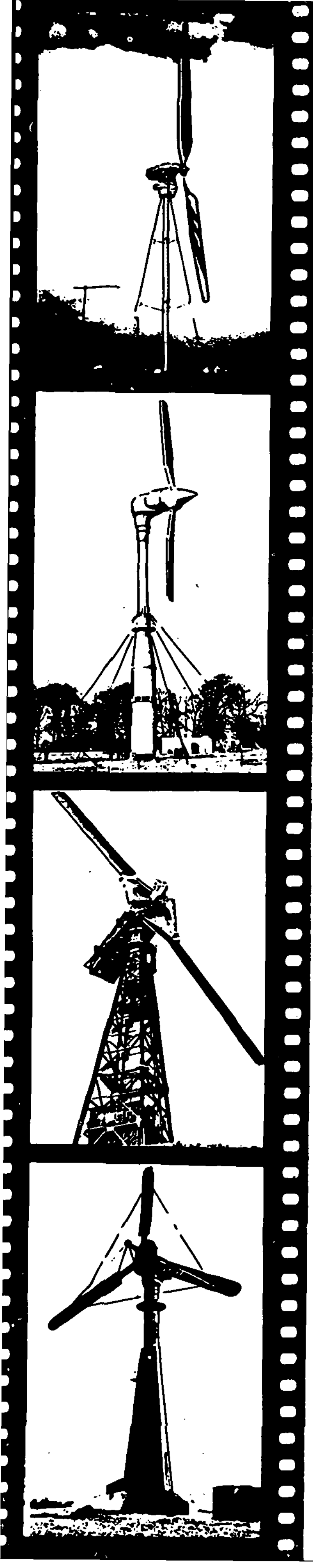

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WIND ENERGY CONVERSION SYSTEMS

WORKSHOP PROCEEDINGS

NSF/NASA

JUNE 11-13, 1973 WASHINGTON, D.C.

NSF/RA/W-73-006

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WASHINGTON, D.C. JUNE 11-13, 1973

Edited by Joseph M. Savino
Workshop Chairman
NASA-Lewis Research Center

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FOREWORD

The wind, until this century, has served mankind faithfully since the early Chinese and Persian civilizations. It drove his ships and his windmills which ground the grain, pumped the water, and generated some of the electricity. It was the discovery of oil, the invention of the steam and the internal combustion engines and the large-scale implementation of central powerplants and transmission systems that caused a rapid decline in the use of wind as a power source so that today the wind is used only in remote regions where other sources of energy are too expensive.

The windmill improved slowly through the centuries and then only as fast as new technology developed. The greatest improvements in size, power output, and efficiency occurred in the time from the late 1800's and through the 1950's when gradually increasing capability in aerodynamics, electrical power generation, and structural design appeared. From 1900 through 1950 there was great interest in many countries such as Russia, Germany, England, France, Denmark, the USA and others in developing large-scale wind-driven generators. Many were built and successfully operated, but none were cost competitive with the energy supplied by coal and oil fired steam plants and hydroelectric plants. It appears that there never was a sustained effort to develop wind generators that were cost effective. The reason for this might well have been because fossil fuels were abundant and very cheap. Furthermore, steam plants supplied energy on demand whereas wind generators could not because of the uncertainties of the wind itself. Thus, it seems, there was no great motivation for developing large cost competitive wind plants. As a result, all interest in developing large wind generators diminished rapidly so that by 1970 practically no one was engaged in a significant sized effort on large wind generators.

In recent years there has been a growing awareness in some quarters that the bulk of the U.S. future energy needs are not going to be met by hydroelectric plant and fossil fuel plants alone as has been the case in the past. The present fuel shortage makes it quite apparent that future energy needs will have to be supplied from a variety of sources such as coal, oil, nuclear, geothermal, direct solar, and, of interest here, the wind.

In 1972 a Solar Energy Panel was organized jointly by NSF and NASA for the purpose of assessing the potential of solar energy (including wind energy) as a national energy resource. One of the conclusions drawn by the Panel was that sufficient energy could be derived from the winds to supply up to 19 percent of the predicted annual electricity require ments by the year 2000. The Solar Energy Panel also recommended that the federal government take a lead role in implementing programs to develop the economic systems that would utilize the wind as an energy source.

Since NSF and NASA were both deeply interested in the wind as a possible source of nonpolluting and inexhaustible energy, it was decided in March 1973 to hold a workshop as a first step in following up the work of the NSF/NASA Solar Energy Panel. The purpose of this workshop was to bring together for the first time in more than a decade all those persons who were actively interested in wind power and as many of the pioneers as could be found to try to determine what was the state of the art of wind energy systems technology and what direction the future efforts should take. Anyone who had any significant knowledge of or experience with wind-driven power systems was invited to make an illustrated oral presentation. In addition, invitations to participate in the discussions were sent out on a selective basis to representatives of the utility industries, government agencies such as the Federal Power Commission, and the Rural Electrification Administration, industries that might be involved in the design and production of the systems and components, and user interests. A total 83 participants attended the workshop. A list of the participants and their addresses is included at the end of these proceedings.

Each participant making an oral presentation was requested to submit a short summary of it plus a few figures for publication in these proceedings. A few of the summaries submitted turned out to be short papers which were quite informative. Rather than mail them back to the authors asking them to condense the paper to a summary, it was arbitrarily decided to publish them as submitted primarily to save time so that the proceedings could be published as soon as possible.

After each oral presentation, a question-and-answer period was allowed between the audience and the speaker. These and the presentations were recorded verbatim on tape. Since all discussion after the presentation was impromptu, the transcript of the tape required considerable editing. For this reason, those persons in the audience who participated in the discussion are not identified. Rather a format where a Q for question, A for answer, and comments from the participants was used.

The workshop was structured to have technical sessions exclusively on the first and second day. On the evening of the second day, the participants convened in separate groups to discuss, assess the state of the art of the particular area, and to draw some conclusions as to the direction future work should take in those areas of potential advancement or insufficient information. A chairman was selected to head each group and to draft a summary report for presentation to all participants on the morning of the third day. On the third day the summary reports were presented by the chairman of each evening session and a discussion of these summaries occurred. This was followed by a programmed panel discussion by the aforementioned representatives of utilities, government agencies, manufacturing and user industries. A question-and-answer period followed the panel discussion.

In the afternoon of the third day, the NSF/NASA Wind Energy Program as it stood at that time was presented and discussed after which the meeting adjourned.

The workshop was proclaimed to be a success almost unanimously by the attendees. The interest and enthusiasm was high throughout the entire three days. From it emerged the feeling that wind power was an inexhaustible nonpolluting energy source with a potential for once again supplying an important fraction of mankind's energy needs. Compared to other sources such as nuclear, fusion, and geothermal, wind energy conversion systems are inherently simpler and could probably be made to be as cost effective and reliable as existing fossil and nuclear plants. The workshop participants believed that the cost of developing wind-driven power systems should be quite low compared to the costs of developing nuclear and other advanced systems and that what was needed was concerted and systematic attack on the economic and technical capabilities of wind energy systems. It is the intent of the NSF/NASA five-year wind energy program to provide such a needed effort.

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INTRODUCTORY REMARKS

Joseph M. Savino

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

Our nation is beginning to experience energy shortages. It has been predicted that oil and natural gas are going to be much less plentiful in the future. Coal is plentiful, but the energy derived from it is going to be more expensive. Nuclear energy may supply a significant portion of our energy requirements, but it will not fill the gap completely. Clearly, the energy needs of the future are going to be met by a variety of sources instead of the few sources we have right now.

Alternatives to coal, oil, and gas must be developed. Wind is one alternative which is inexhaustible and nonpolluting. The wind is within easy reach; we do not have to spoil the land digging for it, nor are there any undesirable waste products. But to make wind energy practical requires a sustained effort.

The National Science Foundation and the National Aeronautics and Space Administration have begun a cooperative program to support such an effort. This workshop is but the first step in the program.

The purposes for holding this workshop are several:

(1) We want to bring together those people and organizations who are interested in wind-derived energy.
(2) We want to promote an exchange of ideas and information among the individuals present.
(3) We want to determine the present state-of-the-art and the possible direction of future efforts.

The agenda reflects our best attempt to identify all the persons who are presently conducting investigations in some phase of wind energy, and to identify some of the pioneers who made important contributions to wind turbine technology.

OPENING ADDRESS

Alfred J. Eggers, Jr.
Assistant Director for Research Applications

National Science Foundation
Washington, D. C.

It certainly is a pleasure to welcome all of you to this first workshop on Wind Energy Conversion Systems.

This is the fourth of the seven major areas of the National Science Foundation's Solar Program in which we have held such sessions as this. The other areas include solar thermal conversion and photovoltaic conversion and their applications to, for example, the heating and cooling of buildings.

We are particularly happy that the National Aeronautics and Space Administration is cosponsoring this workshop in the important area of wind energy conversion. The purpose of all of these workshops is to bring together people in the various disciplines and with various points of view that are vital to the interchange we must have to ensure us that the solar energy program is moving forward in the right directions.

