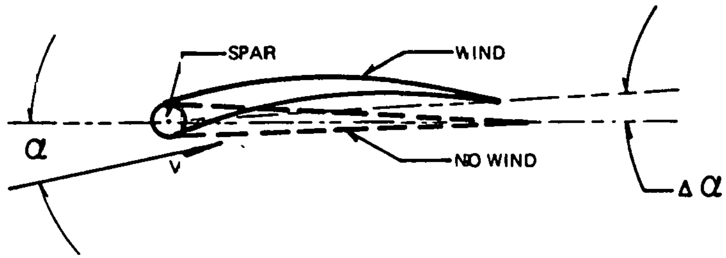

FIGURE 1: SAILWING CROSSECTION AS AFFECTED BY WIND

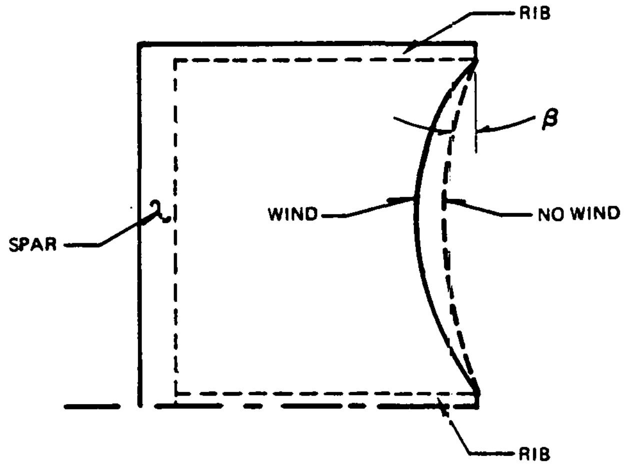

FIGURE 2: SAILWING PLANFORM AS AFFECTED BY WIND

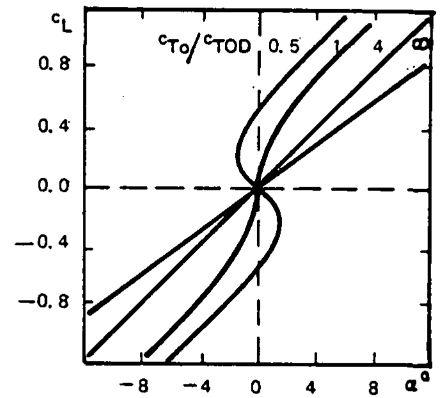

FIGURE 3: SAILWING c_L vs. α CURVES FOR VARIOUS RATIOS OF TRAILING EDGE WIRE TENSION COEFFICIENT OVER CRITICAL TENSION COEFFICIENT c_{To}/c_{TOD}

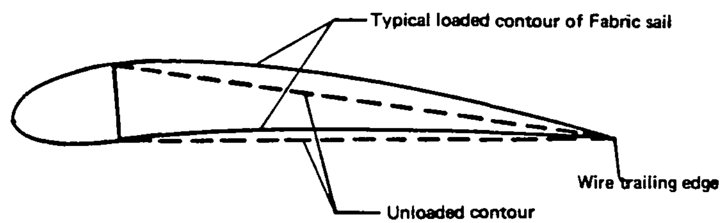

FIGURE 4: D–SPAR CONFIGURATION OF SAILWING

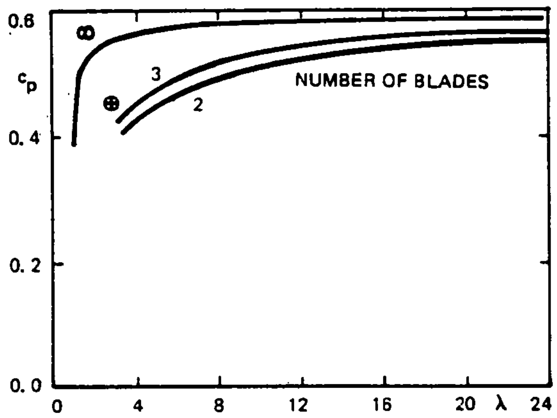

FIGURE 5: c_p vs. λ FOR TWO, THREE AND INFINITE NUMBER OF BLADES

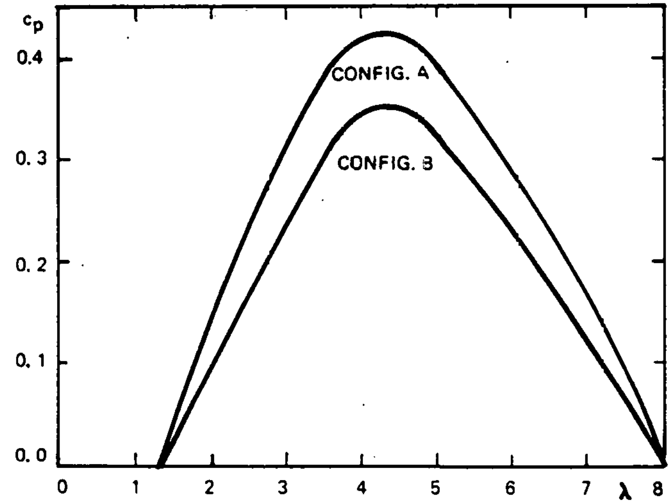

FIGURE 7: c_p vs. λ ASSUMED FOR OPTIMIZATION STUDY

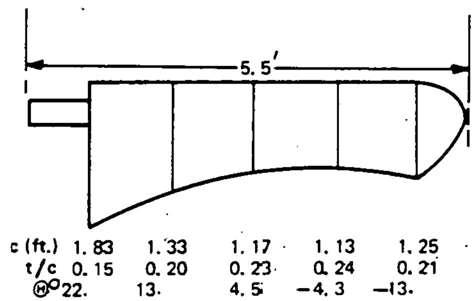

FIGURE 6: PLANFORM OF BLADES FOR THREE-BLADED SAILWING ROTOR MODEL TESTS

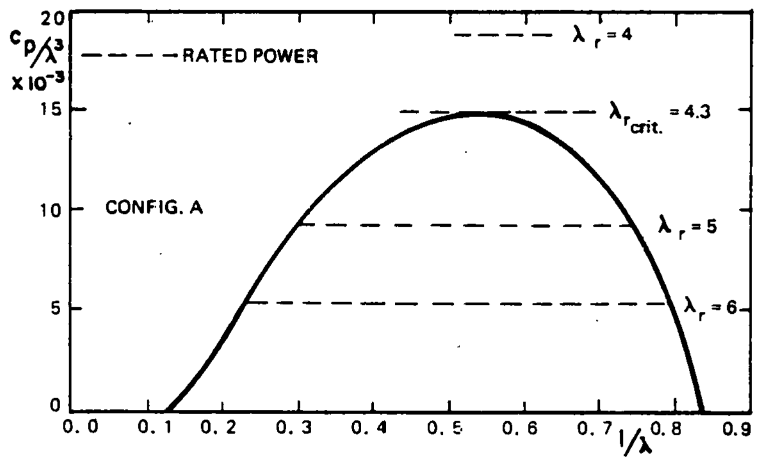

FIGURE 8: c_p/λ^3 vs. $1/\lambda$ FOR SAILWING ROTOR CONFIGURATION A

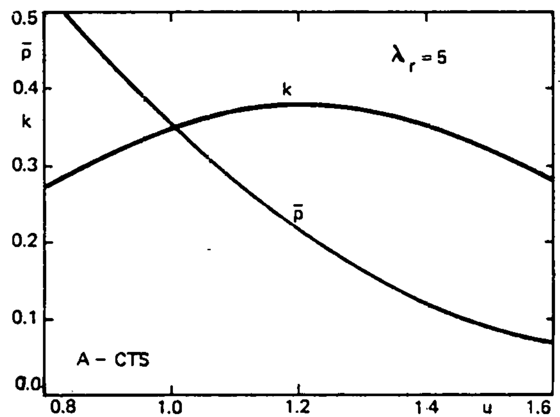

FIGURE 9: AVERAGE POWER COEFFICIENT k AND CAPACITY FACTOR $\bar{p}$ vs. CHARACTERISTIC WIND SPEED u, λ_r =5.0, CONFIGURATION A.

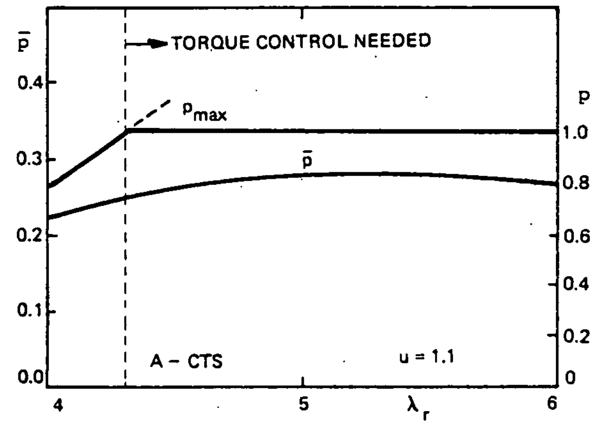

FIGURE 11: NON-DIMENSIONAL POWER $p = P/P_r$ AND CAPACITY FACTOR $\bar{p}$ vs. CHARACTERISTIC TIP SPEED RATIO λ_r, u = 1.1, CONFIGURATION A.

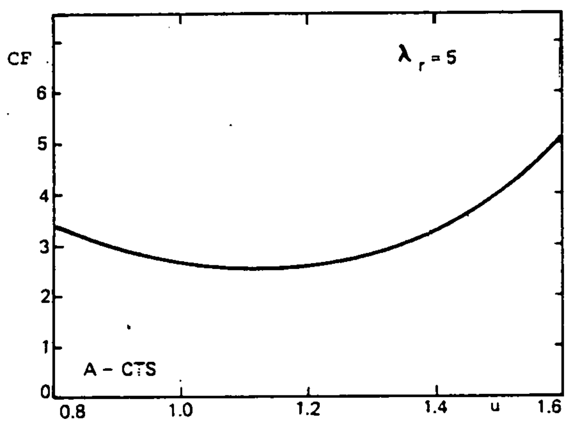

FIGURE 10: INITIAL COST FACTOR C F vs. CHARACTERISTIC WIND SPEED u. λ_r = 5.0, CONFIGURATION A.

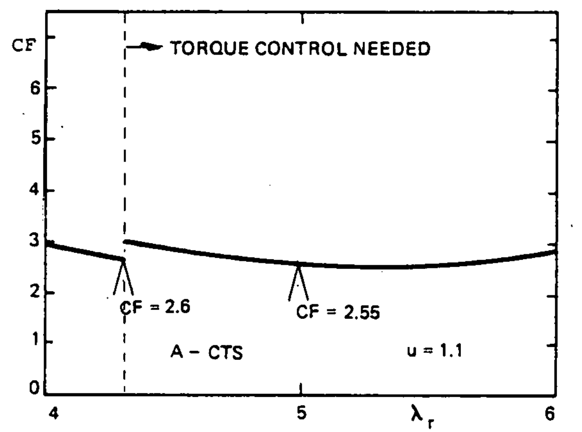

FIGURE 12: INITIAL COST FACTOR C F vs. CHARACTERISTIC TIP SPEED RATIO λ_r, u = 1.1, CONFIGURATION A

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RESPONSE TO THE HOHENEMSER PRESENTATION

Harper, Tetra Tech., Inc.: Did you include the costs of replacing the sails every two or three years? If so, what effect does that have on the cost of electricity?

Hohenemser: It doesn't have a tremendous effect. We have some data on the replacement cost for a 25 ft diameter machine, about $500. If this is done every 2 to 3 years, it amounts to about 1 1/2% of the initial cost per year so that would be equivalent to having a 19 1/2% financial charge instead of 18%.

David Wagner, David C. Wagner & Associates: From your studies, you expect cloth flutter which would fatigue the fibers, and are these sailwings supposed to be self-limiting in speed because of stall? You comment that you need torque limiting devices. Is this to keep the system from overspeeding?

Hohenemser: They actually got something that sounded like flutter on the Grumman machine. It was a very high pitched noise which was eliminated by adding ribs. Instead of having only an end root, additional ribs were added. I mentioned that the stall characteristics have not been measured nor has there been adequate documentation of rpm, normal speed, etc.

Terry Cooper, Nautilus Balloon Works, Inc.: I was wondering what fabric you used and if you thought about using urethane-coated dacron as used in balloons. Dupont has some films that also might be used.

Hohenemser: High grade nylon sail cloth has been used by a local sail maker. If some silicon-covered industrial cloth is used it may actually increase the lifetime up to possibly 4-5 years.

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DEFINITIVE GENERIC STUDY FOR THE EFFECT OF HIGH LIFT AIRFOILS ON WIND TURBINE COST EFFECTIVENESS

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ABSTRACT

The effect of high lift devices on the system cost-effectiveness of wind turbines was studied for the case of both horizontal axis and vertical axis machines. A comprehensive review of the various types of high lift airfoil sections was performed with respect to generalized aerodynamic performance and structural considerations. Airfoils having promise included high lift incipient separation sections, symmetrical high lift airfoils, and extra thick designs. Jet flaps and multi-element sections were determined to be too complicated for practical applications. The performances of both horizontal axis (NASA MOD-X) and vertical axis (Sandia Lab Darrieus) wind turbines were modeled for baseline cases, assuming units rated at 200 kW, for a variety of different rotor airfoil sections and planforms. The aerodynamic performance was coupled with the specified wind duration curve to determine annual power output. Mechanical and operational components were sized and costed according to standard procedures. The results indicate that high lift airfoils as well as improved rotor structural techniques will provide advantages from the standpoint of reduced costs per unit of delivered power.

INTRODUCTION AND SCOPE

This report is a condensation of Reference 1, in which full details are included. It appears that the efficiency of a wind turbine rotor will increase as the aerodynamic lift to drag ratio (L/D) of the turbine blade cross-section is increased. A high lift airfoil will also result in a smaller required blade chord for a given turbine power output, and hence could have reduced blade weight and cost. However, blade strength and rigidity requirements are best satisfied by thick sections, so that there is a resultant weight increase for a blade made from a high lift or thin section.

It can be seen that optimization of airfoil sections with respect to aerodynamic performance and structural requirements is important for an efficient as well as cost-effective design of wind turbine rotor blades. With even only small increases in aerodynamic performance, significant system improvements could accrue from the use of high lift airfoils by reducing the blade area and hence the cost of the rotor. Fortunately for many conventional high lift airfoils, large thickness and high lift-to-drag characteristics are compatible.

As the first step, the generalized airfoil characteristics for high lift sections are developed. For single element airfoils, the current state-of-the-art is represented by the incipient separation airfoil, of which the Liebeck family is the best known. Performance and design of these airfoils depends upon Reynolds Number and very impressive lifts can be achieved. Although the highest lifts are obtained with cambered airfoils, the same design principles can be applied to developed symmetrical airfoils of high lift.