It's particularly important, too, to do so in the wind energy conversion, which, as you well know, is an ancient technology that has essentially lain fallow for more than a generation, at least in this country.

The solar energy program, more generally, is a major focus within the National Science Foundation's program on Research Applied to National Needs, or RANN, as it is sometimes referred to. The purpose of RANN is to focus research on problems of national importance with the objective of contributing to their practical solution. Our responsibilities are far broader, however, than the physical sciences and the technological challenge. We must point each program along lines that relate to the needs of the ultimate user, whether the user be in agencies of the Federal, or State, or local governments or the private sector, including especially, of course, industry. Consequently, we must devote full attention to user needs and such factors as environmental aspects, the esthetics, regulatory matters, economic, and social concerns. We need to consider other matters required to bring a technical idea through all the phases of study, research, proof-of-concept experiments, transfer to users, aggregation of investment capital, and actual approval by responsible government agencies.

Fortunately, we do not have to solve all these problems today as we launch this research effort to apply technology in the area of wind energy conversion, but we do need to keep them in mind. Our attention should be focused on those technological solutions that seem to us to be most likely to survive this process and actually deliver megawatts on the line when the process is complete. That is what I mean when I use the term "systems analysis." Let us look at all elements in the system, including, for example, the unions. We should remember that our nation's energy problems are very severe and that the need for clean, new energy sources will probably increase as we move through the present decade, into the 1980's, and well beyond.

No single solution is likely to provide the whole answer to those problems. Different regions of the country will have the opportunity to use regional resources to meet regional needs. This fact is becoming clear in other parts of the RANN program. One example is geothermal energy. Geothermal resources are available in certain regions and contribute to the needs of those regions. The same is true of wind energy, as well as, perhaps, other forms of energy. In view of the stringency of our national energy problems, we should not fail to cover any such bets.

As you know, the joint National Science Foundation and the NASA Solar Energy Panel reported on the potential of wind energy in its report published last winter, under the auspices of the Office of Science and Technology. Some of the numbers mentioned in that report are quite impressive: More than 300 billion kilowatt hours a year from off the shore of New England; 180 billion off the mid-Atlantic seaboard; 210 billion in the Great Plains; 190 billion off the Texas Gulfcoast; and perhaps 400 billion along the Aleutian chain.

As you also know, a wind machine built in 1940 at Grandpa's Knob, Vermont, generated about 1¼ megawatts of electricity but had to be shut down because of the fatigue failure of one of the blades. We've come a long way since that time in our materials and structural design capability. I am sure we have methods available today that would have solved those problems. So there is a clear opportunity to pick up where the technology stopped and move forward with deliberate haste. Let's concentrate on keeping the capital cost down. We will also need economical systems for energy storage to provide energy when the wind is not blowing.

I was pleased indeed to observe the breadth of the technical issues you have highlighted in this conference concerning wind characteristics and sighting problems, rotors, conversion systems, energy storage, small systems, large systems, and tower structures. Now, when you are through considering all these technical matters, please remember to return to the basic reasons why we're here. The name of the game is utilization. This is not just another opportunity to do our technical thing. Think megawatts on line and all the things that have to be done before they will be on line. In other words, think total systems.

We are very pleased to be moving ahead in this program with NASA and taking advantage of their know-how in aerodynamics and structures.

WELCOMING ADDRESS

Seymour C. Himmel*
Deputy Associate Administrator for Technology

National Aeronautics and Space Administration
Washington, D. C. 20546

Gentlemen, I won't take up very much of your time other than to extend a welcome from NASA to you in this vital activity.

We, of course, find that, when one addresses the energy problem, a lot of the technologies that we deal in in the National Aeronautics and Space Administration are involved with and applicable to the solution of the energy problem. In particular, we feel that our work in aerodynamics, materials, power conversion systems, and the like can play a role in the development of practical wind energy systems.

From our agency's viewpoint there are no technological barriers to overcome. There are no breakthroughs that have to be made other than a very vital one: the economics of wind energy systems. The problem must be approached in a systems engineering fashion, which I always like to describe as "solving your problems subject to a number of boundary conditions."

We are very pleased to be collaborating with the National Science Foundation in attacking this problem, and I believe this represents the first formal exercise between the two agencies, bringing in the outside world, so to speak, in addressing this particular issue. We would like to contribute to the solution of the nation's problems, in this case the energy problem, and we feel we have the people and the facilities to assist in doing this. By collaborating with the National Science Foundation and gentlemen like you from industry and universities we feel we can make notable advances and rapidly, as we define the problem, try out solutions, and ultimately solve it.

We know that there is lots of wind available. The question is how to harness it economically.

Again, I would like to welcome you and look forward to a most productive session and a most successful and aggressive program.

---

*Now Director of Aeronautics, Lewis Research Center, Cleveland, Ohio

SMITH-PUTNAM WIND TURBINE EXPERIMENT

Beauchamp E. Smith
Retired President
S. Morgan Smith Company*
York, Pennsylvania

I am honored to speak to you about the Smith-Putnam wind turbine experiment since it was carried out 30 years ago. Also, I actually had very little direct participation in the project other than to see that the bills were paid - which, incidentally, at times presented some real problems.

I assume that many of you here have read Palmer Putnam's book "Power from the Wind". It was written at my request to try to summarize the story of our efforts to test the feasibility of large scale utilization of the natural energy available in wind for the production of electricity in commercial quantities and to learn something of the economics involved.

Putnam was introduced to us through Mr. Tom Knight, then commercial vice-president of General Electric in Boston, in the early fall of 1939. Mr. Knight and Howard Mayo, the long-time manager of our Boston office, had often worked together on hydroelectric projects throughout New England. They were both concerned about the dwindling market for hydro because most of the commercially feasible sites had already been developed. Our organization was already deeply involved in the promotion of pump storage developments. It seemed to us that wind power in combination with pump storage would be a natural partnership. And, if it could be proven technically and economically sound, it would give us both a new product and an expanded market for our existing lines of hydraulic turbines and pump turbines, which in 1939 supplied the lifeblood for our company.

We fully realized that in undertaking the project we were taking a real risk. We were then a comparatively small family-owned company so it was easy to get a quick decision. Our board of directors voted to take the gamble and the project was born.

Putnam had already done much preliminary work and had gathered together a very knowledgeable group who had been assisting him on a part-time basis as their free time permitted. Having secured a sponsor,

*Presently Allis-Chalmers.

Putnam undertook the task of organizing the group of eminent scientists and engineers who would be responsible for the selection of the site and the design of the prototype test unit. Dr. J. B. Wilbur of Massachusetts Institute of Technology served as chief engineer of the project in collaboration with George A. Jessop, chief engineer of our company. Unfortunately, neither Putnam nor Wilbur, both of whom are still active, are able to be here today because of other long-standing prior commitments.

"Power from the Wind" sets forth the story of the project very completely, so I will not attempt to elaborate except to explain why so much of the fabrication of the unit had to be farmed out. World War II was already being fought in Europe and our manufacturing facilities in York were completely loaded with orders both for our regular products and also for various military items. So, when the time came to actually begin the manufacture of the experimental unit, we had no capacity available in our own facilities, and all components had to be farmed out for manufacture by other companies in order to meet the delivery requirements.

While model tests, design, and site selection were underway in the early months of 1940, it became fairly obvious that the United States would eventually become embroiled in the war. In this event materials and manufacturing sources would probably no longer be available for a project such as ours with little or no chance of being assigned a priority rating. This prospect necessitated making design decisions so that orders could be placed for forgings and other critical items in short supply long before final studies were completed. Unquestionably the calculated risks involved, forced upon us by our timing, ultimately contributed to some of our structural and mechanical problems and to the final failure of one of the blades which brought our test program to an untimely end.

Considering the very difficult working conditions prevailing both in factories and the field, I feel that our team turned in a most remarkable performance in producing and installing such a complex mechanism in a very limited time. The blades of the test unit were rotated by the wind for the first time on August 29, 1941, just 23 months from the time of our first conversation with Putnam and Knight in Boston in 1939.

Putnam's book sets forth the many problems encountered during the tests, and how they were at least partially solved. Electricity was generated in commercial quantity and delivered to a utility transmission network, the first synchronous generation of power from the wind, when the unit was phased-in to the lines of the Central Vermont Service Corporation at 6:56 P.M. on October 19, 1941.

The project thus proved by actual demonstration the feasibility of generating electricity in useful quantity from the wind. What it did not prove is that this can be done on an economically feasible basis!

Putnam, in his book, sets forth the trials and tribulations, delays because of component failures and difficulties in securing replacements, and all the other problems that plagued the experiment until the blade failure, which occurred in a known weak spot, at 3:10 A.M. on March 26, 1945.

After this blade failure, S. Morgan Smith Company, with its limited financial resources, reluctantly made the decision that it could no longer continue to finance the project. The test unit was dismantled and removed from the site, the patents and patent applications were dedicated to the public domain, and the investment was written off to experience.