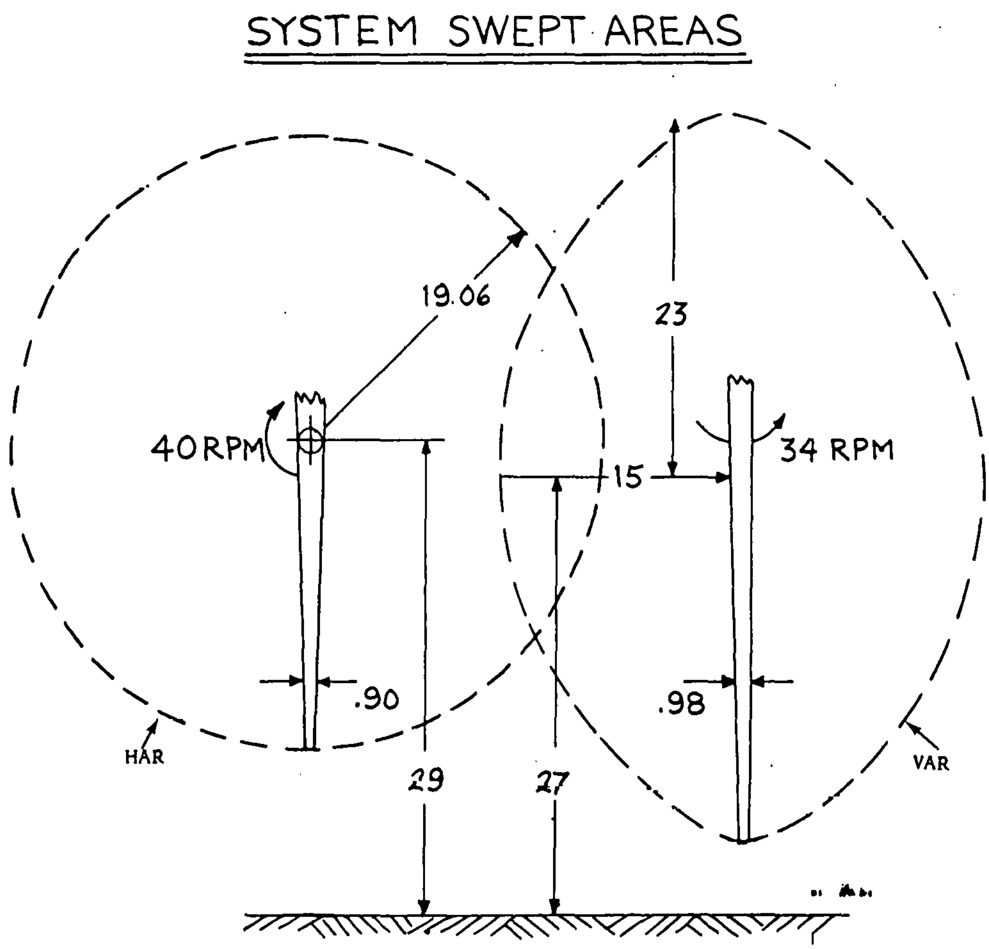

FIGURE 1. Basic aerodynamic geometry of baseline wind turbine (dimensions in meters).

Multiple element airfoils include those sections whose lift is increased by the addition of leading edge devices (slats and nose flaps) and/or trailing edge devices (flaps and vanes). Aerodynamic performance of these devices is indicated in Reference 1. For wind turbine rotors, the structural effects of multiple element airfoils must be carefully considered.

Lift may also be increased by active augmentation or aspiration (i.e., sucking or blowing on the airfoil surface using internal ducting). The well known jet flap provides an example of this method. However, for wind turbines, the cost tradeoffs associated with the internal ducting and flow control must be considered as well as the power necessary to generate the high pressure mass flow for the jet flap.

In the analysis of Reference 1, the effects of blade lift and thickness are optimized for two given baseline rotors, a 200 kW vertical axis rotor (VAR) and a 200 kW horizontal axis rotor (HAR). This is performed for a range of different high lift airfoils. Next, the performance and the overall system cost are determined for installations for which each of these airfoils might be used. The combination of the power production and system cost determines the cost-effectiveness of the system. The cost-effectiveness of each system using the airfoils considered is determined and a mutual comparison is made. The results are analyzed to determine research areas of high potential and a research program is outlined.

Figure 1 shows the basic aerodynamic geometry of the two wind turbines tested. It should be noted that they represent designs rated at 200 kW, operating in the same wind regime and costed according to the same economic factors.

Table 1 indicates thedesign variants that were incorporated in the design optimization and cost-effectiveness studies.

Reference 1 discusses in detail the lift, drag, and section geometry of high lift airfoils suitable for wind turbine rotors. Both active and passive systems are considered there, where the former uses auxiliary air in the form of suction or blowing to modify the airfoil performance. It was indicated that both the active systems and the multi-element passive systems involved complications to both the structure and the cost of a wind turbine blade and hence they were not included in the subsequent performance optimization/cost-effectiveness studies.

Figure 2 indicates the airfoils considered in this study with comments regarding their characteristics. Details of the individual section parameters may be found in Reference 1.

AERODYNAMIC PERFORMANCE OF HORIZONTAL AXIS ROTORS

The aerodynamic performance estimation techniques for horizontal axis rotors are quite well understood, and computer programs exist to evaluate the performance for a range of conditions. Reference 1 describes these conditions and details how they interact in the required calculations.

TABLE 1. Design Variables.

Baseline:	200 kW, 12 mph
HAR:	NASA MOD-X
VAR:	Sandia Darrieus
Type	Design Variables
HAR	Airfoil Lift and Thickness Blade Planform Rotor Solidity
VAR	Airfoil Lift Rotor Solidity

TYPE	SHAPE	COMMENTS	STUDY
Standard		Could be better	Standard Practice
High Lift		Some promise	Full Computer Study
Multi Element		Too thin Too Complicated	Not Studied
Symmetrical		Good for VAR	Full Computer Study
Thick		Good for HAR	Variational Study
Jet Flap		Too much Power too Complicated	Not Studied

FIGURE 2. Airfoils Considered.

Three basic cases were selected for study in which all features of the rotor performance were evaluated, as well as the structural and cost details. The rationale behind these hypothetical designs is described below. All systems are nominal 200 kW units of the same diameter.

Baseline. Here, a straight, tapered rotor of the geometry at the MOD-2 was used. The airfoil was representative of the NACA 23022 airfoil with a design lift coefficient of 0.9.

Optimum 1. Here, an optimal planform rotor was assumed, the chord of which varied approximately inversely with the radius. An improved airfoil was assumed, having a design lift coefficient of 1.3 and a drag coefficient the same as the baseline unit. This blade now becomes narrower than the baseline over most of its extent.

Optimum 2. Identical to Optimum 1 except a design lift coefficient of 1.8 was assumed. Other characteristics were the same as before. This blade is even more narrow than "Optimum 1."

STRUCTURAL FEATURES OF HORIZONTAL AXIS ROTOR

The basis for the specific structural estimate is a 200 kW conceptual design, the MOD-X developed by NASA-Lewis Research Center. The rotor is assumed to be linearly tapered, with a circular, tubular main spar, conically tapered.

The key structural criteria are as follows:

Aero-elastic: The blade natural frequency should be greater than twice the rotor rotational frequency.

Gravitational: The controlling fatigue load is that due to gravitational loads subject to the total lifetime number of cycles of the system.

Survival: The controlling ultimate allowable stress shall not exceed that due to survival wind speeds for the rotor locked and feathered.

Rated: The controlling ultimate allowable stress shall not exceed that due to rated wind speed with the rotor operating at full power.

The analysis of blade geometry which meets these structural criteria was performed in Reference 1. The results of that analysis are presented here in Figure 3 which shows the functional relationship between blade weight and thickness for three different values of the lift coefficient. also indicated are the bounds imposed due to the structural criteria. A design within the cross-hatched region is acceptable from the structural standpoint, although it might not represent an optimum situation from the standpoint of cost.

COST EFFECTIVENESS OF HORIZONTAL AXIS ROTORS

For the specific rotors studied in detail, the weights and costs of the units were determined as well as the annual power produced. This gives the cost of energy (in ¢/kWh) as

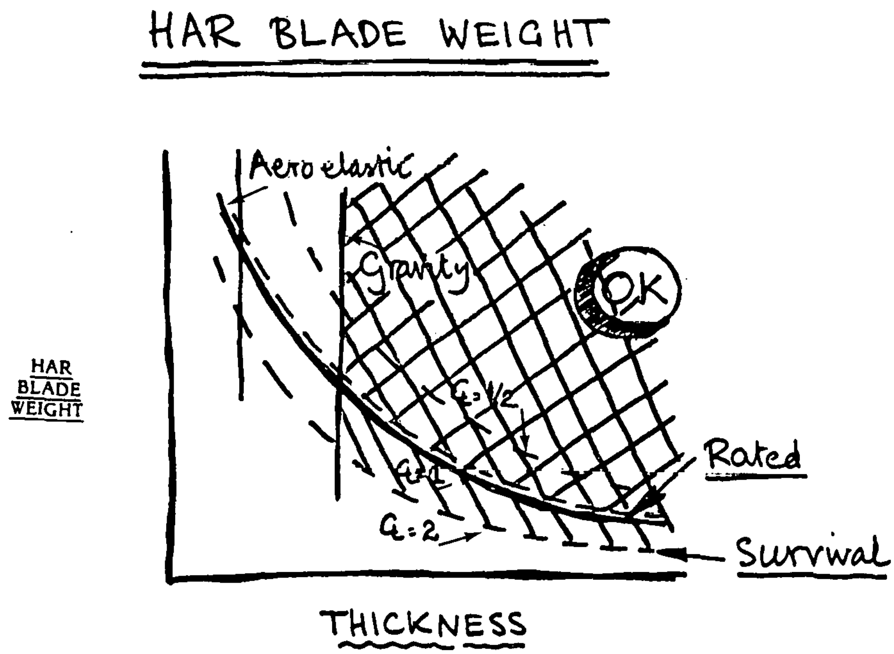

FIGURE 3. Structural design considerations for HAR rotors.

$$COE = \frac{CC \times FCR + (O \& M) \times FF}{\Delta kWh}$$

where:

COE	=	cost of energy
CC	=	capital costs
FCR	=	fixed charge rate
O & M	=	overhead and maintenance
LF	=	leveling factor
ΔkWh	=	annual kilowatt hours delivered

This relationship was applied to the rotor configurations mentioned previously, as well as two variations on them, a thick baseline section, and a thick Optimum 1 section. Variational equations to account for such design perturbations on the COE are given in Reference 1. A tabulation of the results for all of the configurations examined is given here in the "Summary of Cost Systems Studied" as Table 2.

COST EFFECTIVENESS OF VERTICAL AXIS WIND TURBINES

Existing computer programs for both performance and cost analysis already existed for the vertical axis turbine. These computer models were exercised for a range of configurations, and the same parameters generated for the horizontal axis machine were also evaluated for the vertical axis machine. Thirteen blade designs were considered. None were significantly better than the HAR systems. Two of these cases, one for a standard configuration (VAR "baseline") and the other for the best high lift configuration are presented also in Table 2 in "Summary of Cost Systems Studied."

SUMMARY OF COST SYSTEMS STUDIED

The previous discussion has outlined the various systems that were analyzed in this study. In Table 2 are presented the results of this exercise for seven selected designs. It should be noted that they all represent designs rated at 200 kW, operating in the same wind regime and costed according to the same economic factors. The data shown in Table 2 has been normalized by the corresponding data for HAR baseline configuration.

Table 3 summarizes all of the elements regarding cost-effectiveness considerations and where each was obtained.

SUMMARY AND CONCLUSIONS

A critical technical review of the effects of high lift devices on horizontal and vertical axis wind turbines has been made. The approach used was to develop base cases for both types of machines. For the horizontal axis machine, the MOD-X study of a 200 kW, two-bladed 38.125 (125-foot) diameter wind turbine supplied the most up-to-date estimates of costs available for moderate-sized machines. For the vertical axis machines, the Sandia Optimization Code allowed the study of a wide range of machine sizes. A fixed size 30.5 m (100-foot) diameter was used, however, since the Sandia studies indicated that minimum costs for 12 mph reference winds occur for a 30.5 m (100-foot) diameter, 45.75 m (150-foot) tall machine.

Design	Annual kWh	Blade Cost	COE ¢/kWh	Type
Baseline	652,600 1.00	$52,000 1.00	6.8 1.00	
Optimum 1	1.10	1.03	0.91	
Optimum 2	1.15	1.00	0.87	HAR
Thick Baseline	0.98	0.60	0.90	
Thick Optimum 1	1.06	0.63	0.84	
Standard	0.76	0.63	1.09	
High Lift	0.87	6.72	1.00	VAR
Note:	HAR Baseline	Total Cost $202,000 Blade Cost 26% Capacity Factor 0.37		

TABLE 2. Normalized performance and cost features of 200 kW wind turbine designs. Normalized to HAR baseline conditions.

PERFORMANCE:	HAR, VAR (Wilson & Lissaman)
WIND REGIME:	SERI (12 mph mean)
STRUCTURE:	HAR (Fundamental Analysis) VAR (Sandia Code)
COST:	HAR (MOD-X Base) VAR (Sandia Code)
ECONOMICS:	SERI $\left(\frac{CC \times \pi + O\&M \times L}{AkWh} = ¢/kWh\right)$

TABLE 3. Cost Effectiveness Considerations.

Conclusions can be summarized as follows:

1. Airfoil selection is important in rotor design, since although system cost improvements are not very large (of the order of 10%), the best airfoils should be used.

2. In the selection of best airfoils, high lift capability is less important than airfoil thickness.

3. Exotic airfoils, for example, using blowing (jet flaps) or multiple elements (slotted elements) do not show any promise.

4. New structural approaches, in particular, configurations different from the standard single element cantilever blade have good prospects.

Aerodynamic relations were generated representative of airfoil performance for the MOD-X and 30.5 m (100-foot) diameter Darrieus rotor. These aerodynamic relations were used to generate baseline performance and cost figures. The cost of electricity was determined from

$$\text{¢/kW-hr} = \frac{0.18 \text{ Capital Cost} + (\text{Levelized O\&M})}{\text{Annual kW-hr}}$$

Upon establishment of base cases, the effects of high lift were simulated by increasing the maximum lift coefficient, and the rotor geometry optimized to match the new airfoil.

For the horizontal axis rotor, the Glauert optimum served as a model for determining blade taper and twist. For the vertical axis machines, optimum performance is found from analytic solutions to occur at

$$X\ BC = .92,$$

however, manufacturing costs and aerodynamic drag caused optimum cost to occur at lower blade solidity than given by the analytic solution. Because of manufacturing techniques, constant chord rotors were used for the vertical axis units.

A short analytical exercise (Reference 1, Appendix A) indicates that regardless of the capital costs of the jet flap, the performance penalties are sufficient to delete consideration of the jet flap.

The vertical axis system suffered from the assumed mean wind speed being only 12 mph. Since the Darrieus energy capture at speeds above V_{rated} depends upon $C_{L_{max}}$, the lack of "hours" above V_{rated} for the 12 mph wind hurts the Darrieus more than the horizontal axis wind turbine. A further note on the Darrieus is warranted. Increased Darrieus performance does not give better cost. What happens is that the increased performance causes the machine to be rated at a higher wind speed. As a result, the efficiency is decreased at off-designed conditions and a larger generator is needed. Thus capital costs are increased and with decreased efficiency energy capture does not keep up with capital costs.