"Power from the Wind" was published in 1948 as our final contribution to the public. I and, I am sure, all of the many dedicated individuals who labored so hard and contributed so much to the experiment found it a fascinating episode in their lives. And, I believe, most of us still harbor the hope that some day, somehow, someone will revive interest in carrying on further research and experimentation in this field.

With shortages of power developing all over the world, with the growing realization that the world's fuel reserves are not inexhaustible, and with the knowledge that our present known methods of using our dwindling fuel reserves are damaging our environment, I believe the time has come for another close and hard look at wind power as at least a partial solution to some of these problems.

I am delighted that this workshop has been convened and I am very hopeful that you learned gentlemen gathered together here in Washington will produce some novel and useful approaches which will lead to further research and experimentation and to a solution which will make power from the wind a practical and useful energy source for mankind.

MOTION PICTURE HISTORY OF THE ERECTION AND OPERATION OF THE SMITH-PUTNAM WIND GENERATOR

Carl Wilcox

Allis-Chalmers*
York, Pennsylvania

A color movie presented scenes at various stages in the assembly of the major subsystems of the Smith-Putnam wind generator such as installing the rotor blades and the rotating platform at the top of the tower. In addition, scenes are shown of the wind generator in operation.

DISCUSSION

Q: What safety factor did you use in the design of this system?
A: We used the safety factor, I think, of 1½, plus an ignorance factor of 1½ - just like an airplane. You can't afford to have too big a safety factor. We tried to do most of the erecting work on windless days during spring. We worked any hour of the day or night if the wind wasn't blowing.

Q: Why were the rotor blades made of stainless steel instead of aluminum?
A: I think the answer is we had the Budd Company build the blades, and they build out of stainless. The grids were stainless, but the spar that runs through is not stainless. It was cortane.

Q: How closely did the blades match each other in weight?
A: The blades matched very closely; in fact, they both weighed within a very few pounds of each other. After the assembly we, of course, could not weight them on top of the hill, and they did not seem to be out of balance at all. We made some balance checks later on, and there was no problem.

Q: Did you ever build a scale prototype?
A: No.

Q: What was the length of the chord of the blade?
A: 11 feet, 4 inches.

Q: Was there any twist to the blade?
A: Yes. The blade was twisted about 5° in three sections, being straight between each one.

*Formerly the S. Morgan Smith Company.

Q: How long did actual installation take?
A: The tower was started in early 1941. We turned it over in August of the same year, so the erection was pretty fast.

Q: Did you encounter any high winds when you were installing the blades to shut down the work?
A: No, we didn't. This was done in July, and there was very little trouble with wind at that time.

COMMENT 1: Carl, I would like to point out that we had some rather expert forecasting. It was a great help to us.

COMMENT 2: Yes, we had some MIT's meteorological department forecast the weather day by day, even hour by hour if we needed it, so that you could plan on windless periods for erection.

Q: Did you feather the rotor blades under a high wind or let it rotate?
A: We feathered it under high winds. The scheme of operation was to set the blades at about 14^{o} with no wind. As the wind velocity increased, the rotational speed increased, and at approximately rated speed, the blades were rotated to the design angle.

Q: What was the rated speed?
A: The rated speed was 28.7 rpm. And then as the wind velocity picked up, the generator was put on the line and the power increased until you got the rated power of your generator. At that time you would start to pitch the blades or start towards feather to control the power output at your rated low. Originally, it was planned that at 60 miles an hour we would go to full feather and take the unit off the lines. However, we found that under certain conditions we ran in to 70 or 75 mile an hour winds. The reason for cutting it off at 60 was a feeling that your gust energy was too great in those cases to control, but that did not work out to be the case.

Q: What was the tower natural frequency?
A: I don't know as I can answer that.

Q: How well did you control speed?
A: We controlled speed with a Woodward governor. The generator ran at 600 rpm, and we controlled the speed as a function of generator output, and we have some charts where generator output is very smooth. It took a lot of adjusting on the governor and so forth to get it that way.

Q: What was the minimum wind velocity that you could operate at full power?
A: The minimum velocity at full power was about 30 miles an hour.

Q: What percentage of the time were you below minimum wind velocity?
A: I think about 30 percent.

Q: How did you check the balance to the blades?

A: We just checked the balance by its effect on the yaw motion of the housing at the top of the tower and on stress readings, and we found there was very little difference between the weight of the two of them. We added some weights in one case on one side but it didn't seem to make very much difference.

Q: Why did you position the rotor on the downwind side of the tower?
A: There were various reasons; if you make a dynamic study it looks like that is the place to put them.

Q: What was the icing problem, if any, and what did you do about it?
A: Icing was one of the things that worried us a little, but that's why the system was down on a lower hill (Grandpa's Knob) where it was. We found we did not get too much icing especially on the blades. The blades collect some ice, but during rotation the ice would break up. The idea, I think, is to make your blades flexible enough to break ice off them.

Q: What's objectively the character of the vibrations involved here when the unit was operating? Can you give any G-levels or anything like that?
A: No. There was motion, of course, from every revolution. There was motion in the pitching drive all the time.

Q: Do you know what frequencies it was?
A: It was twice per revolution.

Q: Would you be able to summarize the cost of this project?
A: Do you mean total cost? I think I'll let Mr. Smith answer that question. I'm sorry, I didn't look it up. The total cost was about a million, three-quarters of a million, somewhere like that. We had great cooperation from various component suppliers. The Budd Company contributed a great deal to the designs; American Bridge Company built the tower and also handled the actual erection. We paid the costs. The total cost was just over a million, somewhere around that.

Q: Do you have a recollection of the total weight of this machine including the tower and the blade factor and the lot?
A: The total weight was about 500,000 pounds.

PERCY THOMAS WIND GENERATOR DESIGNS

Charles W. Lines

Federal Power Commission
Washington, D. C. 20426

For the benefit of all present, I would like to begin with a general description of the organization and responsibilities of the Federal Power Commission. The Federal Power Commission is a federal regulatory body, administering the National Gas Act and the Federal Power Act, and is comprised of five commissioners appointed by the President and confirmed by the Senate and supported by a staff, which includes members of all professions and activities - legal, engineering, economic, and many others.

As such, the Federal Power Commission has no responsibility, authority, or funds for any research and development activity. It, nevertheless, remains interested in all these activities and does contribute indirectly to the advancement of the art and science. Through the Uniform System of Accounts (the reports made to the Commission about the cost and expenditures of regulated industry and its actions through rule-making processes and hearings) the Commission can give encouragement to the regulated industry. One such example is allowing for the cost of research and development activity in the determination of allowable consumer rates (that is, wholesale rates) so that the costs may be recovered by the utility which makes the expenditure. The Commission and its staff is also interested in any development that would affect, of course, the various aspects of reliability, adequacy, economics, and things of that nature.

But I would emphasize that anything I say that might be construed as an opinion is mine and not that of the Commission. Any Commission activities always are a result of hearings in rate, or similar, cases, or are produced in the form of orders made public and followed by industry.

Mr. Thomas devoted about 10 years, in addition to his other duties, to a detailed analysis of wind power electric generation and its effect on the electric utility industry. He actually produced, and they were published by the Commission, four monographs, the first one was titled "Electric Power from the Wind" (March 1945). (Notes on these monographs appear at the end of this paper.) This first monograph was prompted by the 1941 to 1945 construction and operation of the 1,250-kilowatt installation on Grandpa's Knob near Rutland, Vermont, which we have just seen. This installation was integrated with the Central Vermont Public Service Corporation, and, as we know, it suffered fatigue in blade failure.

As Mr. Smith and Mr. Wilcox have advised, it was not rebuilt because of economic considerations.

Now, Mr. Thomas envisioned wind power electric generation for use on interconnected utility networks firmed up by hydroelectric storage facilities in order to overcome the firm power deficiencies of wind driven generators. He used to a great extent the economic data from the Grandpa's Knob operation, and he concluded that between 5,000 and 10,000 kilowatts were necessary for economic viability.

In the first monograph, he described the twin wheeled, two bladed propeller design for a 7500-kilowatt unit and a twin wheeled, three bladed propeller design for a 6500-kilowatt unit. In order to overcome, in part, the difficulty in coupling a variable speed, wind driven mechanical source to a synchronous speed, alternating current commercial system, Mr. Thomas' design proposed a wind driven, direct current generator, electrically coupled to a dc to ac synchronous converter. He calculated the cost, based on extrapolations and estimates from Grandpa's Knob, to be $68 per kilowatt capacity for the 7500-kilowatt unit and $75 per kilowatt capacity for the 6500-kilowatt unit. Mr. Thomas concluded that with certain assumptions the economics warranted the collection of wind data in greater detail and specifity than that then accomplished. He also suggested testing propeller designs in wind tunnels over and above that done, and, in addition, the necessity of constructing a full-size 7500-kilowatt prototype.

I would like to emphasize that in not only Mr. Thomas' first work but the three that succeeded it, and probably in all the works and treatises of people writing in the same area, that there is almost universal agreement that wind data including duration curves be acquired over a very wide area.

In March of 1946, the second monograph was published. It is devoted primarily to the detailed design features of the twin-wheel 7500- and 6500-kilowatt wind powered generators he discussed, in general, in the previous monograph. He commented on the March 1945 shutdown of the Grandpa's Knob installation and reiterated the desirability of larger units, between 5,000 and 10,000 kilowatts for utility operation.

In January 1949 the third monograph was published. In it Mr. Thomas compared the detailed aerodynamic designs of the Grandpa's Knob unit, an English designed unit, and his design. It's interesting that in this monograph Mr. Thomas modified, for comparison purposes, his 1946 design of the 7500-kilowatt unit by increasing the blades from two to three for each wheel, shortening each blade, and increasing the designed rotational speed. In all cases the general overall height of Mr. Thomas' design approximated that at Grandpa's Knob, though it has been postulated and he mentioned designs that might go up as high as the Eiffel Tower or the Washington Monument, 500 or 600 feet. In this third monograph Mr. Thomas again emphasized that, because of intangible characteristics and uncertainties of extrapolation, wind tunnel tests and full scale prototype construction were imperative to efficient design.

In February 1954 the last of Mr. Thomas' works was published. In this last work Mr. Thomas digressed from the detailed technical design features that he dealt with in his first three works. This work is largely general in nature, commenting on utilization or integration of wind generated electric energy in an electric utility network. He discussed generally the possible benefits of firm and secondary power, derived from wind power generation, when supported by large interconnected electric systems. By this time steam electric generating units having 250,000-kilowatt capacities were in operation, and the economic benefits of economy of scale of these units presented at that time a stiff challenge to competing electric generation sources. Mr. Thomas moved away from comparative cost base justification for windpower generation in favor of more general statements. In other words, windpower electric generation would be justified if the cost would be no greater than that then being produced by modern steam plants. So, if I may insert at this time from my readings of the literature that you can find today, there are no real good present day costs that one can put a handle on to make an economic comparison. Mr. Thomas also stated, regarding wind powered electric generation, and this is to a degree at variance with his earlier implications, that economies of scale were a questionable attainment and implied that capacities of 2,000 to 4,000 kilowatts might yield maximum economic benefits. He had moved away from the 5 to 10,000 kilowatt installations, and there is no reason given why he made his statements in what he had written. But he did say that the 2,000 to 4,000 kilowatt units might be a maximum size. Again the implication is that there is a lot of study needed in an economic way.

I believe that no one in this room, or no one with any construction background whatsoever, would question the technical feasibility of constructing a windpowered electric generator. We have actually seen one work, and the fact that the blade suffered that failure is really no criticism, since in development activities things of that nature happen all the time. But even today there is a lack in economic justification for the use of the wind as a source of energy.

In his previous publications Mr. Thomas made some reference to the use of windmills to generate mechanical power, not necessarily associated with conversion to electric energy. In this last work he also commented on a windpowered waterpump and some general applications, including its use as a pumping source for hydroelectric pump storage operations.

That, essentially, gentlemen, constitutes the works of Mr. Thomas. They were rather lengthy, and in deference to the program I have abstracted them briefly and the abstracts are given at the end of this paper.

I might comment from my own reading that, while it is technically feasible to construct such a plan and to integrate it into a central station operation, in the economic evaluation of any generating source two main costs must be borne in mind. One is the cost of the fuel, which is a production cost for the energy so generated, electric energy. In the case of wind it essentially is nothing; therefore, it enjoys that advantage. Now, because of the nature of electric energy and its use by the consumer it does not allow, in general, a storage of that energy except in an indirect form. It can be stored in hydroelectric storage; it can be stored in fuels which then are called on in accordance with the demand of the customer. That is the serious defect in getting a good, firm power worth to electric generation if it's merely integrated into an operating system. And it appears, from what I have seen, the costs are the biggest obstacle to overcome to the adequate use of this source.

DISCUSSION

Q: You mentioned there were two costs. One thing that I didn't detect in your comment was the cost of eliminating the traces that had made the power, or to use the word "pollution." Do you see this becoming a factor, or do you see a shortage in fuels becoming a factor that would influence the balance of economic trade-off for this power?

A: We are very aware of the economic cost of environmental controls on methods of generating electricity. In the end the consumer, the purchaser of the energy, will be the one who actually determines what steps are taken in these regards.

We have coal resources that can be exploited for all the foreseeable energy needs until such times as our breeder nuclear reactor program, or our fusion program, or anything else comes into being. So what we are really asking, are we not, is what will we pay in an intermediate time period for the home environmental freedom that windpower offers?

Now, even though there is nothing in the sense of air pollution or water pollution that windpower generation implies, it does require certain land uses, and there are certain esthetic aspects of mile after mile of windmills scattered over the landscape. Those are environmental costs also. But, to answer your question, I think the consuming public by the cost of what they buy will be the eventual decider of what environmental degradation they will stand.

There is another thing, too. We are prone to, I think, attribute too great an advantage to some things and consider that the money supply is inexhaustible. After all, money is a resource and does come from production and other efforts, and if we waste money, then we are implying a resource waste in other areas.

Q: Could you tell me where I could get these four pamphlets?

A: They have long been out of print. I have four copies, which are actually the file copies. The Office of Information of the Federal Power Commission can arrange to have them reproduced.

Q: What are your impressions on the subject of storage, not just on the wind energy system, but the solar energy system?

A: Whenever I look at pumping energy into the electric utilities system, I relate it really in terms of the proportion of windpower that could be supplied in proportion to the total power output of the utility. If the proportion of windpower is relatively small, I really don't see the need for storage, because you have basically three systems in the utility where the intermediate and backing systems essentially can perform the storage function. Obviously, if a large proportion of wind energy is being pumped into the utility, then is there a storage problem. I disagree that carte blanche storage is a problem. It depends on how much of the energy is being supplied.

There is a cyclical value to energy produced in the electric utility operation; in other words, the cost of energy varies second by second. The economic computers that load and unload the various components of generation are so programmed that they evaluate the incremental cost of energy as it's produced on cyclical basis.

If I might use a rather basic evaluation, if you are generating under pump-hydro, or even run-of-the-river hydro, that has a nonline at the time worth of 2 mills, then any energy produced by wind power will not have a higher value in the planning phase.

Q: Do you have any information on the attempt to get money to build a larger prototype in 1951? I have a copy of the Congressional Record in which the hearing was reported, but I have not been able to get any information on what happened in that attempt.

A: I have no other information except the hearing record myself.

Q: I was wondering if Mr. Smith had any comments to say in collaboration with the Federal Government. Were there ever any attempts to work with Mr. Thomas of the FPC?

A: We had a good many sessions. We came to New York very frequently and discussed this with Mr. Thomas. The problem Mr. Thomas had was that his economic evaluations were rather broad.

COMMENT: I am manager of a municipal light plant in Massachusetts. With regards to the economics and to energy storage, let me say that, at the time that these wind generators were being made the total demand for electric energy was quite different than it is today.

For example, total electric living was not being pushed to as great degree at that time. Today they are pushing a total electric home, as an example. In the total electric home, your greatest need is for heat, almost 70 percent.

Therefore, the greatest potential of the wind generator is to generate heat directly, not to go to electricity and then make heat. The efficiencies of a direct conversion from mechanical to heat energy, such as in our community, are greatest when it is the coldest. That's when the wind is blowing the hardest and all the heat is blown out of the buildings, and therefore we would have a direct need at that time for the greatest amount of heat and a peak demand for electrical needs.

This appears to have significance. I mean heat storage is becoming a great thing - using heat exchanges, heat pumps, and storing up by water in tanks for big commercial buildings - all of this in order to combat the problems. If you buy power on peak, the cost of power is greater than off peak, so all these things figure into peaking and storage which is being substantially pushed already to reduce the demand costs.

The following are abstracts of Percy H. Thomas' four monographs which were the results of his studies on the potentialities of wind power.

ELECTRIC POWER FROM THE WIND
March 1945

Percy H. Thomas

Federal Power Commission
Washington, D. C.

This monograph by Mr. Thomas on the general subject of power from the wind was prompted by the 1941-1945 construction and operation of a 1,000-kilowatt installation at Grandpa's Knob near Rutland, Vermont, on the system of the Central Vermont Public Service Corporation. This unit suffered a blade failure on March 26, 1945, and was abandoned because of economic considerations.

Mr. Thomas envisioned wind powered electric generation for use on interconnected utility networks, firmed up by hydroelectric storage facilities in order to overcome the firm power deficiencies of wind driven generators. Using certain economic data from the Grandpa's Knob operation, the author concluded that units of a size between 5,000 and 10,000 kilowatts were necessary for economic viability. The author described a twin-wheeled, two-bladed propeller design for a 7,500-kilowatt unit, and a twin-wheeled, three-bladed propeller design for a 6,500-kilowatt unit. In order to overcome in part the difficulty in coupling a variable speed, wind-driven mechanical source to a synchronous speed alternating current commercial system, the design included a wind-driven, direct-current generator electrically coupled to a dc to ac synchronous converter. The author's calculated costs were $68 per kilowatt of capacity for the 7,500-kilowatt unit, and $75 per kilowatt for the 6,500-kilowatt unit.