Finally, because the balance of rotor blade cost and power output indicated that reductions in blade cost were more significant than improvements in aerodynamic performance, a number of cases for the horizontal machine were analyzed using large thickness, wide chord blades. These were studied as variations on the cases costed in detail. It was found here that significant improvements will come not from increasing airfoil maximum lift, but from increasing airfoil thickness. In other words, all other factors remaining constant, an increase of 10% in thickness chord ratio is more advantageous than the same increase in maximum lift coefficient. This casts a new light on rotor airfoil requirements.

Now, while the improvements in cost of energy are not very large in the total system frame of reference, it must be clearly noted that substantial rotor cost savings can be achieved by using improved airfoils. The relative rotor cost saving (improved rotor cost/standard rotor cost) should be considered as the proper criterion for assessing improvements. Here, for example, Design 4, the thick airfoil baseline case shows a 40% reduction in rotor blade cost. The total system costs analyses conducted here are still important, in that they indicate that the rotor costs are generally uncoupled from the cost of the rest of the system. In other words, an improved rotor will not cause cost increases in other parts of the system, which might negate its benefits. A simple analogy may clarify this point. The road wheels of an automobile represent a minor portion of the total system cost. An improved, less costly wheel design, which caused no other effects upon the system would create a very minor reduction in the cost-effectiveness of the system, yet it would clearly be worthwhile if it could be accomplished at minimal development costs.

The most striking feature in the horizontal axis case is the importance of thickness in the airfoil characterisitc, not the high lift features of the airfoil. This indicates that new structural configurations do show promise in reducing blade weight and cost. For example, an extreme case of the importance of wind-wise depth (the effective blade depth resisting the rotor drag moments, that is depth of blade in the direction of the rotor axis) is illustrated in the biplane or space frame configuration. Here, a single rotor blade is composed of two airfoils separated in a direction normal to the chord, as shown in Figure 4. Such a system does not call for any special high lift airfoil performance characteristics, and indicates potential rotor weight reduction. The cost-effectiveness of the space frame system involves detailed structural analyses, not high lift airfoil aerodynamics, thus is beyond the scpe of this report; however, we observe from Figure 4 that, because of the geometry of the space frame, it is now possible to use structural material at the leading and trailing edge of the blades, resulting in substantially increased system stiffness.

As a result of this work, we can make the following recommendations:

1. Improved large thickness airfoils of moderate high lift capability should be developed for horizontal axis machines.

2. Improved symmetrical airfoils should be developed for vertical axis machines.

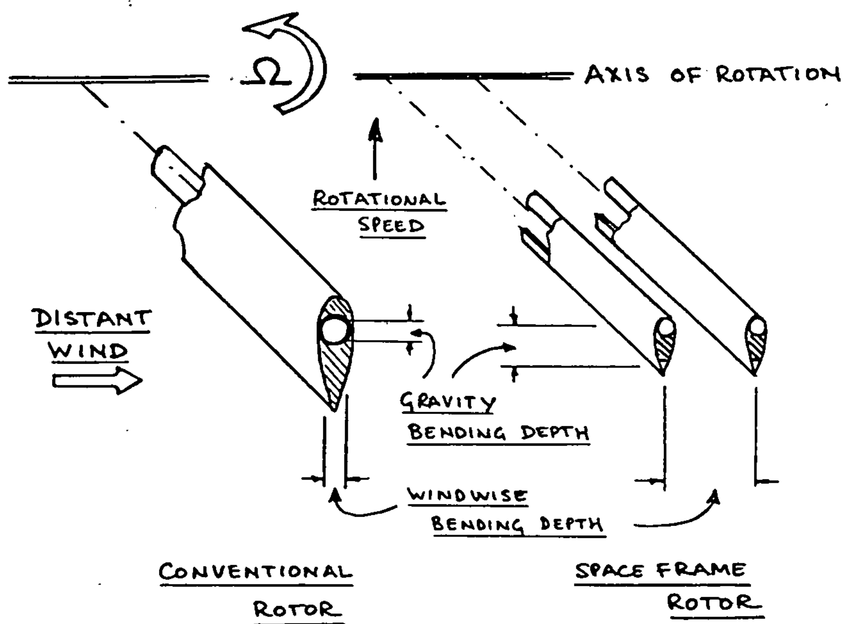

FIGURE 4. Diagram of structural elements of conventional and space frame rotors.

3. New structural configurations for rotors should be investigated which have the potential of reducing blade weight and cost. These could be applicable to both horizontal and vertical axis machines.

RECOMMENDATIONS

As a result of these recommendations, we are in a position to identify a number of research topics and to define them with some precision.

I. Improved Thick Airfoil Development

The goal here would be to design a family of monoelement airfoils having thickness-to-chord ratios ranging in steps from, say, .25 to .35, and to determine, analytically and experimentally, the lift and drag properties of these airfoils in the range of Reynolds numbers from one to six million. Any special manufacturing features should be identified.

II. Improved Symemtrical Airfoil Development

This program is of the same nature as I and, performed independently, would have the same cost and duration. However, if the programs were conducted in conjunction, or in series, substantial savings would result.

III. Investigation of Advanced Rotor Configuration

The goal here would be to develop rotors of substantially lower cost by utilizing novel configurations. A particularly attractive contender is the space frame or biplane type rotor, but an exhaustive analysis of configurations should be made. The work would involve the analytical structural studies, coupled with some detailed design work involving features of the special configuration; for example, root and tip attachment methods and feathering techniques. The proposed designs should then be cost estimated.

REFERENCES

1. Lissaman, P.B.S., R.E. Wilson, R.W. Thresher, and S.N. Walker, Definitive Generic Study for the Effect of High Lift Airfoils on Wind Turbine Cost Effectiveness, AeroVironment Final Report AV FR 9518 to Solar Energy Research Institute, May 1979.

RESPONSES TO THE LISSAMAN PRESENTATION

George Tennyson, DOE: When you say the aerodynamic efficiency is the same for the biplane as for the other, what about mutual interference effects?

Lissaman: You don't have any significant mutual interference effects at these tip speed ratios. You get a very weak increase in drag because the Reynolds number is lower.

Question: Then why did biplanes go out of business?

Lissaman: Biplanes went out of business for just the same reason that they should come back into business. It had nothing to do with interference, it had to do with high speeds and the extra drag associated with high speed. The biplane itself was the lightest possible sail that you could handle. If you make an airplane that flies at 30 mph, you should have a braced structure like the Gossamer Condor which is a large, light, externally braced structure. At low speeds, below 60 mph, it is better to save weight by using external bracings. The weight saving is considerable as compared to the increased drag required for the system.

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OPEN DISCUSSION 3

Richard Oman, Grumman Aerospace Corporation: In the aerospace industry a great deal of cost and care is devoted to the design of air-frame structures that are built for orders of magnitude more dollars per pound, and that last for shorter periods of time with continual inspection and repair than proposed wind machines. I would like to discuss horizontal axis machine design and costing policy relating to life expectancy of the blades. If the cost of blade replacement was really estimated and factored into the cost of horizontal axis machines, we would not be debating whether we are 1.8 or 1.2 times the cost of the horizontal axis machine with some of the more benign concepts that are being offered in the innovative program. We cannot make a fair evaluation of general or specific innovative concepts until this issue is addressed. Specifically, how can you build blades to last 30 years, when the helicopter people have to replace their blades every several hours? What is the basis for believing that you can design for infinite life at low stress levels when the aerospace industry has been unable to do so?

David Spera, NASA Lewis Research Center: Do you believe that our technique for calculating costs is unfair with respect to innovative systems? If that is not your question, I don't think I should answer it here as it has nothing to do with the innovative systems.

Oman: I think it has to do with the innovative systems, as the innovative systems are being asked to beat your cost projections, which, in my opinion, are unrealistic because the life cost of the blades is not being addressed correctly.

K. H. Hohenemser: You have said that since helicopter blades have a short life, horizontal axis wind turbine blades should also have a short life. That is not really true. For a typical helicopter blade with a life expectancy of 10,000 hours, based on the number of cycles, a large wind turbine blade on the basis of number of cycles may have a 30 year life expectancy. The difference is not really present. There may be a difference for the small system, but not for large systems.

George Tennyson, DOE: I would like to comment as follows. In the aerospace industry when we man-rated spacecraft, the costs and the reliabilities were different than for unmanned spacecraft such as the meteorological satellites. Blades on a horizontal axis machine are not man-rated but blades on a helicopter are man-rated. If one breaks a blade on the horizontal axis machine, it is inconvenient, noisy, and publically spectacular, but frankly, unlikely to kill anybody under any circumstances. In the aircraft industry, the larger companies tended to make things which were made to be maintained. Consequently we must consider the blades for the task for which they are designed.

David Wagner, David G. Wagner & Associates, (to Peter Lissaman, Aervironment, Inc.): As I understand you correctly, you are optimizing the thickness of the blade. You would expect a blade to fail as a result of bending stress from wind pressure, rather than tensile failure from centrifugal force or from bending stress due to gravity forces, is that correct?

Peter Lissaman, AerVironment, Inc.: For the MOD-X, the design criterion is the rated load, and there is always an advantage to increase depth, if that's the design criteria. As you make the chord bigger, the design criteria is determined by survival. We kept finding that thicker blades were better. By cutting the blade in two, and moving the sections a meter apart it looked even better. But we never studied that situation in detail.

Wagner: From the experience of blade failures, what is the typical mode of failure one might expect, tensile failure or bending stress failure?

Lissaman: The answer depends upon the machine, and the way it is rated.

Jain-Ming Wu, Engineering Research & Consulting, Inc.: You say that bi-plane type air foil is probably better. Maybe you can give a different lift to each airfoil. If two is better than one, is three better than two?

Lissaman: For bending, two flanges are all you need. You don't need any more than that, hence three is not better than two.

Ernest Rogers, Windworks, Inc.: Thank you Peter and others who stick their chin out for a new idea. I think it's grossly unfair for people to destroy work on a new idea because it doesn't happen to match some cost criterion today; in fact, I can't believe that SERI would actually do that. I've heard it said that wind devices are simple and that nothing new is going to be discovered. Everything was worked out by von Karman and others several years ago, and all we need to do is to build upon those old designs with new material. I think it's great for someone to show that there are some new blade concepts.

Peter Moretti, Oklahoma State University: We are doing a lot of analysis on the basis of two dimensional blade element theory, however, we have a rotating field with either centrifugal or Coriolis forces and effects. Is there a deterioration of the performance of the full-scale devices compared to the theory because of the effects that we cannot adequately calculate with simple two-dimensional or blade element type aerodynamic theory?

Paul Migliore, West Virginia University: The answer to your question is yes, the full-scale devices will suffer a deterioration in performance as a result of not accounting for these effects. We have been able to pinpoint the centrifugal effects and the curvature effects. By analysis of the curvature effects, we feel that we can explain the difference in performance between simple element blade theory, and what we actually experience. But there is an increment which is at the moment explained by the centrifugal effects but which is not as yet proven. It's a very complicated phenomena. When you're on the upwind side of the turbine, the low pressure side of the airfoil is affected in a positive way, and on the downstream side of the turbine, the low pressure side of the airfoil is affected in a negative fashion. I do not know how this works out over the entire cycle. It is a fairly simple matter to investigate and segregate the boundary layer effects by a simple, experimental matrix study which isolates curvature effects and centrifugal effects.

Lissaman: In general, there are two types of rotary flows, the propeller type and the Darrieus type. For the propeller type machines, rotational effects provide more favorable results than for the equivalent two dimensional air flow. This has been shown numerous times at low Reynolds numbers for propellers. For the Darrieus tip vane type of rotational flow, it seems that the rotational effects are bad. I think that van Olten has indicated that if you use the right type of airfoils you can actually get better performance than from the two dimensional equivalent.

Migliore: I think we can actually get better performance from an airfoil with optimized camber. Also the optimization does not simply involve cambering the airfoil in a manner inversely proportional to the radius of the machine. It's more involved than that, although it's not difficult. Getting the camber right should go a long way towards improving the performance of large scale machines. The boundary layer effects are yet to be solved.

Irwin Vas, SERI: What has been done to date in terms of theory and experiment? Is this a three dimensional boundary effect?

Migliore: The only thing would be to conduct a theoretical analysis showing that the pressure gradients are proportional to the tip speed ratios squared. These effects are an order of magnitude larger than for normal curved flow.

Richard Walters, West Virginia University: Thus far, a viscous theory has been used which has looked at the order of magnitudes in the terms of the equations. But the equations have not been solved.

Gerald Leigh, University of New Mexico (to David Spera, NASA, Lewis Research Center): Do you know if the large welded steel blade you described is being fabricated from the new, high-strength, high-fracture, tough steels like HY130 or HY180, or is it being fabricated from more conventional steels?

Spera: It's being fabricated from a conventional steel, A633, with a yield strength level of around 42,000 psi. The steel is a high-fracture resistance, low strength, but very tough steel.

Leigh: I might suggest that you look at some of the high-fracture, tough steels. I share the concern with Dr. Oman that the full fatigue durability issue has not been addressed. We have not seen a fatigue test on a large blade as we have seen on the Boeing 747 or any other commercial or military aircraft. Fatigue durability continues to be a major design consideration and a major cost throughout the life of all the aircraft. I think that when this problem is addressed turbine blade aspects will come out as being a significant cost item.

Spera: I don't disagree with you on the importance of fatigue as part of the design. With regards to a full-scale test, NASA would desire that the first machines go in restricted areas, because we feel that the best way to conduct a full-scale fatigue test is on the machine. We plan to conduct a subcomponent test which will deal primarily with the inner section between the tip of the blade and the fixed portion of the Mod 2, which contains the pitch change mechanism. This portion is probably the most critical fatigue area of the blade and will be full-scale fatigue tested.

J. K. Ramstetter, Solar & Wind Energy Systems: I would like to make a short comment. I have been around a long time, and have over fifty years of flying experience, and in my opinion these wind machines are a new thing. The only way we're going to know about blade length and answers to a lot of these other questions is to let the consumers have them for a few years, and get feedback from them. Right now, we're not too sure about anything. The only way we are going to find out about the machines is to build them and let the customers test them.

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GIROMILL OVERVIEW

Robert D. McConnell
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ABSTRACT

The Giromill is a vertical axis wind turbine having straight airfoils whose angles of attack are controlled so as to maximize wind energy conversion. Each airfoil is rocked during a revolution in order to maintain a constant positive angle of attack over one half revolution and a constant negative value over the other half revolution.

McDonnell Aircraft Company completed a feasibility study of the Giromill in 1976. Their initial work was followed by model tests in a wind tunnel in 1976 and 1977. Presently the Pump Division of Valley Industries, Inc., is cooperating with McDonnell Aircraft to design, build, and deliver a 40-kW (8.9-m/s) Giromill for the U.S. Department of Energy. Delivery to Rocky Flats is scheduled for the end of 1979.

In addition to describing the above work, this paper presents an evaluation of the Giromill concept in terms of some wind energy rules-of-thumb.

INTRODUCTION

Consider a rotor consisting of a set of straight vertical airfoils attached to a vertical axis. When this system is rotating in a wind stream, energy can be extracted from the stream just as it can be extracted by a Darrieus rotor. Straight airfoils, however, can be controlled so as to maximize lift throughout the rotor's revolution. Such a rotor is the vertical axis analogue of a horizontal axis wind turbine having blade pitch control.