Mr. Thomas concluded that, with certain assumptions, the economics warranted the collection of wind data in greater detail and specificity than that then accomplished, the testing of propellor designs in wind tunnels, and the construction of a full size (7,500 kW) prototype.

THE WIND POWER AEROGENERATOR -- TWIN WHEEL TYPE
March 1946

Percy H. Thomas

Federal Power Commission
Washington, D. C.

This monograph is devoted to the detailed design features of the twin wheel, 7,500- and 6,500-kilowatt wind powered generators discussed in the previous monograph.

The author commented on the March 1945 shutdown of the 1,000-kilowatt Grandpa's Knob unit, and he reiterated the desirability of larger units having capacities between 5,000 and 10,000 kilowatts for utility operation.

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AERODYNAMICS OF THE WIND TURBINE
January 1949

Percy H. Thomas

Federal Power Commission
Washington, D. C.

In this monograph, the author compares the detailed aerodynamic designs of the Grandpa's Knob unit, an English design, with his design. Mr. Thomas modified his 1946 design of a 7,500-kilowatt unit for this comparison by increasing the blades from two to three for each wheel, shortening each blade, and increasing the designed rotational speed.

Mr. Thomas again emphasized that, because of intangible characteristics and uncertainties of extrapolations, wind tunnel tests and full scale prototype construction were imperative to fix a design.

FITTING WIND POWER TO THE UTILITY NETWORK
February 1954

Percy H. Thomas

Federal Power Commission
Washington, D. C.

This is the last of the four monographs published by the Federal Power Commission relative to the studies made by Mr. Thomas in the 1944-1954 period regarding wind powered electric generation.

The author's prior works involved highly technical and specific design matters, particularly in the field of aerodynamics. This shorter work was largely general in nature, commenting on the utilization, or integration, of wind generated electric energy in an electric utility network. He discussed generally the possible benefits of firm and secondary power derived from wind powered generation when supported by large interconnected electric systems. By this time, steam-electric generating units having 250,000-kilowatt capacities were in operation, and the economic benefits of economy of scale of these units presented, at that time, a stiff challenge to competing electric generation sources. In this monograph, Mr. Thomas moved away from comparative cost based justification for wind powered generation in favor of more general statements; i.e., justification would be sufficient if steam generation costs were met. He also stated, regarding wind powered electric generation and to a degree at variance with earlier implications, that economies of scale were of questionable attainment, and he implied that units having 2,000- to 4,000-kilowatt capacities might yield maximum economic benefits.

In previous publications, Mr. Thomas had made some references to the use of wind mills to generate mechanical power, not necessarily associated with conversion to electric energy. In this work, he also commented on a wind-powered water pump and some general applications, including its use as the pumping source for hydroelectric pumped storage operations.

PAST DEVELOPMENTS OF LARGE WIND GENERATORS IN EUROPE

Ulrich Hutter

University of Stuttgart
Stuttgart, Germany

This presentation describes the more important large wind-driven power systems that have been proposed or built in this century in the various countries of Europe. Some of these are shown in the accompanying figures 1 to 9. The physical size, maximum power output, and other characteristics of each system were described with the aid of slides. The most important of the large-size wind-driven plants in Europe were built in Germany, England, Denmark, France, and Russia.

Also described, in some detail, was the 100-kilowatt wind-driven generator that was designed and built by the author in cooperation with the Allgaier-Works of Wurttenburg, West Germany (figure 10). A short movie was presented to show the 100-kilowatt Hutter-Allgaier machine in operation. In figure 11 is displayed the measured output in kilowatts for various wind speeds. For comparison, the data of Andreau-Enfield-Cables wind generator system are shown.

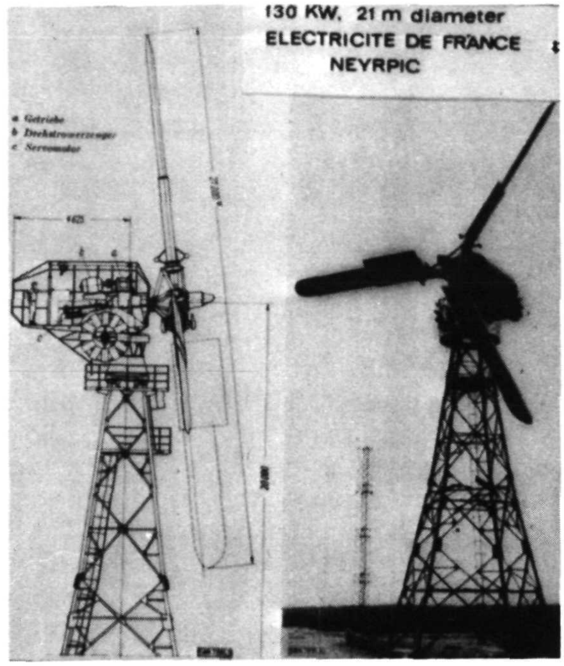
30 m Ø. 100 KW DC RUSSIAN WIND-TURBINE, YALTA, BLACK SEA, 1931

Figure 1

Figure 2

8 m Ø/10 KW DC AND 18 m Ø/50 KW AC PLANTS,
TESTFIELD VENTIMOTOR GMBH, WEIMAR 1942.

Figure 3

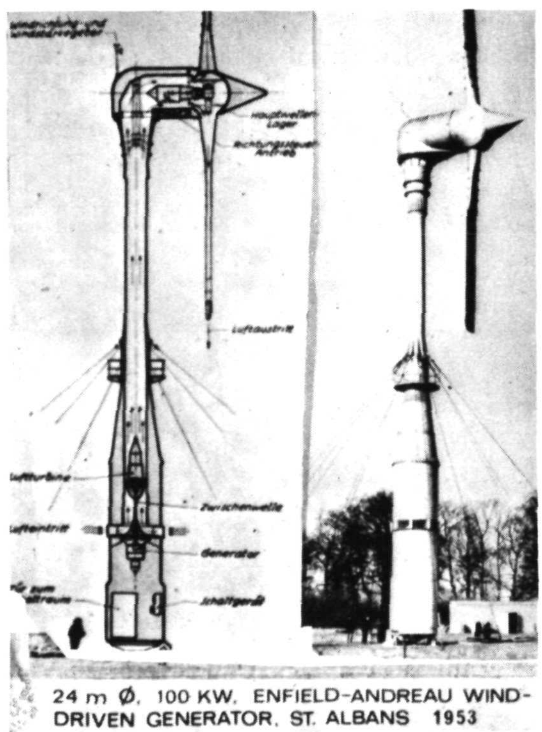


130 KW, 21 m diameter
ELECTRICITE DE FRANCE
NEYRPIC

Figure 4

31 m DIAMETER, 800 KVA, NOGENT LeROI,
FRANCE, 1958-1960

Figure 5



24 m Ø, 100 KW, ENFIELD-ANDREAU WIND-DRIVEN GENERATOR, ST. ALBANS 1953

Figure 6

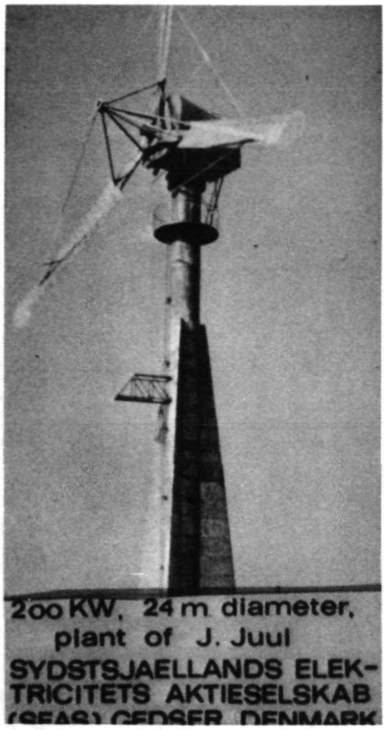


Figure 7

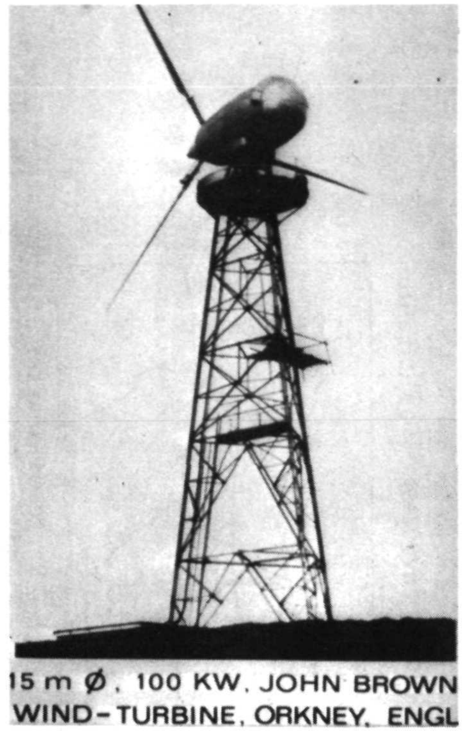
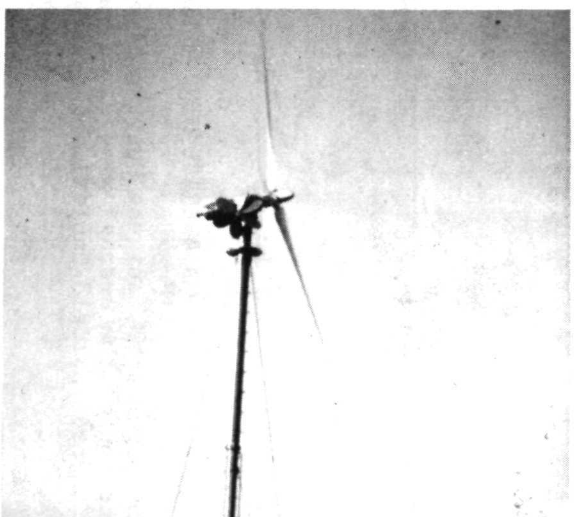


Figure 8



10 m DIAMETER, 10 kW, U. HUTTER - ALLGAIER DESIGN, WEST GERMANY, 1950-1960

Figure 9

35 m DIAMETER, 100 kW, U. HUTTER - ALLGAIER DESIGN, WEST GERMANY, 1961-1966

Figure 10

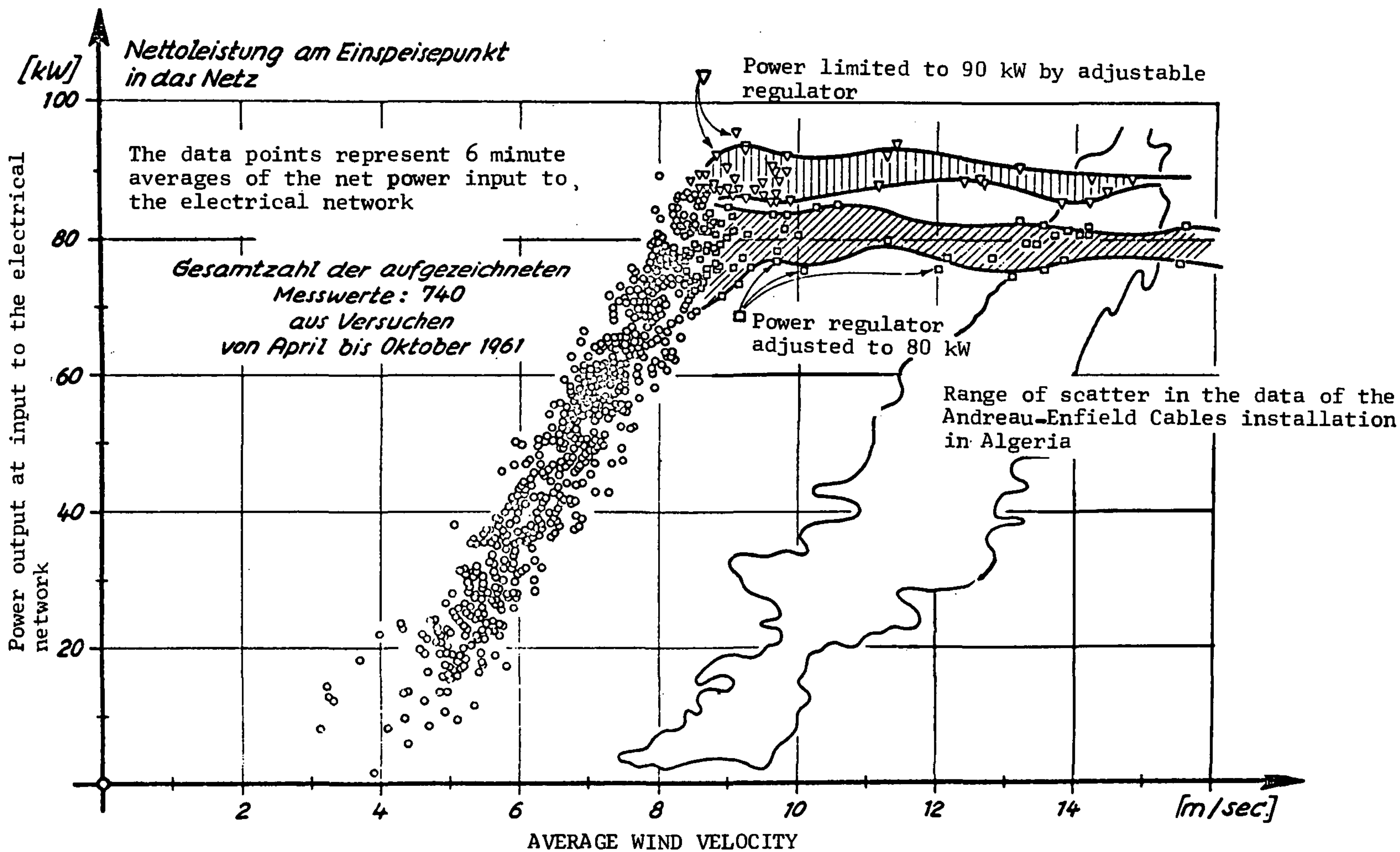


Figure 11.- The power output of the Hutter-Allgaier 100 kW wind-driven generator plant as a function of the average wind speed and a comparison with the performance of the 100 kW Andreau-Enfield-Cables wind generator.

INTRODUCTION TO VOIGT'S WIND POWER PLANT

Joseph Tompkin

Salem, Oregon

The late Hellmut R. Voigt's manuscript entitled "Von der Windmuhle zum Winderaftwerk" -- ("The Design and Operation of Wind Power Plants") comprises 230 pages and 270 illustrations. One of the leading authorities that certified the document was Professor Flugel, Hannover, Germany. This investigation has been examined by experts of leading universities (found in the bibliography of the text) who all testified to the correctness of the author's findings of his own wind power plants. Other engineering authorities who personally certified Hellmut's document were Professors Pantell, Witte, and Schleichert.

The Cyclone D-30 is a high-speed three bladed wind turbine (diameter, 30 m) that operates at a height of 50 meters. The blades are rigidly connected to the hub and the revolutions of the turbine change linearly with the wind velocity, maintaining a constant speed ratio of u (blade tip velocity) to v (wind velocity). This "ideal" wind turbine holds its high efficiency over the full predetermined range of wind velocities. The three generators installed in the gondola generate either dc or ac current. In case of dc installation, the turbine turns by means of a transmission, a set of dynamos. In case of ac installation, the turbine turns by means of an infinitely variable speed drive (patented), a set of synchronous three-phase generators. The generator-gondola with its streamlined shaft can turn around the tapered mast top by means of a journal bearing and a king pin. This motion is controlled automatically by two wind rosettes in such a way that the wind turbine always opposes the wind direction. The mast, a truss and shell construction, pivots about a central foundation and is held in position by steel cables. The wind turbine is equipped with an aerodynamic brake system, and the blades are equipped with an anti-icing system. The low-speed control wind turbine (3-m diameter) located at the tip of the gondola, controls load and speed of the wind turbine by means of a differential regulator driven by both the main and the control wind turbine (patented). The total efficiency of the wind power plant is 66 percent.

Based on the wind conditions at Cuxhaven, Germany, the maximum output is 720 kilowatts at a wind velocity of 16 meters per second. The total installed electrical capacity is 750 kilowatts, and the power output pear year is 2,125,000 kilowatt-hours.

The turn-key installation cost of a wind power plant is not a function of its installed electrical capacity as in steam or diesel power plants. The cost is determined by its towering structure, which has to withstand maximum wind gusts of 50 meters per second (115 mph). The installation cost of a wind power plant should be plotted versus the wind turbine diameter. Such a curve leads to the conclusion that a plant with a 30-meter wind turbine diameter represents the optimum in costs. The price per output rises quite rapidly for smaller wind turbine diameters, as well as for larger ones. In 1951, the turn-key installation cost of a wind power plant Cyclone D-30 was about $244,000.

The operating cost of a wind power plant is not a function of the installed capacity but instead depends on the number of wind power plants operated in a certain area. The more plants that are interconnected to form a wind power central, the lower the operating cost. For instance, in my feasibility study at Cascade Locks, Oregon (Bonneville Dam sector) one unit produced over 14,000,000 kilowatt hours per year for approximately 68.3 percent of the time per year at about 4.3 mills per kilowatt-hour. If 20 units were located, the cost is reduced to approximately 0.8 mill per kilowatt-hour.

The cost savings of a nonweather vaning aggregate over a weather vaning aggregate amounts to $25,000, or about 10 percent of the total installation costs. The difference in operating costs is almost negligible.

Mechanical coupling of wind turbine and water pump is prohibitive, due to the tremendous torques developed by a wind turbine of considerable size.

We have included the production of hydrogen from the electrolysis of water for producing electricity by the hydrogen fuel cell. The installation of this system would supply the needed electricity during peak load demands or augment power during the year, if wind velocity is below the prescribed velocity (8 mph).