McDonnell Aircraft Company (MCAIR) has been one of the developers of the concept [1,2]. MCAIR coined the term Giromill for their system because the theory previously developed for a powered cyclogiro airborne vehicle was readily adapted to their version of the windmill. Other straight-bladed vertical axis wind turbines are being studied in other countries [3]. In the United States, a 2-kW cycloturbine, which is similar in many ways to the Giromill, is under test at DOE's small wind systems test center at Rocky Flats [4]. A 40-kW version of MCAIR's Giromill is being designed and built by MCAIR and Valley Industries for test at Rocky Flats later this year. As a result of the cooperation of the MCAIR engineers, who are presently deeply involved in completing the project, this article will describe the MCAIR work on the Giromill design selected for test at Rocky Flats.

SERI has the task of developing techniques, including so-called rules-of-thumb, for evaluating innovative wind turbines on a consistent basis. Ratios, such as the performance-mass ratio reported recently, are useful for comparing new designs with conventional wind turbines [5]. Parametric cost equations are also being identified for innovative wind systems.

Cost-mass ratios are often used for simple cost estimates of wind turbines. By combining these parametric ratios it is possible to estimate the cost of energy produced by an innovative wind turbine. It is important not to place too much emphasis on the results of such an analysis because of the approximations involved and the resulting uncertainty in the answers. Nevertheless, the invitation to present an overview of the Giromill provides an opportunity to demonstrate the use of the evaluation techniques for the MCAIR 40-kW Giromill.

A 40 kW GIROMILL

MCAIR's Giromill Research

An early ERDA-sponsored project had as its objective the theoretical determination of the feasibility and cost effectiveness of the Giromill on the basis of a detailed design study [1]. A cyclogiro vortex theory computer program was developed to analyze parametrically Giromill configurations for devices as large as 1500 kW. The study was completed in May 1976 and verified the feasibility of the concept.

In a second study a Giromill model was tested in a wind tunnel to verify its theoretical performance [2]. The test results were not decisive, however, because two independent tunnel velocity measuring systems gave two different results. Careful scrutiny of both measuring systems failed to pinpoint the reason for the discrepancy. The conclusion was drawn, however, that even on the basis of the lower measured coefficient of performance, C_p, a full-scale Giromill would achieve a maximum C_p larger than that of a Darrieus rotor [6]. The most recent work began in September 1978 when Rockwell International, working under contract to DOE, awarded MCAIR a contract to design, build, and deliver a 40-kW Giromill [7]. Fabrication is scheduled for completion in December 1979 and testing at Rocky Flats is scheduled to begin in February 1980. In order to complete the work a teaming arrangement was made by MCAIR with the Pump Division of Valley Industries, Inc. The Aermotor Division of this firm has successfully marketed farm windmills since 1888. Valley is participating in the design and fabrication of most of the parts and, if the windmill is successful, will market the Giromill under a license agreement.

The Rotor

The selected configuration is shown in Figure 1.* The Giromill has three straight 12.8-m blades attached to a long vertical column. An 18.3-m tower supports the Giromill, whose swept area center line is 22.9 m above the ground line. The symmetrical airfoil blades (NACA 0018) have a formed aluminum leading edge

*Figure 1 was furnished by MCAIR with English units. As required by the conference guidelines, SI units will be used in the remainder of the paper.

and spar with aluminum trailing edges. All parts are riveted. The airfoil chord is 0.69 m. Horizontal support arms have been located so as to minimize the bending moment in the blades. The overall diameter of the Giromill is 17.7 m. Each arm has a streamlined steel shell to minimize drag losses and contains the electric actuator which controls the blade's angle of attack. A lightning rod, extending 38.4 m above the ground line, protects the actuator bearings from possible damage by lightning strikes on the blades.

The Giromill's vertical column is connected to the generator shaft by a speed increaser and a toothed belt, which together give an overall ratio of 54.7:1. The Giromill's nominal speed is 35 rpm. The peak electrical output is estimated to be 40 kW; an adapter kit is to be provided which would convert the machine to a mechanical output capability.

The projected electrical power versus wind speed curve is not shown but it is similar to that of a horizontal axis wind turbine. The cut-in wind speed is 4.5 m/s (10 mph) while rated net power of 40 kW is reached at 8.9 m/s (20 mph). Constant power is maintained between 8.9 m/s and the cut-out windspeed of 17.9 m/s (40 mph) by changing the blade's effective angle of attack as the windspeed changes. (All of these windspeeds refer to those measured at the centerline of the Giromill.) These performance estimates are based on MCAIR's C_p versus tip speed ratio curve, which has an estimated maximum value of 0.5. Estimates of power losses are shown in Figure 2. The power versus windspeed curve, as well as the annual energy production estimates, should therefore be considered as preliminary and, indeed, they will be evaluated further at Rocky Flats.

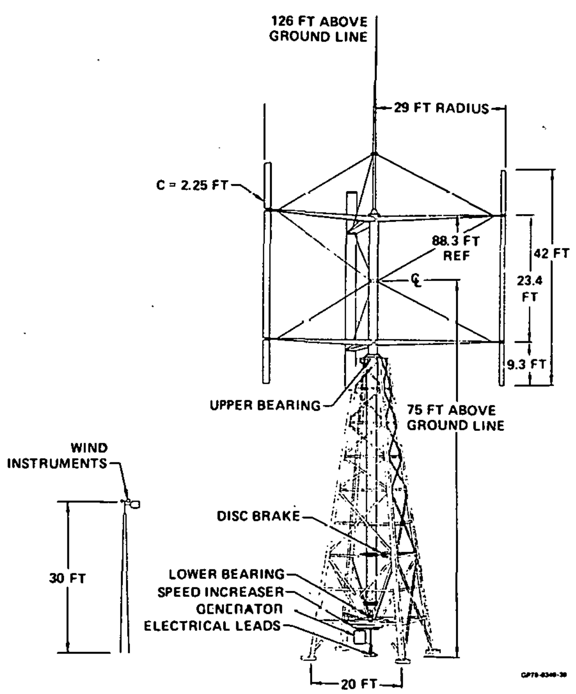

Figure 1. Selected Configuration for the 40-kW Giromill

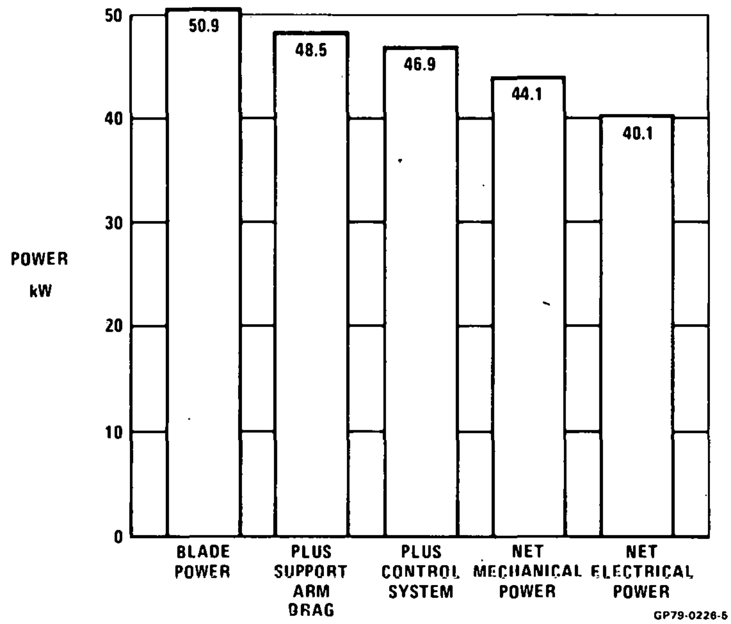

Figure 2. Estimated Power Losses for Giromill

Actuator Controls

The details of rocking the Giromill's blades during a revolution have been presented previously [2]. In simple terms the effective angle of attack is kept constant, -12° for winds below 8.9 m/s, over one half revolution while, for the same winds, a +12° angle of attack is maintained over the other half revolution. The blade rocking angle, also measured with respect to the chord line, is therefore a complex function of blade position in one revolution, wind direction, and windspeed. At a windspeed of 17.9 m/s, the effective angle of attack is ±3°. Blade flip occurs twice in each revolution, when the blade chord is parallel with the wind.

Various mechanisms have been studied by MCAIR for rocking the blades during rotor revolution. The 2.1-m diameter by 1.5-m span wind tunnel model used a central cam and three push-rod and bell crank assemblies [2]. Hydraulic control mechanisms also have been considered. The selected actuator control for each blade is a d.c. motor connected to the blade's pivot axis by a toothed drive belt. Power for the d.c. motor comes from a 24V battery, alternator, and voltage regulator set. Control signals for the actuators are provided from the wind instruments shown in Figure 1. As noted in Figure 2, 1.6 kW, which is about 3% of peak power, is the estimated average power consumption for the actuator controls.

Design Criteria

The Giromill is designed to withstand a 56 m/s (125 mph) peak gust. It must survive ice, hail, lightning, dust, and coastal extremes as well as temperatures ranging from -40° C to 60° C (-40° F to 140° F). The fatigue life of the Giromill is to be at least 30 years.

These constraints affect the selection of materials and components used in the Giromill; this effect becomes clearer when the details of the design criteria are known. Details of the ice criteria, which happen to be stringent, can serve as an example. In operation the blades must survive an 8.9-m/s wind with 13 mm of ice on the leading edge. When the Giromill is stopped, the blades must withstand 76 mm (3 in) of ice over one half of their surface simultaneously with the occurrence of a 56-m/s (125-mph) wind. Similar requirements must be met for the support arms, central column, and the fixed tower. When the loads are known for each of these situations, a safety factor of 1.5 has been specified to determine dimensions of the various components.

These criteria are related to the endurance of the Giromill when exposed to extreme environmental conditions. Operating criteria also have a significant impact on the Giromill design. An important example is related to the Giromill's actuated blades. The hinge point for the blade is 22% of the chord away from the leading edge, and the blade center of gravity has been specified at 23.25% from the leading edge. The location of the center of gravity is significantly different from that of an extruded blade for a Darrieus rotor. (The largest Darrieus rotor built, the Magdalen Island machine, has its blade's center of gravity at 44% chord). Thus, the Giromill blade has 4-mm thick aluminum sheet metal in the leading edge and spar, while the trailing edge thickness is 0.5 mm. In addition some ballast is needed to obtain the desired c.g. location. As a result, the blades make up 6% of the total system weight and account for 16% of the cost.

Another important operating criterion is, of course, that the Giromill produce 40 kW_e in an 8.9-m/s wind. All of these design criteria determine the dimensions and consequently the mass (weight) of the Giromill's components.

ELEMENTARY EVALUATION CONSIDERATIONS

Energy Output Estimates

SERI is interested in simple cost evaluation techniques for innovative wind energy systems. A useful parameter in these studies has been an estimate of the electrical energy produced by a wind energy system of a given size, in one year, at a site having given wind characteristics. The evaluation is made, not surprisingly, in terms of a comparison with the characteristics of conventional horizontal and vertical axis wind turbines. Because of the approximations necessary to make the comparisons, there is considerably more uncertainty in such results than there is in results derived from field comparisons of machines.

Consider a wind turbine site having an annual average wind speed of 6.7 m/s (15 mph) as measured at a height of 9.1 m (30 ft). Assume the site has a wind height profile with an exponent of approximately 0.13, a Rayleigh distribution for the wind speeds, and a standard air density of 1.23 kg/m^3 (0.076 lb/ft^3). (See Ref. 8 for further discussion on wind profile and wind distribution). The electrical energy output of several machines has been estimated using wind site characteristics similar to these (see Table 1). All of the calculations assume 90% availability of the machines when the wind is above cut-in speed. As shown in Figure 2, engineering estimates have been made for drive train and generator losses. The energy estimate for the Hütter machine is based on its measured power curve (11), the assumptions given above for wind site characteristics, and Golding's energy/peak power graphs (14).

System Masses

Some of the parameters shown in Table 1, when combined with the total wind turbine system mass, appear to rank the systems in terms of their mass efficiency. Mass ratios are expected to be important because many approximate correlations exist between component masses and component costs. Peak kilowatt ratios may have some use as they tend to indicate effective or ineffective utilization of rotors and drive trains designed for high power. Such ratios are often called "rules of thumb" and should be used with care because of the approximations necessary for their application. Table 2 presents some ratios, suggested by other wind energy researchers, for the systems of Table 1. These ratios are annual energy/mass [5], mass/swept area [15], annual energy/peak power [14], and peak power/swept area [11].

The system masses shown in Table 2 include (approximately) all component masses located above the tower foundations. "Approximately" is placed in parentheses because of slight differences; for example, some quoted total system masses include electrical controls and some do not. Utility components such as transformers, however, are not included. The uncertainties associated with these discrepancies are estimated to be small since completed designs or built systems are being considered. The Giromill has an additional uncertainty in its weight estimate because the design has only recently been completed and is subject to review. An earlier estimate of 8,165 kg (18,000 lb) was only recently revised to be 9,072 kg (20,000 lb) [7]. Other uncertainties exist for some of the annual energy estimates (due, for example, to different assumed wind profiles) so that the overall uncertainty in the energy to mass ratio is probably between ±10% to ±20%.

It is important to note that different materials, typically steel and aluminum, make up the total mass. Aluminum accounts for about 6% of the total Mod OA and Giromill masses and from 20% to more than 30% of the Darrieus rotors' masses. About 13% of the Hütter machine mass was contained in the fiberglass reinforced plastic blades. The majority of the mass is steel, however, for each of the systems in Table 2.

Another caveat has to be made for Table 2 because of slight differences in the design criteria for the various sytems. Fatigue life, safety factors, special wind gust conditions, temperature and environmental extremes are not uniform for the systems of Tables 1 and 2. The Giromill has perhaps the most severe ice loading criteria. The Hütter machine was required to withstand a 60 m/s (134 mph) wind with the blades stopped but in normal operating position [11]. However, the Mod X must survive a slightly lower wind speed of 54 m/s (120 mph) with the blades feathered [13]. The Darrieus rotors are required to withstand similar high winds, 67 m/s (150 mph) for the Sandia Darrieus, but the winds are incident on the blade planform (the so-called buckling case). As mentioned previously, the design criteria affect the thickness, structure, and consequently the mass of the system components. Ideally, all of the systems, or at least all generic systems, must have the same design criteria before comparisons are made.

TABLE 1

ANNUAL WIND ENERGY ESTIMATES

Wind System	Swept Area (m^2)	Wind Shear Exponent	Peak Power (kW_e)	Rated Wind Speed (m/s) (center line height)	Annual Electrical Energy (MWh)	Reference
Sandia Darrieus (A)*	84	0.17	30	13.4	60	9
Giromill	226	0.14	40	8.9	190	7
Sandia Darrieus (K)	279	0.17	120	15.0	221	9
Magdalen Islands Darrieus	595	0.13	224	15.0	387	10
Hütter	915	0.13	~90	9.0	365	11
Mod OA	1,140	0.13	200	9.5	892	12,13
Mod X	1,140	(Ref. 8)	200	9.5	950	13

* (A) denotes a point design completed by Alcoa Laboratories for Sandia Laboratories while (K) refers to a point design completed by A.T. Kearney.

TABLE 2

MASS AND WIND ENERGY RATIOS

Wind System	Mass (Mg)	Weight (lb)	Energy/mass (Wh/g)	Mass/swept area (kg/m^2)	Energy/yr/power (kWh/yr/kW)	Peak Power/m^2 (W/m^2)
Sandia Darrieus (A)	3.82	(8,417)	15.7	45.7	2,000	357
Giromill	9.07	(20,000)	20.9	40.1	4,750	177
Sandia Darrieus (K)	11.51	(25,383)	19.2	41.3	1,842	430
Magdalen Islands Darrieus	22.00	(48,500)	17.6	37.0	1,728	376
Hütter	13.15	(29,000)	27.8	14.4	4,056	98.4
Mod OA	40.37	(89,000)	22.1	35.4	4,460	175
Mod X	33.08	(72,920)	28.7	29.0	4,750	175

Despite the assumptions and uncertainties associated with the results of Table 2, the table does allow an evaluation to be made of the potential for the selected Giromill configuration. The energy-mass ratio of 20.9 Wh/g is higher than that for the conventional vertical axis turbines as one would expect for a more aerodynamically efficient design. The ratio, however, is less than those estimated for the horizontal axis wind machines which, admittedly, are second and third generation turbines. The mass efficiency of the Giromill, as determined by this ratio, is good since it is similar to that of the conventional machines. Note that the DOE goals of 25 to 40 kWh/lb correspond to about 55 to 88 Wh/g [5].

The mass-swept area ratio of the Giromill is one of the higher values in Table 2. This is perhaps the result of stringent design criteria but is also partially a result of choosing a three-bladed configuration. The use of three blades increases the rotor's solidity. The Hütter machine is outstanding in this respect because its mass-swept area ratio is two to three times smaller than those of the other systems.

The next ratio, annual energy per unit of peak power, is related to the system load factor, an engineering measure of the effective utilization of the system. Dividing each ratio by 8760, the number of hours in a year, gives directly the system load factor. The Giromill ratio is one of the highest, partly as a result of its relatively high C_p.

The last column in Table 2 provides a measure partially related to the load factor, but a low value also gives an indication that the system will perform well in wind sites having lower average wind velocities [11]. The Giromill value of 177 W/m^2 is about average for the group.

In general, the Giromill ratios are reasonably good when compared with those of advanced low cost designs (Mod X, Sandia Darrieus) as well as with those of built machines (Mod OA, Magdalen Islands Darrieus, the Hütter machine). An important item to verify for the Giromill is the power versus wind speed curves which form the basis for the annual energy estimate. The recommendation is based on the high value estimated for the annual energy-peak power ratio. The conclusion of this elementary comparative evaluation is that the selected Giromill configuration has a potential for producing cost-competitive energy equal to that of the comparison systems.

Cost Considerations

The following discussion indicates, in a general way, the cost considerations necessary for the Giromill and other wind systems. In addition, since the Giromill costs are not presently available, an estimate will be made of its total installed cost and, consequently, its cost of energy. Note that these preliminary cost estimates are our own and are subject to revision by MCAIR as their design efforts continue.

Several major cost areas have been identified to ensure equitable evaluation cost estimates. First the costs have to be normalized in terms of dollars of a particular year (1979), and in terms of how many units will be produced (100). Second, the costs need to be complete, although research and development costs are excluded. Table 3 is a list of cost considerations with their definitions. Table 4 gives some rules-of-thumb for cost items in Table 3 based on a review of DOE-funded design studies. Table 4 will be used to estimate the capital costs of the Giromill.

It is important to note that the ratios used to calculate the cost of the Giromill are preliminary and require further refinement. Several problems do exist within the current database (see references noted in Table 4). One discrepancy is that components are grouped in different ways; that is, electrical and control component costs are sometimes included in generator cost. Another area of concern is that it is often difficult to separate direct field costs from indirect field costs. The wide ranges for the ratios shown in Table 4 are a result of these discrepancies as well as the previously mentioned differences in materials and designs. SERI expects to update these and other cost ratios as more cost information for new machines becomes available.

The Giromill blades and arms, together, have a total mass of about 1100 kg. Assume a rotor cost ratio of \$10/kg, simply to avoid the most optimistic value noted in Table 4. The tower mass is about 4,100 kg and \$2/kg ratio will be

TABLE 3

COST CONSIDERATIONS FOR INSTALLED WIND SYSTEMS

Item	Definition
Manufactured Equipment	Total of wind system components
Wind Generator	Rotor and drive
Drive	Speed increaser, shafts
Rotor	Blades, hub, pitch and yaw system
Electrical	Generator, power conditioning
Controls	rpm control system, safety systems
Enclosure	e.g., fairings
Tower	Support structure, tie downs, etc.
Site Specific Costs	Land, transmission lines, access roads
Foundation	Concrete, anchors
Materials	Transport, fencing, lights, conduit, wire, site preparation
Installation	All labor costs to site assemble, erect and check out the system
Manhours	Labor hours for installation
Site Preparation	Excavation, cleaning, dewatering, fill
Total Direct Field	Sum of all direct costs, which is everything above
Indirect Field	Indirect field and office costs accrued during installation; e.g., temporary construction facilities, craft benefits, payroll burdens, construction equipment
Interest	Cost of capital during installation
Spares	Initial replacement parts
Contingency	Reserve fund
Fee	Fee for installation firm
Total Capital	Total of all of costs
Operations and Maintenance (O&M)	Normal and unscheduled maintenance plus normal operating costs
Levelized O&M	Annuitized O&M costs, 30 year life
Carrying Charges	Annual financial charges on total capital
Total Annual	Total of carrying charges and O&M

assumed because it is a slightly modified tower concept. Assume a \$5/kg ratio for the remainder of the mass. Then the Giromill system cost is estimated to be \$38,500. Note that DOE's estimated goal for mature wind machines is between \$4 and \$7/kg [5] so that \$38,500 may be considered optimistic but not completely unrealistic for a mature Giromill. An additional \$6,000 is estimated for foundations (20 m^3 of concrete). The Total Direct Field Cost is therefore estimated at about \$53,400.00. The Cost of Energy, COE, is calculated by [13]:

$$COE = \frac{(0.18)\text{ (Total Capital)} + \text{Levelized O\&M}}{\text{Annual energy production}}$$

A summary of the Giromill COE estimation is shown in Table 5.

The Giromill's COE, 8.2¢/kWh, is illustrative only because of the generalizations involved in the system costing and the assumptions made for the Total Direct Field Cost modular factor of Table 4. Wind systems having similar mass-energy ratios, like the Sandia Darrieus or the Mod OA, will have similar costs of energy, a fact which indicates the weakness of the technique. More specifically, it is possible but unlikely that three so dissimilar systems — the Giromill, the Sandia Darrieus (K) and the Mod OA — would have about the same Cost of Energy. To improve these simple costing techniques it appears that some measure is needed to represent the complexity of a wind turbine system. Perhaps the number of moving parts needs to be known so that correlations can be established between that number and system costs and O&M costs. Another problem is the lack of

TABLE 4

COST ESTIMATIONS [9,13,16,17,18]

Item	Estimates
Rotor	\$5 to \$37/kg
Drive	\$3 to \$11/kg
Electrical	\$5 to \$22/kg
Controls	\$24 to \$79/kg
Enclosure	\$1 to \$13/kg
Tower	\$1 to \$4/kg
Foundations	\$300/m^3
Total Direct Field	Larger of {Wind Generator cost X 2.5 / Manufactured Equipment X 1.2}
Indirect Field	16% of Total Direct Field
Interest	2% of Total Direct and Indirect Field
Spares	3% of Wind Generator Cost
Contingency	10% of Total Direct Field
Fee	10% of Total Direct Field and Spares Cost
Total Capital	Total of Direct Field, Indirect, Interest, Spares, Contingency and Fee
Annual O&M	2% of Total Direct Field
Levelized O&M	2 X Annual O&M
Carrying Charges	0.18 X Total Capital
Total Annual	O&M plus carrying charges

validation for both energy estimating and simplified cost estimating techniques. Comparisons need to be made between field results and design estimates. In any case, simple cost estimating techniques cannot replace detailed costing techniques because of these discrepancies. The justification for contracting a detailed cost analysis of a wind system will, however, depend on the results of simplified techniques such as the one outlined in this section.

CONCLUSION

A 40-kW Giromill, a vertical axis wind turbine with vertical modulated airfoils, is being designed and fabricated by McDonnell Aircraft Company and Valley Industries Inc. The Giromill is to be delivered to Rocky Flats in late 1979 for tests in early 1980.

An evaluation of the selected Giromill configuration, in terms of wind energy system ratios, indicates that the Giromill has the potential for producing energy at a cost equivalent to or lower than the energy costs of some conventional horizontal axis and vertical axis wind turbines.

ACKNOWLEDGEMENTS

The author acknowledges the cooperation and help so graciously provided by John Anderson, Robert Brulle, and Howard Clark of McDonnell Aircraft Company.

Joe Lavender and Erin Moore provided valuable guidance for the cost considerations while Dick Braasch kindly provided a draft of Sandia's economic analysis study. I would also like to thank Irwin Vas for the opportunity to present this work.

TABLE 5

GIROMILL COST ESTIMATION

	$ (1979)
Giromill System Cost	38,500
Foundations	6,000
	44,500
Total Direct Field	53,400
Indirect Field	8,544
Interest	1,239
Spares	550
Contingency	5,340
Fee	5,395
Total Capital	74,468
Annual O&M	1,068
Levelized O&M	2,136

$$\text{COE} = \frac{(74{,}468)(0.18) + 2{,}136}{190{,}000 \text{ kWh}}$$

$$= 0.082/\text{kWh}$$

$$= 8.2¢/\text{kWh}$$

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RESPONSES TO THE McCONNELL PRESENTATION

Irwin Vas, SERI: Have you received comments from McDonnell on this paper?

Robert McConnell, SERI: Yes, I did send them a copy of the paper. They added a few details concerning the design. McDonnell Aircraft is working with Valley-Pump Industries, which once marketed the Aermotor wind mills, as early as 1888. The only change they indicated related to skin thicknesses which is included in the design criteria. The cost estimates provided are our cost estimates and not theirs.

Marcel Harper, Tetra. Tech, Inc.: You indicated that a high capacity factor was highly desirable. If you took this machine and changed the rated power, you might find the cost of electricity is less as the rated power is increased, even though the capacity factor would decrease.

McConnell: That may be true, and it can also work the other way—as they are finding out for the vertical axis machine. There is not a complete understanding of the aerodynamics for the Darrieus rotor. The actual test measurements indicate that the capacity factor being used is perhaps to low.

Carl Aspliden, DOE: In the beginning of your talk, you listed objectives, specifications, constraints, etc. Machines should operate between -40°F and +140°F. The highest temperature on our globe, in the Libyan Desert, North Africa, is 132°F. Furthermore, let's also realize that if more realistic constraints like 0°F to 100°F were used wouldn't it be possible, then, to reduce costs considerably both in construction and maintenance operation?

McConnell: I agree that the design criteria need to be considered carefully. These criteria as I understand it, were a combination of criteria provided by Rocky Flats and McDonnell Aircraft. The temperature criteria had their impact principally on the bearings and on the actuator controls. The final actuator control mechanism was chosen partly to meet that constraint. They considered the mechanical cam used in their wind tunnel that is similar to that used in the Drees cylo-turbine. The chosen actuator control was a DC motor in each arm, with a toothed rubber belt which costs more than the simple mechanical actuator mechanism. I don't feel that the trade-off has been made properly, though, because they were restricted by the contract requirements.

David Bailey, Bailey Engineering: Is there any information available on the curvilinear problem and the camber problem of the rotational field?

McConnell: None that I know of. Again, I don't know everything that McDonnell is doing. I don't know if they've contacted Professor Migliore to discuss some of the very interesting possibilities that he discussed yesterday. Another interesting problem would be the vertical shear and the change in the angle of attack because of the resultant vector angle change with height.

Gerald Leigh, University of Mexico: I have two questions. You stated that the turbine operates in the variable pitch mode up to 20 mph, and then goes into a fixed pitch mode with maximum pitch and runs at constant speed from that point on. Does it run at variable speed below that point, and what controls it to retain a constant speed beyond 20 mph—is it load control, if not pitch control? Also, can you tell us about the power coefficient curve? What is the maximum power coefficient achieved and what does the curve look like?

McConnell: The answer to the first question is that the power curve is very similar to that of a horizontal axis wind turbine. I drew it up from their date, and it looks identical. They're working with constant rpm operation over the entire wind regime. When it reaches 20 mph they will start modulating the blade between angles less than $\pm 12^{\circ}$. To answer your second question, the power coefficient curve is based on their wind tunnel studies, which they did in 1976 and 1977. A particular problem is associated with those wind tunnel studies, which has never been completely resolved. Basically, they measured two different power coefficients, because they had two different measurements for their wind tunnel velocity. They reported the problem, and tried to determine it, but the C_p which they worked with had a maximum value of about 0.5 and that maximum value corresponded to the minimum C_p that was found from wind tunnel measurements.

Leigh: Where is the center of their power curve lie with respect to

McConnell: I think it's around three or four.

Paul Migliore, West Virginia University: The last comment you made about this problem with the wind tunnel data is very appropriate. A number of us who have been working in this field for quite a few years have been looking at the data provided by McDonnell. In light of the fact that the wind tunnel data, in my opionon at least, was practically useless, and that the analytical studies available are very doubtful, how was the configuration optimized? And how was a cord to radius ratio of approximately .08 selected?

McConnell: I have the same question: I don't have an answer.

Migliore: In your opinion, what can we do to get McDonnell to share some of their data with us?

McConnell: I thought it was fairly well documented in their wind tunnel report, as well as in the comments, which they gave in the second and third workshops on wind energy. They indicated quite clearly there was a problem and that they don't know the answer. But they based the workshop papers on the minimum values that they got out of their wind tunnel study, which may be optimistic. As I indicated from these very simple parametric ratios, it looks pretty good from an energy viewpoint. The power curves or the energy estimates are a key and should have a high priority in the testing schedule. Obviously they have a high priority in the development schedule, and I guess they have done the best they can with the data.

Richard Oman, Grumman Aerospace Corporation: I would completely concur in your comment about needing a complexity factor. I suggest that perhaps someone at SERI devise such a factor; for example, the rotating mass, or the reciprocating mass, normalized by some energy quantity. I feel strongly that we must learn how to measure complexity as a cost driver, both in the initial cost and in the life cost of all machines. In my opinion this machine stands out as being probably the most complex of any that we've seriously pursued. Do you agree?

McConnell: I've seen more complex machines.

Tom Hansen, Windfree: I noticed on the giromill that it had a lightning rod. There is a company in Los Angeles called Lightning Elimination Associates which has a system for deionizing air around an installation. These systems are used to protect oil tank farms.

They will issue a guarantee against lightning strikes when their system is installed. The system cost for 110 ft machine was about $4,000. Instead of protecting you after the strike, they guarantee you against the strike.