Some technical data of the TORNADO wind power plant DIOO are as follows:

Diameter of wind turbine, ft	100
Operating height of wind turbine, ft	150
Total height of wind power plant, ft	200
Diameter of generator gondola, ft	10
Diameter of supporting tubular tower, ft	7.5
Height of observation platform, ft	90
Diameter of air rosettes, ft	12
Speed range of wind turbine, rpm	15 to 60
Utilized wind velocity range, mph	9 to 36
Average annual power output:	
kW	250
HP	340
Maximum power output:	
kW	700
HP	950

Annual net current output, kWH	2,125,000
Normal voltages:	
dc	440
ac	525
Total efficiency of wind power plant, percent	66

DISCUSSION

Q: What year were those dollars?
A: 1951 dollars.

Q: I didn't quite understand the meaning of the 66 percent efficiency.
A: This is the total overall efficiency, including mechanical.

Q: From the total energy?
A: Yes.

Q: Assuming an ideal windmill is 100 percent?
A: Yes.

Q: Which is an efficiency of about 60 or 70 percent ideally?
A: The ideal is 59.3.

Q: 59.3 times about 60 then.
A: Yes, so it takes it down to about 40.

Q: About 40?
A: The overall power coefficient.

Q: Let's go through that just once more to make sure everybody agrees. If you have a hundred energy units in the wind, an ideal windmill will give 59.3 percent. Now you are saying you can expect 66 percent of that 59?
A: True.

Q: Since Dr. Tomkins didn't have any slides, I'm not sure whether he built one of these or what.
A: No, this was design based on a small unit. This was simply the design. The two units were built for the 50-foot units, not the 100.

Q: I would like to hear some comments on the availability of some of the older windmills. For instance, if somebody wants a 50-kilowatt unit, are any of these available to be rehabilitated? Where can you buy a 50-kilowatt unit - who deals with used windmills?
A: The unit just discussed was not an actual unit but a prototype. However, the data that have been compiled were on actual units (12½ feet, 25 feet, and 50 feet). Mr. Voight didn't live to realize a 100 foot unit.

Q: Is it being built now?
A: No. There seems to be a lack of interest as far as funding is concerned.

Q: Are there windmill units that are available as a production kind of unit or as a used unit?

A-1: The machine just shown in the film (the 100-kW Hutter-Allgaier machine) can be produced, but it would be much more expensive than under the conditions we were working on then. We built about 1800 plants of 10-meter plants (10 kW). There is a fine market, like used cars, for these plants. If anybody has a plant to sell, there are five buyers. There is a market. Plants of the size I have shown are available. It's a question of delivery and price.

A-2: I have been doing some research to find out if there are any in production. Those I found are small-scale units up to about 5 kilowatts. There is a company in Switzerland building a 5-kilowatt unit with a 5-meter diameter blade, and they are in regular production. You can order one and get it in 6 weeks. As far as I know, this 5-kilowatt unit is the largest unit presently in production in any quantity.

Q: Do you know the cost?

A: The unit itself, the wind plant, and the control system cost about $1,900. Freight to this country is not a large factor - about $200.

Q: Now we are selling a minimum power. They need 14 knots of wind, have a diameter of 9.2 meters, and they deliver ac current. They can be used to either charge batteries or produce wattage. We can accept orders for 4.21 machines.

Q: This machine is in production, 4.1 kilowatts, and 9 meters in diameter?

A: Yes. In 2 weeks I'll have photographs of this machine. Last month we tested 4.6-kilowatt machines.

A: There is a machine made in Germany which will generate a maximum of 400 watts ac, rectified dc for charging batteries. It is very useful for household purposes. There is another one in Italy which will generate 1000 watts, very much the same thing, but it's dc. There is also a machine in production which can generate about 40 horsepower dc in a 30-mile-an-hour wind.

Guest Speaker

WHERE THERE IS A WIND, THERE IS A WAY

Honorable Charles A. Mosher
Congressman, Thirteenth District, Ohio

When I received Dr. Savino's invitation to be your speaker, I must admit I was at first surprised and amazed. My instant reaction was to ask, "Why me?" I protested that certainly few people in Washington are less qualified than I to talk about the winds. But on second thought, now I do understand why I am here today; I stand before you as "Exhibit A", a living, panting demonstrator of wind power.

Just as a pun is alleged to be the lowest form of humor, similarly a politician may be the lowest form of an energy machine. For example, starting from an almost zero knowledge of the subject before us today, but using my own wind power (lung power) - or hot air, you may say - I will now turn that nothing into a 15-minute speech. And that, I submit is a very real, though elementary, form of energy conversion.

Loosely harnassed, a vast amount of that low form of energy conversion is best known as the Congress. And that is why some folks irreverently refer to Capitol Hill as "Windy Knoll"; and the Congressional Record, where the amounts and velocity of our energy conversion are daily logged, is sometimes called "Cave of the Winds".

And, I want you to know that I have still another qualification which you may not suspect. I'm not kidding, it is literally true that back in 1906 I was born next door to a windmill factory, and I lived there until I was 5 years old. That was in a small town out in Northern Illinois. We lived next door to the Enterprise Windmill Co., and as a kid, often visiting the friendly farms of that area, I knew well the clank, clank, clanking sound of the windmills that pumped water on those farms. One of my own favorite toys in those days was a model windmill such as salesmen for the Enterprise Co. used in demonstrating their products to prospective customers.

But historically, it is significant that immediately across the street from that windmill factory there was located another factory, one that my own family operated for three generations, where we built corn shelters, grain elevators, hay presses and loaders, side delivery rakes, manure spreaders, and, fortunately, gasoline engines. So, the Enterprise Co. went broke, and we survived, because those gasoline engines gradually took the place of windmills on most American farms. And then, in turn, several years later those engines went out of use when the rural electric cooperatives brought cheap, government subsidized power lines into most of the farms.

Also, when I was a sophmore in high school, the dramatics event of the year was our staging of an operetta called "Windmills of Holland". I was in the chorus and much of the time played part of a windmill. Suddenly, as I was preparing this talk, I remembered a verse from that operetta. I won't sing it, but I believe it went like this:

> "Touch a button, you or me, and then that great electricity will do the rest, while we with zest will <u>sit</u>, and look our very best."

The plot of the show, of course, was the demise of the windmills, displaced by electricity.

So since childhood, I have been somewhat aware of the waxing and waning of wind power. But for 40 years or more I had not given the subject any serious thought until early last year when I received a letter from an Ohio constituent who urged that Congress solve our national "energy crisis" by encouraging the location of huge windmills on top of all tall buildings. He suggested that the Empire State and all other such skyscrapers, each could and should satisfy their own electricity needs by means of wind power generators.

Frankly, my staff and I assumed that constituent was some sort of nut. I'm sure my reply to him was little more than a courteous brushoff. But now that I've met you folks, I feel guilty about what I thought of him. I promise you, I'm going to dig into our files and resurrect his letter and take a more serious look at it. I expect to find it in the file we have labeled "Crank Mail", but maybe now we should file it under "Ideas Worth Considering".

And I judge that is precisely the significance of this NSF/NASA Wind Energy Conversion Systems Workshop. You have gathered to take a new look at some old ideas and technologies, long neglected, ignored, laughed at, which in the contexts of today and tomorrow begin to look very promising, and to me certainly very fascinating.

I am confident you are here to usher in a real technology resurrection, a very much deserved and needed second coming for wind power. In the perspective of centuries of human history, I suppose this would be no mere second coming but the umpteenth coming, only the latest of innumerable chapters in man's discoveries of how to make good use of the winds. All of us have been raised on the wise old adage that "It's an ill wind that blows no man good", and I take that wisdom to mean that nearly every wind could be put to some good use. So, we count on you who are here to see to it that that goal is accomplished.

I asked Frank Huddle, Senior Science Specialist at the Library of Congress, to tell me where, when, and how human beings first learned to control and convert the winds for their own uses. Obviously, no man today knows the sure answers to those questions. But Frank is imaginative, and he is confident that observant savages very early learned the ways to harness the winds. Surely, primitive man (or was it first a woman) quickly noticed that a cold wind made him feel colder than cold without wind; so he (and she) retreated into the caves, not only for protection from animals but perhaps, even more so, from the winds.

And perhaps men first discovered fire by observing forest fires caused by lightning. But Frank says it is just as likely that he saw firey particles dropping from branches of trees forcibly rubbed together in a high wind, and so perhaps the wind taught him to make fire.

Certainly man's discovery of the sail was one of the most important technological innovations of all time; it converted his crude raft or dugout canoe into an ocean-spanning transportation system. Frank suggests the inspiration for that first sail may have come when primitive man watched curled leaves being blown across the surface of a pond.

Having harnessed the wind for transportation, it was inevitable that man should similarly harness it to grind his grains and pump his water. I'm told that the windmills of Holland enabled the Dutch to reclaim vast acreages from the sea; and in Yorkshire, England, they also were used to pump water from the lowlands.

I already have mentioned that era in Midwest America when most farmers used patent windmills to pump water from wells for themselves, their livestock, and crops. But then came cheap electricity to do those chores, and so not many of those old mills are clanking today.