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A SUMMARY OF THE WIND ENERGY INNOVATIVE SYSTEMS PROGRAM

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INTRODUCTION

SERI commenced operation in July 5, 1977 to serve as the U.S. Department of Energy's (DOE) lead institution for solar energy research, development, and demonstration. The Midwest Research Institute, a not for profit research institute with headquarters in Kansas City, Mo. was chosen to manage SERI for DOE. SERI is programmatically responsible to the Assistant Secretary of Energy Technology, and responsible to the Chicago Operations Office for business, financial, and contractual matters. The SERI mission is comprehensive, involving each of the solar technologies. To accomplish its goal, the acceleration to commercialization of solar technologies, it conducts and manages research, development, and demonstration projects and programs.

SERI fulfills this function in the wind energy area by providing technical management for the advanced concepts program entitled Wind Energy Innovative Systems (WEIS) Program. The objective of this program is to determine the technical and economic feasibility of potentially cost competitive innovative systems. Studies performed in this program are subcontracted to small and large private companies as well as to universities. At present, 14 studies are funded. Eight of these are R&D studies which address various types of augmentation and electrofluid dynamic type systems. Six of the studies are short-term, assessing the value of innovative systems by generic order. Technical papers on the innovative concepts and assessments of these concepts have been presented by the principal investigators. Highlights of these concepts are indicated in this paper.

To keep abreast of new promising concepts, SERI issued an RFP in February 1979 requesting R&D studies which include theoretical aerodynamic and thermodynamic studies, model tests, and performance and economic evaluations. Depending on the cost and performance competitiveness of innovative concepts, a system could go into the proof-of-concept phase.

REVIEW OF CURRENT INNOVATIVE STUDIES

The responsibility to provide program management for the innovative systems program was authorized by the Wind Systems Branch, Department of Energy, during the latter part of FY78. Technical monitoring of eight R&D studies was to be performed by SERI. A listing of these projects is provided in Table 1. All projects included theoretical thermodynamic and aerodynamic studies to confirm energy viability, and performance characteristics and capabilities. These initial studies are followed by model design and test, economic evaluation, and finally, the establishment of concept costs competitiveness. There is no doubt that many innovative systems can develop energy; however, the cost competiveness of the concept determines whether or not it will find acceptance in the energy market. For those concepts that have the potential of being cost effective, additional proof-of-concept tests are to be conducted. From these tests, costs, performance, and engineering data will be developed to determine with reasonable accuracy the cost of energy of a manufactured system.

Table 1. RD&D SUBCONTRACTORS

Project Title	Subcontractor	Principal Investigator
Innovative Wind Turbines (VAWT)	West Virginia Univ.	Richard E. Walters
Diffuser Augmented Wind Turbines (DAWT)	Grumman Aerospace	Ken Foreman
Tornado Type Wind Energy Systems (Tornado)	Grumman Aerospace	James T. Yen
Tests and Devices for Wind/ Electric Power Charged Aerosol Generator (EFD)	Marks Polarized	Alvin M. Marks
Electrofluid Dynamic Wind Driven Generator (EFD)	Univ. of Dayton Research Institute	John E. Minardi
Energy from Humid Air (Humid Air)	South Dakota School of Mines and Technology	Thomas K. Oliver
The Madaras Rotor Power Plant Phase I (Madaras)	Univ. of Dayton Research Institute	Dale H. Whitford
Vortex Augmentors Wind Energy Conversion (Vortex)	Polytechnic Institute of New York	Pasquale M. Sforza

The Innovative Wind Turbine project of West Virginia University has been ongoing for about four years. The objective of the study is to investigate the technical and economic feasibility of vertical axis wind turbines having straight blades constructed with circulation controlled airfoil sections (Fig. 1). The study included a theoretical analysis of the blade performance with circulation control and viscous effects, aerodynamic tests that complement the analytical studies, and a system cost study. The theoretical studies were completed; however, the experimental activities were curtailed because the test equipment was seriously damaged in a wind storm. The system cost study identified a filament composite blade as being structurally acceptable and cost competitive. Current efforts in this program are directed toward the reconstruction of the vertical axis wind turbine and tests to be carried out in a zero wind velocity to demonstrate system integrity and blade aerodynamic characteristics. An optimum geometry for the circulation control blade will also result from these studies.

The Diffuser Augmented Wind Turbine (DAWT) project of Grumman Aerospace Corporation has been continuing for about three years. The objective of the study is to establish the performance and determine the potential of the DAWT for commercial scale machines. Preliminary wind tunnel studies have indicated that the DAWT may develop a power coefficient of 1.5 (BETZ limit = 0.593) (Fig. 2). The results of the preliminary design study for a field demonstration unit indicate that the major weight and cost component is the diffuser and that reduction of this weight and cost is essential to make the system cost effective. The current effort is directed at performance trade-off studies in the design of the DAWT in order to optimize the system.

The Tornado Type Wind Energy System project of Grumman Aerospace Corporation has been continuing for about three years. The objective of the study is to determine the technical and economic feasibility of the tornado type system. The system utilizes

Figure 1. The WVU, Vertical Axis Wind Turbine Test Machine

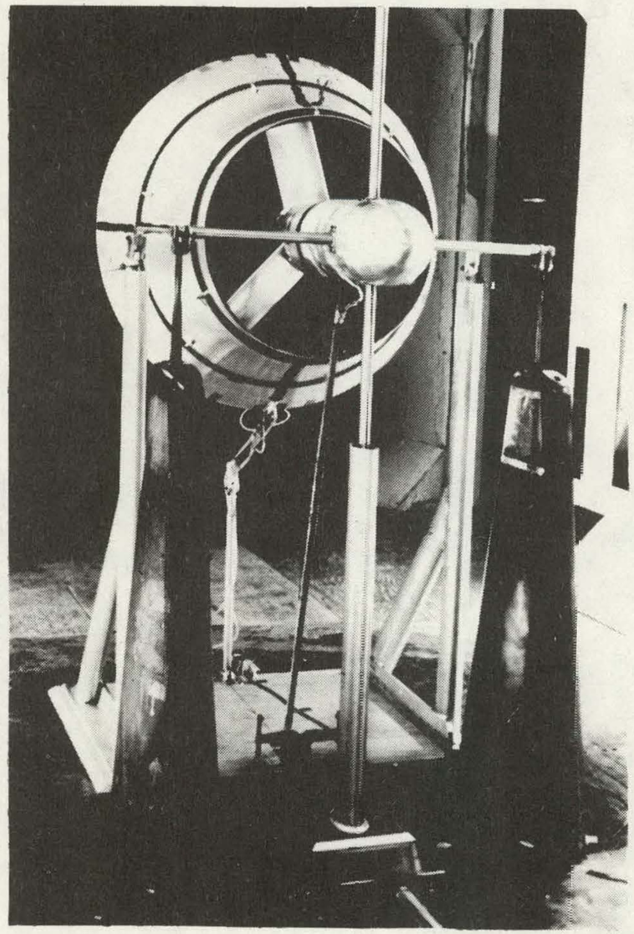

Figure 2. The Grumman Diffusor Augmented Wind Turbine Model in a Wind Tunnel

primary air which passes across the turbine and secondary air which passes across the louvers to generate the "tornado". Preliminary analytical studies have been conducted to predict performance and scaling effects. Wind tunnel tests have been performed with small models to verify the concept. Recent studies have indicated that a fixed louvered configuration would be more likely to be cost effective than one with moving louvers. Wind tunnel tests made with a 10 in. base diameter tower have indicated power coefficient levels of approximately 0.11 at 8 m/s. Model tests are planned for a 5-m high system with fixed louvers with a turbine of approximately 0.75 m in diameter (Fig. 3). Additional detailed studies are planned to model the vortex flow and to develop a procedure to predict the performance of full size cost effective systems.

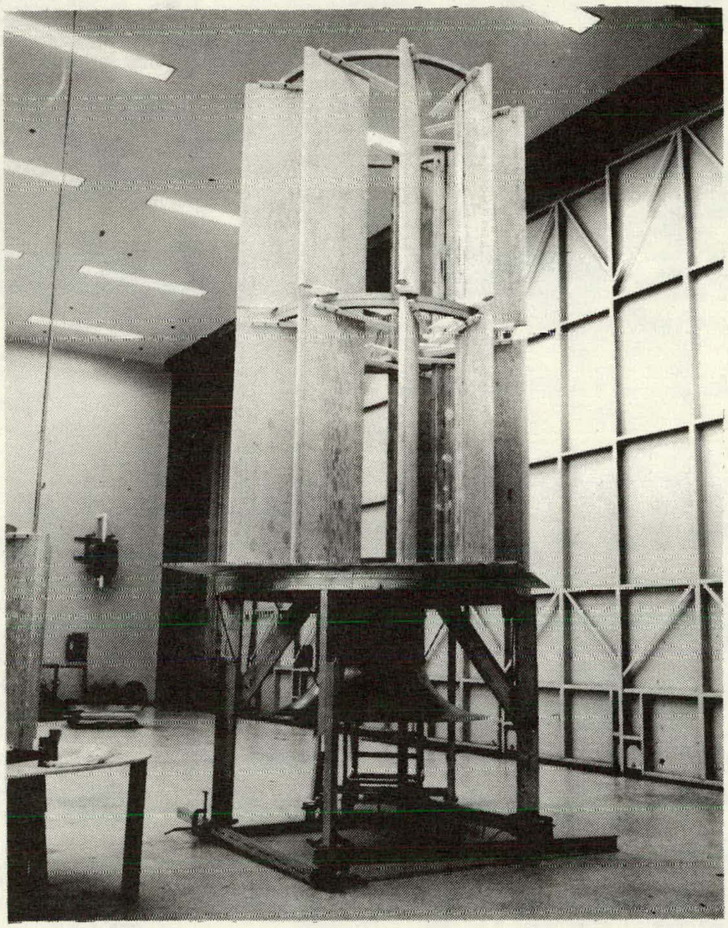

Figure 3. The Grumman Fixed Vane Tornado Wind Turbine Model

The Electrofluid Dynamic Aerosol Generator project of Marks Polarized Corporation has been continuing for several years. The objective of the study is to evaluate various techniques of producing charged droplets. Several charging methods were identified and four of these methods were investigated experimentally during the past year, and the results compared with available prediction methods. It was concluded from the study that the induction charging micro water jet technique indicated the best potential for success (Fig. 4). A planned effort to investigate and evaluate the performance capabilities of the system utilize this charging method is scheduled as a follow-on effort to the ongoing studies.

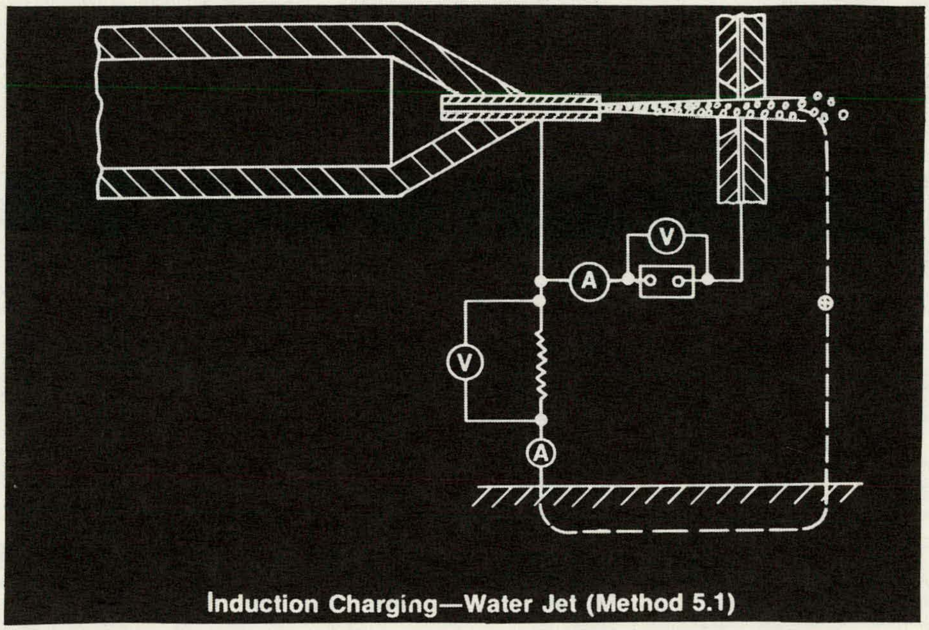

Figure 4. The Marks Method of Producing Charged Particles

The Electrofluid Dynamic project of the University of Dayton Research Institute has been continuing for about three years. The goal of the project is to develop techniques for providing low mobility charged water droplets for wind energy applications in a cost effective manner. Analytical models were developed to provide limiting conditions for droplets and generator performance. Wind tunnel studies were conducted using various geometries and charging methods and the results were compared with given analyses. Wind tunnel models were devised to optimize the system performance (Fig. 5). Preliminary wind tunnel tests have measured energy levels of approximately 45 W/m^2 at a velocity of 8 m/s. Additional studies are aimed at optimizing system performance and assessing system cost performance for full scale systems.

The Energy from Humid Air project conducted by the South Dakota School of Mines and Technology has been continuing for the past three years. The objective of the project is to determine a cost effective method of converting the latent heat of water vapor in humid air into mechanical work. One of the models studied was a natural draft tower for various shape, size, and atmospheric conditions. The study indicated that even under optimum conditions this technique was not cost effective. A second concept utilizing an expansion-compression technique appeared to have the potential of being more cost effective than the natural draft tower. The current study is to consider a vortex type flow both in the expansion and compression portions of the system (Fig. 6) and losses which may result from friction drag, turbine inefficiency, mixing, separation, and cooling effects are to be evaluated in order to assess the potential of the system.

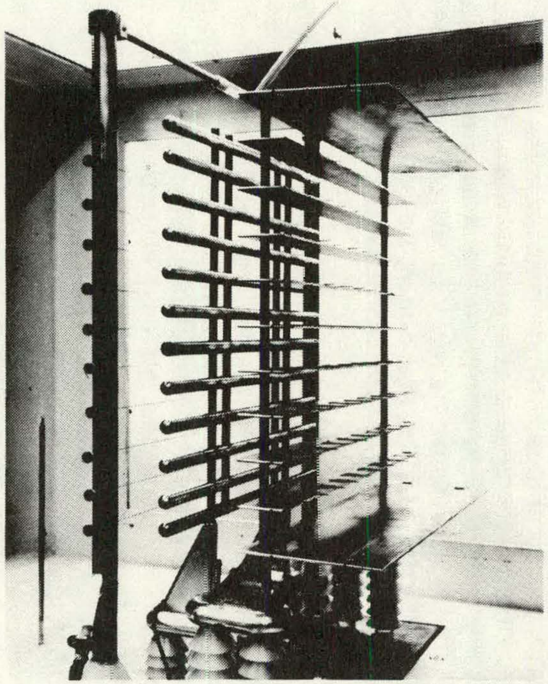

Figure 5. The University of Dayton Model for Extracting Power from Charged Particles in the Wind Tunnel

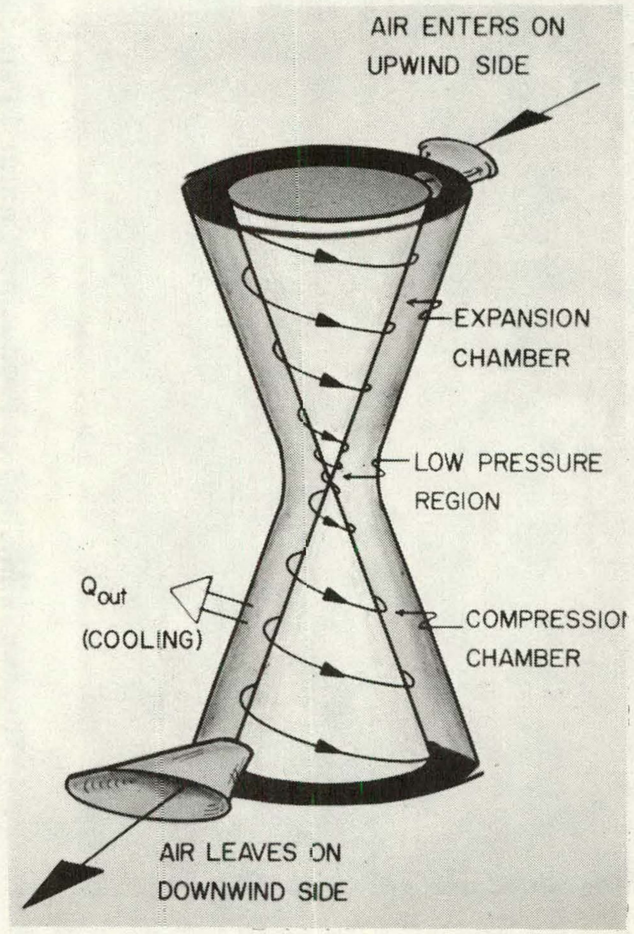

Figure 6. The University of South Dakota Concept of Utilizing Humid Air in a Vortex System to Produce Energy

A study of the Madaras Power Plant has been conducted by the University of Dayton Research Institute. The objective of the study was to determine the cost effectiveness of a power plant in the 100 to 200 MW range. The study included the theoretical and experimental investigations of rotating cylinders and a performance and economic evaluation of a system including the structural, electrical, and mechanical components. Preliminary results of the study indicated that the system could compete favorably with the first generation conventional horizontal axis wind turbine. Complexity of the system is associated with the carriage, generators, and rotor components of the tracked system. A circular tracked system is illustrated in Fig. 7.

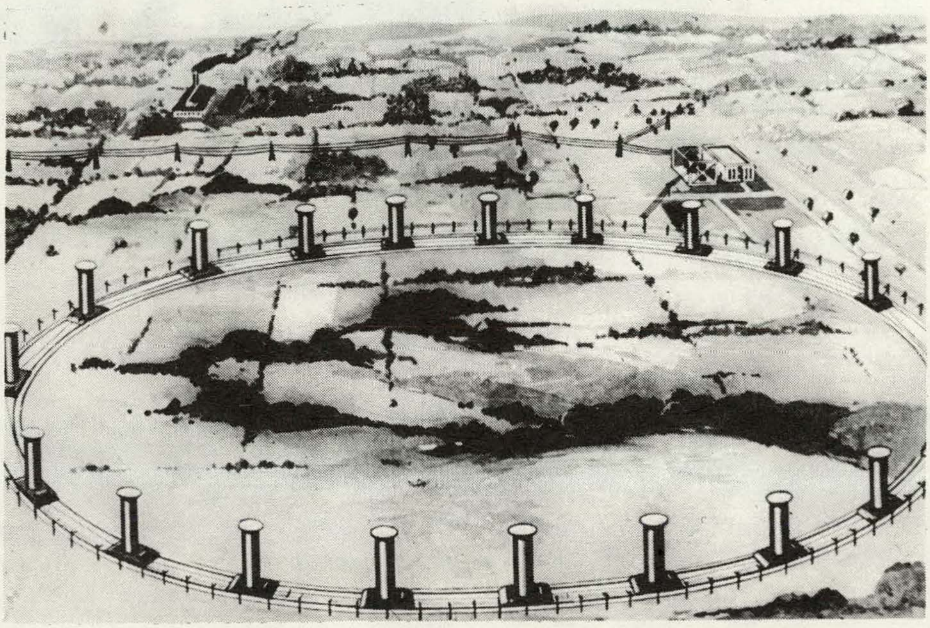

Figure 7. The University of Dayton Madaras Rotor Tracked System Concept

A study of Vortex Augmentor Conversion Systems is being conducted by the Polytechnic Institute of New York. The purpose of the study is to determine the technical feasibility, performance, and economic potential of the concept. Analytical studies have been conducted and wind tunnel model tests have been carried out to develop performance characteristics for the concept. Detailed studies are being carried out using an instrumented full scale model in order to obtain performance characteristics and to provide data necessary to perform an economic evaluation of the system (Fig. 8). It is anticipated that the major problems relating to the stability and control of the system will be answered in conducting these prototype tests.

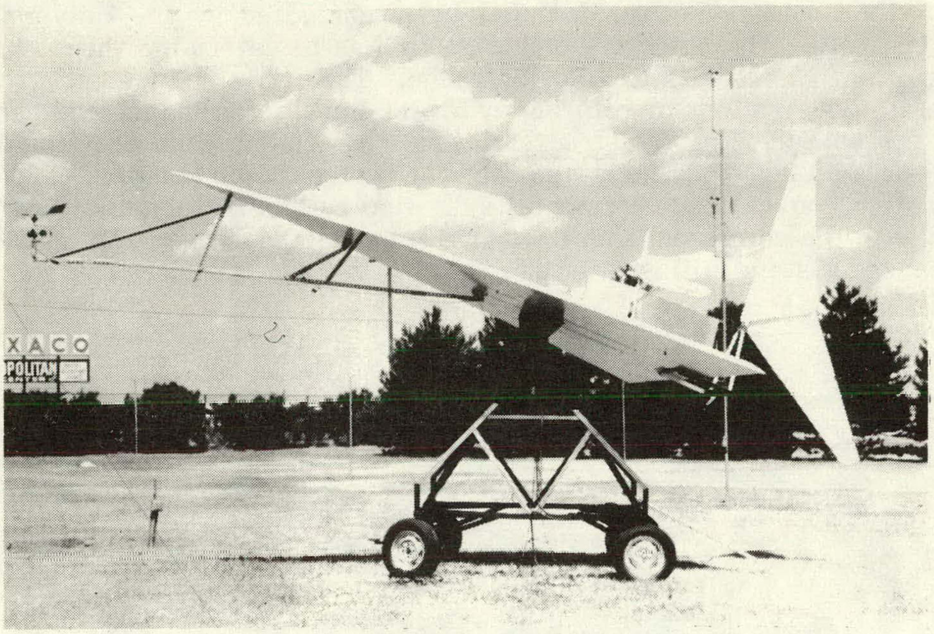

Figure 8. The Polytechnic Institute of New York Vortex Augmentor Wind Turbine.

A list of six short term generic studies conducted to assess the advanced concepts is presented in Table 2. In addition to the reports presented in these proceedings, the results of these studies are to be available in final reports in the near future.

Table 2. GENERIC STUDIES SUBCONTRACTORS

Project Title	Subcontractor	Principal Investigator
A Definitive Generic Study of Augmented Horizontal Axis Wind Energy Systems	Aerovironment, Inc.	Peter Lissaman
A Definitive Generic Study of High Lift Device Wind Energy Systems	Aerovironment, Inc.	Peter Lissaman
A Definitive Generic Study of Augmented Horizontal Wind Energy Systems	Tetra Tech., Inc.	Mark Harper
A Definitive Generic Study of Augmented Vertical Axis Wind Energy Systems	New York Univ.	Martin I. Hoffert
A Definitive Generic Study of Sail Wing Wind Energy Stystems	Washington Univ. Tech. Associates, Inc.	K. H. Hohenemser
A Definitive Generic Study of Vortex Extractionn Wind Energy Systems	JBF Scientific Corp.	Theodore R. Kornreich

PROGRAM MANAGEMENT

SERI is providing technical and program management for the WEIS program for DOE. Management activities include the monitoring, reviewing, and assessing of ongoing studies including site visits and project reviews. Unsolicited proposals submitted to the Department of Energy and SERI are reviewed and assessed by in-house staff members and non-SERI experts. The early FY79 generic studies were solicited in eight different areas. Six short-term studies were funded and their preliminary results are presented at this meeting. In early FY79 an RFP entitled "Advanced and Innovative Wind Energy Concept Development" was issued. It is anticipated that multiple contracts will be awarded during the fourth quarter of this fiscal year.

One of the major activities in the program is to conduct a conference to provide a means of disseminating the latest technical information on innovative concepts, to review the studies, and to solicit suggestions and recommendations to achieve program goals. The technical information presented at this meeting by the speakers and attendees and recommendations provided by the conferees indicates the continued strong interest and concern of researchers in the Wind Energy Innovative Systems program in support of the Federal Wind Energy program.

RESPONSES TO THE VAS PRESENTATION

Terry Cooper, Nautilus Balloon Works: The last slide was very appropriate to what I have to say. There has only been one comment on small machines, and that was the first day in regard to remote machines. According to statistics there are approximately 2 million shallow water pumping wind machines in Texas and New Mexico. I don't know how many more there are from Kansas to Canada. There should be an opportunity for small machines, 1-4 kW, to compete in an RFP as there is probably a billion dollar industry in this area. The cost per kilowatt for this size of machine is not going to be $500 but will be somewhat higher. Right now Aero sells thousands of small wind machines a year with the next competitor selling ten. To me, a good opportunity exists for small machines. There are many innovative ideas that could be funded by DOE at $10,000 — $25,000 each. The funding would be shortlived as there is venture capital for good ideas. I would like to suggest that under another RFP the competition could be divided into small and large machines since most small machines are not going to be competitive with large ones in the market place. In addition, most small machines do not readily scale up to megawatt machines.

George Tennyson, DOE: I remind people periodically that nobody, as yet, has built a big machine as cheaply (per kilowatt or per kilowatt hour) as they have built a small one.

Vas: The innovative program looks at the concept and does not separate small, medium, and large but does separate conventional, horizontal, and Darrieus vertical axis machines from others.

Martin Hoffert, New York University: In view of SERI's interest in cost effectiveness why has not more attention been given to the use of wind energy for space heating applications? In this case, the interest rates paid by individual homeowners for home heating would be considerably less than the 18% that is used for utilities. Also, the cost of displaced fuel in the space heating application is enormously important, particularly given the inflation rate that we have experienced in the price of home heating oil. How do you respond to this?

Vas: Your questions relate to the end use of the wind system. Several studies are being conducted by USDA relating to heating, cooling, refrigeration, water pumping, etc. In FY80 SERI plans to do some economic market incentive studies which will address some of the issues you have raised. They are , however, not innovative.

Richard Oman, Grumman Aerospace Corporation: Do you have a better image for the emergence model of an advance concept than that of the giromill? It went into a competition that was not specific to advance wind concepts and won a place in the Rocky Flats program. Is there a conscious programmatic plan for those wind energy advance energy concepts that graduate from the program? What are the criteria?

Tennyson: I guess it is easier to say that we don't have another scenario at the present time. I'm not criticizing your comment, however. Whenever a system is ready to "graduate" it should be able to compete in the appropriate classification. There are some innovative concepts that appear as though they may never graduate. We cannot continue their funding and provide funding for the newer ideas also. We've got to cut the umbilical cord. To me, the ideal federal activity is to provide the tools and the answers; stand back; stay out of the way; and let free enterprise take hold.

OPEN FORUM

Irwin Vas, SERI: The purpose of this open forum is to elicit your help, direction, advice and suggestions on our current and proposed activities. The Department of Energy (DOE) is very interested in your input. With me are Carl Aspliden, Wind Systems Branch, DOE; Peter Moretti, Oklahoma State University, Stillwater, and Paul Klimas, Sandia Laboratories, Albuquerque, N. M.

Several people have stated that we are not considering the end use of systems. In fact DOE is interested in end use; for example, current projects carried out by USDA include heating, cooling, and refrigeration. These projects do not fall within my program area.

Paul Johnson, Kansas Legal Services, Inc.: Given the importance of demand charges for electricity and how it will make wind power competitive in the future, (being studied by Stone and Webster) what is DOE doing to make sure that a fair demand charge will be written into any new rate design that DOE recommends to Congress?

Moretti: There have been considerable efforts to determine the true economics of wind systems within a large system; for example, the utility company. That issue is really a part of a different effect. We can only determine the true cost of the wind system as the rate is not determined by Wind Systems Branch. We can look for economics in order to find economically competitive systems but we are not in a position to mandate rate schedule. Rates are normally determined by state utility commissions in conjunction with state and federal organizations.

James Yen, Grumman Aerospace Corp.: I have a question and a comment. First why have three utilities picked designs opposite DOE's; two blades versus three blades and fixed pitch versus variable pitch? Secondly, since wind has such a large potential, as Lou Divone has pointed out, it's more than just a cost problem. It is important to meet the utility requirements of supply and demand, total reliability, and system fit.

Moretti: Six studies have been done in this area, five of them directly relating to utility integration. These application studies indicate how a utility company would integrate wind into their system, maintain their loss of load probability, and affect economics. Your point that utilities would prefer large machines rather than several small machines is very well taken. It is much easier for a utility company to cope with one large machine that large farms of small machines in terms of their staffing, maintenance, and operation. In terms of maintaining reliability and reserves, the problem is more complex than you suggest. Several of the studies have addressed this issue.

Vas: As Peter indicated, six studies have been initiated with three of them being near completion. There is a strong interest within DOE to determine the value of wind machines to a utility. The effort is going to be undertaken by SERI working with specific utilities as well as PNL and NASA Lewis. It is not a part of the innovative program.

Moretti: Southern California Edison bought a three bladed fixed pitched machine. They selected from two or three machines that were being offered with the manufacturer's assurance of low cost and short delivery. It was not an economic decision, but an availability decision.

Ernest Rogers, Windworks: I didn't understand Dr. Yen's question the way the rest of you did. The purpose of our meeting is to advise you on how to go about selecting the best innovative ideas. I heard him saying that in the final analysis, the actual selection will be made by the user. One should realize that if there are 100 ideas, of which 30 are good and 70 are bad, adequate funds may not be available to support the good ones. I noticed that most of the ideas discussed in this conference, are over 10 years old. A lot of the good ideas, and people creating these ideas, aren't even here because they are keeping the ideas secret. I notice an absence of small concepts. I see good ideas, but most of them are rather large and take a significant amount of time to work out. Here are some solutions: Have conferences that accept only new ideas. If the idea is 10 years old or available in literature, it should not be presented. I think it would be great if SERI could figure out a way to have small grants with absolutely no strings attached. This might encourage people to tell us about their ideas. The money that would pay for these small grants may not have to be government money. I think it would be great if an association like American Wind Energy Association or the American Institute of Physics, raised money for small grants, with SERI administering the money. I'm afraid that a lot of good ideas get to SERI and vanish. If some of us knew of these ideas, we might support them.

Moretti: You certainly have some good points. Suppose you sit in Irwin's chair and ask, "how do I pick the good ideas". The ratio of good ideas to bad ideas is not as high as we might like. Many reproductions of early Persian drag device type windmills are proposed. In industry, a capitalist puts his money on the line and makes his decision: If he's wrong, he goes bankrupt; if he's right, he gets rich. Irwin has neither that risk nor that kind of power. He has to try to make decisions by processes that are very difficult to institutionalize and therefore there is a possibility of overlooking good ideas. I think we have all worked very hard to try to generate institutional and review procedures that carefully evaluate concepts. It is a difficult sitiuation to handle. One of the ideas suggested was to give out several small grants in order to give people a chance to develop a good proposal. My experience with this idea has not been entirely satisfactory. When people get money in order to impove their understanding of their concept, they are not always objective. I give credit to West Virginia University as being the only case proposal that I have known that withdrew their ideas when they turned out to be not promising. Every other proposer that has been funded either has been immensely successful or claims to be. Irwin has tried this past year to get a third party to review the concepts. I think that some good information came out of these studies. Irwin's idea was good: even though these reviews and evaluations do not give the final word they give a useful third input.

Paul Klimas, Sandia Laboratories: I would like to add to Peter's comment. Not only is Irwin getting objective third parties to make these evaluations, he's getting objective third parties that are not beholden to anybody to pick the objective third parties who make the evaluations. He's done a good job in that.

Vas: You (Rogers) have done a good job in identifying some critical issues. SERI, on behalf of DOE, is supporting a University Small Grants Research Program. University people may wish to contact the SERI Contracts Office on this matter. The purpose of this conference, our first one, is to have an open discussion on current supported efforts. The next conference, I hope, will be an open conference featuring papers on new ideas.

Richard Mitchell, SERI: It has been suggested by some of the attendees that we have a small grants cost-sharing basis program with 80% from the individual and 20% from SERI. This would allow the proposer to build a model and do enough work to be able to present in a proposal a detailed description of the concept. This might give him a better chance for success in response to an RFP.

Richard Oman, Grumman Aerospace Corp: I chaired a panel on advanced concepts at the last meeting with Bill Sullivan from Sandia. A big effort was expended in putting together ideas and problems relating to innovative systems. A lot of information was gathered which could be used in planning innovative wind energy systems. SERI should find a way to provide canonical costing rules for proposers. I think we need a set of costing standards.

Paul Migliore, West Virginia University: I have to respect the engineering judgement and intuition of the people at SERI. I think that in large part they're fairly capable of determining the merit of a concept. I feel that qualitative judgement is an important item in the evaluation of innovative concepts. I also feel that you need to have some costing models. I'm not sure that they need to come into play immediately because a new innovator may not even be sure of the performance potential of his machine. I feel that the judgement of the panel of people that are involved in this interplay is pretty good.

Vas: Review proposals are carried out by two panels, a SERI panel and a non-SERI panel. I am the only common member in both panels. Input is provided from both groups separately, and then a final judgement is made. We are trying to be unbiased. In general, I've known many of you for many years—longer than I've known people at DOE, I've only been acquainted with DOE for the past two years. We try to do our best in the proposal evaluation and be as unbiased as possible.

Rogers: When I called you early in March, I had two types of proposals. One was the RFP that you had put out here, the other was the small appropriate grants technology program sponsored by DOE. I participated in one of the ten regions, region six in Dallas. The person is much more protected with his own ideas in that particular grant proposal. The reason that I didn't submit here was merely the time limit placed upon me.

Aspliden: You can be absoutely assured that every proposal that comes in either to DOE or SERI is very carefully evaluated. Generally, you don't know who reviews your proposal. If you're not happy with the SERI or DOE review, you can send it to the National Bureau of Standards (NBS) where it may take 3 or 4 months for response. You can always get a satisfctory evaluation of your proposal regardless of the system.

Gerald Leigh, University of New Mexico: The Appropriate Technology Small Grants Program was assigned on a regional basis. Appropriate technology, in general, is oriented towards low technology. For the state of New Mexico, all proposals sent into Dallas from the state of New Mexico go back to the state of New Mexico to a panel appointed by the state Energy and Minerals Department that will do a first review and screening. It will then be sent back to the regional Dallas office, where further screening is conducted based on budget and regional considerations. Final consideration is provided by Washington.

Aspliden: An RFP is issued by the Appropriate Technology Program and approximately once a year there may be 5,000 aplicants. There are three program areas, one that gives a maximum of $10,000 for a paper study, the next for $50,000 to prove the idea, and the last for $50,000 to demonstrate the idea. The total funding is about $500,000 with 5,000 people providing proposals. The chances of getting funding is small.

Leigh: Mr. Chairman, I would like to respond to your comment about NBS Innovative Program. Approximately 1 or 2% of the proposals submitted to that organization get passed on to DOE with a recommendation of funding. There may be many bad proposals, but I certainly would not recommend that route for funding. I would like to suggest another possibility for your consideration. It is difficult for an ordinary citizen to find his way through the maze of various existing programs such as appropriate technology and innovative systems. One doesn't know whether to go to Rocky Flats, SERI, or some other agency. I believe that there is not a provision in the federal procurement regulations to permit funding through a verbal approach. A person could call or write to SERI, and ask for a personal audience, and be given a specific appointment to explain his idea to SERI staff. A preliminary approval could be made at that time. If the concept is feasible, a small grant — $2,000 to $5,000 — could be provided to carry on the work to the point where he could submit a proposal to the appropriate agency without extensive paperwork. If perhaps $1,000,000 were set aside out of SERI's budget, several hundred ideas could be funded and developed for open competition. I would like to suggest that you think about a verbal approach program that can lead to an award of some small amount of money with minimum paperwork.

Aspliden: I agree with you, it is very difficult to find the right person in the right area. The Wind Program Summary identifies all the current work. I'm not sure that the verbal approach will work, we certainly respond to the many inquiries that come to us. We try to direct people to the right places, still, I realize there are many people who never reach us.

Vas: We receive many inquiries. I also attempt to point people in the right direction. Very few people have requested $2,000 to $5,000. Some have requested $10,000,000. Just remember one thing, this is federal money, and therefore we must justify every dollar. Recall that our FY79 program was only $750K which is not a large amount of money. I admit it is a problem and I hope that with your help we can find a solution.

Moretti: I do want to plead for some sympathy for the person on the other side of the desk. If he makes a decision on his own without getting the proper justification, and gives the money to one person and not to another, the one that didn't get funding will probably write to his Congressman. I think that simplified procedures are good, but every simplified procedure involves institutional safeguards.

Victor Bolie, Albuquerque: For more than 150 years, we have had a U.S. Patent Office which has the job of encouraging innovation. Innovation, novelty, and usefulness, are the key items in every patent issued by the U.S. government. That seems to me to be a good preliminary screening method for proposals. Have you considered using that institution for screening assistance?

Aspliden: Let me give an example of why this is not feasible. A visitor arrives at our office to discuss his patented invention and after we discuss it, we may determine that it is not cost effective. You can patent almost anything, but is it cost effective?

Bolie: It is true that cost effectiveness does not enter into patentability. Some degree of screening for what is novel and useful could be carried out by this institution. Do you use that institution?

Vas: The answer to your last question is no, I have not used the Patent Office to screen innovative concepts.

Paul Migliore, West Virginia University: How can you determine cost effectiveness at such an early stage of the proposal of an innovative concept? Maybe a little further down the line, perhaps, but not at the proposal stage. A good way to start this process would be to examine proposals for feasibility by providing small grants less than $50K, for preliminary analysis of the performance potential using only analytic tools. Then, I would suggest a preliminary cost effective analysis to be done, possibly some combination of the measures of merit mentioned by Bob McConnell or some SERI cost model. I think it is a bad idea to have any costing done by the innovater. I think that SERI should call upon professionals in the cost estimating area who are not involved in the business of proposing or developing concepts to provide the estimates. The cost effective analysis is quite involved and I don't think that innovators should be doing their own costing.

Vas: Thank you for your comments. It turns out that in FY79, a SERI task was to develop a methodology for doing the cost studies. In FY80 we are to refine that study. We plan to have a costing/screening methodology available so we can review, from a neutral point of view, the work being submitted to us. In the meantime we try to get professionals to help us.

Migliore: I worked for a number of years evaluating proposals for the Naval Air System Command. We had collected a vast data bank of previous developments. If you look carefully at that data and combine them parametrically you can make some very accurate predictions regarding the performance of machines. By virture of these quick and dirty parametric methods we could provide recommendations. You might start developing a methodology so that you could apply it to the evaluation of proposals.

Moretti: Bob Thresher and I were both very interested in methods you mentioned. We would look for key features and estimate performance of the concept. Unfortunately a quick and dirty evaluation is not satisfactory for debriefing purposes.

Hohenemser, Washington University: My comment may not be directed to the right person but I'm disturbed about the whole wind program. For example, when you want to do something pertaining to wind energy in the aero mechanics area, there is really no government agency at present that can support such work. Where can a person go who wants to do some of the very sophisticated aero mechanics work that is necessary for wind energy systems? I believe that the government is too project-oriented and not enough research-oriented in this field. It would be a good idea if the Innovative Branch would sponsor some basic research on windmills.

Moretti: I endorse that idea because many people have spoken for large demonstration projects and this is one of the first voices that has spoken for doing things right and not just putting up a large project. We do need a few people concentrating on the real nitty gritty and the correctness of the testing methods and the correctness of aerodynamics used so that when we build a big machine it doesn't fail because it was designed wrong. We do need some basic research people and I don't know where they fit into the program.

Vas: Do many of you feel the same way? (General concensus.)

John Telle, Fort Carson Utilities: In reference to assistance for individuals, the state of Montana funds an organization called the Montana Energy Research & Development Institute that has a branch called CFI designed specifically to assist inventors. Inventors are provided technical advice in evaluating their concept.

Ernest Rogers, Windworks: I believe that SERI is doing a great job at evaluating proposals and concepts. However, we've seen an example of an economic analysis that was done by a well respected group, that was almost violently rejected by a highly respected researcher. I felt that it was unfortunate that we had well-qualified people on both sides that apparently had not gotten together before the meeting. It would have been good to have had that economic analysis reviewed by the researcher first.

Vas: Everyone has time constraints. The generic studies were initialed in February. The people doing the generic studies did them as best they could. I informed the subcontractors of the upcoming generic studies. The studies will be reviewed by SERI staff and non-SERI experts in the field of wind energy.

M. L. Desrosiers, Raytheon Service Company: In Wind Systems Branch, DOE has four permanent employees. They try to do a good job in evaluating and answering the many questions that come to them. Consider that when you write to your Congressman to say that the Wind Systems Branch isn't giving you a fair evaluation.

Aspliden: Thank you Mac. Paul Migliore probably did not understand me. Out of 100 proposals, 95 of them have repetitive features. We review the proposals, but they come back with a minor modification. I hae a proposal now for $2.7 billion. I have suggested paper studies or model studies, as I prefer to make the mistakes on paper than in concrete. You can be sure that anything that comes to us and looks innovative is thoroughly reviewed.

Migliore: I would like to get back briefly to the discussion of aero mechanics. The basic aerodynamics work was not really funded by DOE. As Irwin points out, this kind of work is not currently under the purview of innovative concepts. We are making progress in this area — how can we make this information available to the people who need it? To refer specifically to the Darrieus turbine, Sandia, the Canadians, and McDonnell have all done a lot of work in this area. How can we share information with others on products which have graduated from the innovative concepts program so that they can benefit from the taxpayer funds expended on these projects? Many people are doing good research, but all the work performed in the program needs to be pulled together and organized. Is there some mechanism in the innovative concepts program or other wind research programs that will allow us to do this?

Aspliden: The medium through which most reports are published is the National Technical Information Center (NTIS). I'll send you a program summary that discusses all the ongoing programs and you can keep in contact with us or NTIS to find out about these projects. It is a very good source.

Vas: I think it's a little broader than what you have mentioned. I think that Paul would like us to have closer contact with some people. Discussions should be caried out on a one-to-one basis or in small groups. We're very glad to talk to people either in person or on the phone and discuss their innovative or advanced concepts.

(Concluding remarks) As there are no further comments, I would like to close this conference. Lou Divone, George Tennyson and I would like to thank you on behalf of DOE and SERI for attending this conference and providing us with your recommendations and suggestions to make the Wind Energy Innovative Systems Program an active program in support of the federal program goals.

Agenda

WIND ENERGY INNOVATIVE SYSTEMS (WEIS) CONFERENCE

May 23-25, 1979

AGENDA

WEDNESDAY A.M. (May 23, 1979)

Overview

Federal Wind Energy Program	G. Tennyson, DOE
Session I	R. McConnell, Chairman, SERI
Program Overview for the Wind Characteristics Program Element of the United States Federal Wind Energy Program	A. Miller, Battelle PNL
Energy Technology and Commercialization Issues	A. C. Parthé, Jr., The Charles Stark Draper Laboratory, Inc.

Luncheon

WEDNESDAY P.M. (May 23, 1979)

Session II

Rocky Flats Small Wind Systems Program Overview	T. J. Healy, Rockwell International
Darrieus Wind Turbine Program at Sandia Laboratories	P. C. Klimas, Sandia Laboratories
The Madaras Rotor Power Plant—An Alternate Method for Extracting Large Amounts of Power from the Wind	D. H. Whitford, University of Dayton Research Institute
Electrofluid Dynamic Wind Driven Generators	J. E. Minardi, University of Dayton Research Institute
Wind/Electric Power Transduction Using Charged Aerosols Under Various Atmospheric Conditions	A. M. Marks, Marks Polarized Corporation

Open Discussion

THURSDAY A.M. (May 24, 1979)

Session III	P. Moretti, Chairman, Oklahoma State University
Technical Development of the Diffuser Augmented Wind Turbine (DAWT) Concept	K. M. Foreman, Grumman Aerospace Corporation
Recent Developments of Tornado-type Wind Energy Systems	J. T. Yen, Grumman Aerospace Corporation
Preliminary Technical and Economic Evaluation of Vortex Extraction Devices	T. R. Kornreich, JBF Scientific Corporation
Vortex Augmentors for Wind Energy Conversion	P. M. Sforza, W. J. Stasi, Polytechnic Institute of N.Y. (presentation by P. Moretti, Oklahoma State University)
Augmented Horizontal Axis Wind Energy Systems Assessment	M. R. Harper, Tetra Tech, Inc.
A Definitive Generic Study of Augmented Horizontal Axis Wind Energy Systems	P. B. S. Lissaman, AeroVironment, Inc.
Open Discussion	
Luncheon	R. Kuharhich, Colorado Springs Dept. of Public Utilities

THURSDAY P.M. (May 24, 1979)

Session IV	C. Aspliden, Chairman, DOE
Large Horizontal-Axis Wind Turbine Development	D. A. Spera, NASA Lewis Research Center
Innovative Straight-Bladed Vertical Axis Wind Turbine	R. E. Migliore, West Virginia University
Augmented Vertical Axis Wind Energy System Evaluation	M. I. Hoffert, New York University
Energy from Humid Air	T. K. Oliver, South Dakota School of Mines and Technology
Sailwing Wind Energy Systems Assessment	K. H. Hohenemser, Washington University Technical Associates
Definitive Generic Study for High Lift Devices	P. B. S. Lissaman, AeroVironment, Inc.
Open Discussion	

FRIDAY A.M. (May 25, 1979)

<u>Session V</u>	I. E. Vas, SERI
Giromill Overview	R. D. McConnell, SERI
A Review of the Wind Energy Innovative Systems Program	I. E. Vas, SERI
Open Forum	

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