So, always, as civilization advances, technology and economics interact and what's new replaces the old. But, often what's new is merely an updated version of what's old. And that, I repeat, seems to be what this Wind Workshop is all about.

Now, gentlemen, I'm going to conclude these remarks by tossing at you a list of 4 or 5 personal opinions which perhaps have some bearing on your work here. There's a great deal of interest and concern in the Congress about today's so-called "energy crisis". It's a very popular, fashionable subject on "Windy Knoll"...lots of speeches, hearings, studies, reports, etc. But I do not pretend here to speak for the Congress or for any other members. These opinions (hopefully somewhat provocative) are strictly my own. I will state them with little or no attempt to explain or defend; they are tossed to you just for what they may be worth.

FIRST OPINION - I am convinced that we in the U.S.A. should decide right now, as a matter of national policy, to free ourselves from any dependence on oil or natural gas; we should completely back away from those fuels as major energy sources.

Now, I don't pretend to know exactly when that revolutionary change might be fully accomplished, but I would hope it could be largely underway before the end of this century, less than 30 years away.

My present guess as to a time table is that for the short run, the next 8 to 10 years, we will be forced to scramble in every direction for our energy using a lot of undesirable expedients, such as unhappily increasing reliance on Mideast oil and temporarily postponing some of the desirable, stricter environmental standards. But, I emphasize, that should be a short-term temporary situation.

In the intermediate period, from 1980 to past the end of this century, we must encourage an increasing reliance on our still immense coal resources (by goal gasification and liquefaction) as well as construction of conventional nuclear fission power plants (with increasing emphasis on safety and environmental controls) and then the breeder reactors, as quickly as they can be proved practical.

But for the long run, a third stage from the year 2000 on, certainly our energy goals must emphasize thermonuclear fusion, and most important of all, ultimately a major reliance on solar energy.

And am I not correct that the energy in the winds is in fact a form of solar energy, a product of solar heat beating down on our earth and sea surfaces? So, it seems to me entirely reasonable that your big goal in this important three-day workshop should be a major change in that timetable I have just outlined. Perhaps a dramatic shortening of the timetable could be brought about by bringing on line commercially feasible wind energy conversion systems (and thus, a form of solar energy) well before the end of this century, long before any of us have thought possible!

SECOND OPINION - Obviously, the success of that revolutionary shift to new energy sources can be accomplished, and hastened, only by means of a massive, diversified, but selective and coordinated, energy research and development effort, probably including some so-called "crash" programs. And, of course, that R & D will require federal appropriations at levels and at a pace not yet contemplated in any budget proposals of which I am aware.

Within the next year or two there must develop a concentrated emphasis and momentum for energy related research if we are to have any chance at all of bringing on line in practical, commercial form those alternative energy sources that will be so necessary by the turn of the century.

I am guessing there might be general agreement that the prime candidates for considerably greater R & D funding should be the following:

(1) Coal stack gas removal,
(2) coal gasification and liquefaction, plus vastly improved

techniques for mining safety and environmental protections in mining,

(3) fast breeder reactors, with increased emphasis on alternatives (gas cooled?) to the currently emphasized liquid metal fast breeders,

(4) long term nuclear waste disposal technology,

(5) thermonuclear fusion,

(6) solar energy,

(7) pollution controls, and

(8) energy conservation technologies, including new concepts in building construction, more efficient storage and transmission of electricity, and surely more efficient, economically feasible, productive systems for recycling wastes.

Much of that R & D effort will be extremely sophisticated - far out stuff, terribly costly, and at best a big gamble, adventuring into the unknown. I believe those big investments are necessary, even though they are a gamble.

But the point I reiterate right now is this: In our fascination with sophisticated and costly new technologies, we will make a tragic mistake if we ignore those great opportunities that exist in new uses of older, familiar and relatively simple technologies...and, of course, by that I mean it is very important that we adequately fund this fresh, innovative look at wind power. I repeat the point made early in these remarks, that innovation more often than not means a new, imaginative look at old information and old experience.

THIRD OPINION - My third opinion is a quickie, merely to express my doubt that there exists in Washington today, either in the Congress or in the Executive Branch, a sufficient understanding or adequate, effective, decision-making machinery to provide the aggressive leadership and national policy decisions which are desperately needed in the realms of science and technology...and especially needed to solve our energy problems.

I see some hope in our authorization of the Office of Technology Assessment, as a new staffing arm of the Congress. If and when it is funded, OTA should provide innovative impetus. I also see hope in the new presence of Charles DiBona and his energy staff at the White House level. And I believe the Administration's reorganization proposal makes good sense, that we create a new umbrella Department of Energy and Natural Resources. But, as yet, I see no sign that OMB (the Office of Management and Budget) is likely to approve really adequate R & D funding in the near future. However, I can assure you that there are at least a few of us in the Congress who are aware, and pushing for the level of determination and effort we believe is imperatively needed.

Time itself is a major human resource, a major national resource. We must use it wisely, effectively, vigorously; we must not fritter it away, and that is why I am so heartened by your efforts here.

And, of course, the winds are no respecter of national boundaries or national sovereignty. They blow alike on the just and the unjust. Certainly, in the winds we have a superb opportunity for sharing the fruits of scientific and engineering effort with all mankind. So, I am heartened to know that there are representatives here from several other nations, as well as our own.

I salute you all!

And now in closing I have a slogan to suggest for your workshop. It results from my very strong feeling that in our national science policy today we are somewhat lacking in sufficient commitment; we need a greater sense of purpose and urgency, a sense of the will to overcome our problems.

All of us know that old saying "Where there is a will there is a way". So I suggest the guiding motto for this workshop should be a slight variation on that theme:

"Where there is a WIND, there is a way!"

NEED FOR A REGIONAL WIND SURVEY

Vaughn Nelson

West Texas State University
Canyon, Texas

and

Earl Gilmore

Amarillo College
Amarillo, Texas

The economically favorable utilization of wind power on at least a modest scale will most likely occur in those regions of the U.S. where the greatest potential exists and where the intermittent nature of the wind speeds is small. Golding and others (ref. 1) have emphasized the need for accurate measurements designed specifically for the purpose of estimating wind energies, but in the U.S. only a small amount of work has been done. Thomas (ref. 2) indicated that the Southern Great Plains is a region over which wind speeds are significantly greater than in almost any other part of the nation, a fact that is common knowledge to residents of the area. The area is large, flat, and accessible (both financially and physically).

The general wind characteristics as indicated by data from the National Weather Service are as follows:

(1) The average wind speed is high (table 1). The 31-year mean for Amarillo, Texas, is 13.7 mph (anemometer height is 23 ft.), and the wind speed is greater than 15 mph 35 percent of the time.

(2) The average wind speeds are consistently high throughout the year with the strongest winds in the spring.

(3) The wind occurs both night and day with a small diurnal variation. The low and high averages by time of day for any month differ by approximately 3 mph from the average value during windy months.

(4) The duration of calm periods (zero speeds) is short. For Amarillo, Texas, from 1968 to 1972 there were only two, 9-hour calm periods and six, 6-hour calm periods. The lowest daily average for the 5-year period was a speed of 4.3 mph, which was on one of the days with a 9-hour calm period. The wind speed frequency curves (fig. 1 and 2) show that over 90 percent of the time the wind speed is greater than 5 mph. In fact for 1970-72 (3-hr observations) the wind was 9 mph, or greater, approximately 80 percent of the time.

(5) High wind speeds are also common (table 2) with gusts of over

80 mph. During the spring of 1973 gusts to 100 mph caused extensive damage in the area.

Preliminary calculations made from National Weather Service data (Amarillo, Texas) give an indication of the energy in the wind, 153 to 212 kW-hr/(ft^2- yr) for 1970 to 1972 (table 3). Comparable results were obtained for other years (fig. 3 and 4, data from the 1950's), and a somewhat smaller value was obtained for Oklahoma (ref. 3).

There are several limitations that must be recognized in using weather station data to evaluate the wind power potential. Wind speed is known to vary with height. Obstructions are sometimes found close enough to anemometers to affect their readings. And the method of taking an average reading may indicate too little energy. Relatively small increments in wind speed values lead to large differences in the calculated values of the energy. For example, systematic errors of 2 and 4 mph give calculated energy differences of approximately 32 and 69 percent respectively. (See fig. 3 and 4.) Such differences in the available energy magnitude may well determine whether wind energy capture is economically feasible.

We are beginning a wind energy survey based on the data compiled at the 10 National Weather Service Stations within 275 miles of Amarillo (fig. 5). The wind survey will provide data from which the wind energy potential can be estimated for an integrated network. The type of information calculated will be the statistical characteristics of the wind and the time correlations between the stations. As stated earlier, this area is large (area of the circle is greater than the combined areas of New England, New York, and Pennsylvania), essentially flat, and accessible; and it encompasses the high wind region.

We are also planning to collect data at sites in the immediate vicinity of Amarillo. These data could then be correlated with the data from the National Weather Service.

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DISCUSSION

Q: When you have a Weather Bureau Station a different height than you like, how feasible is it by relatively short-term measurements at different heights to get the effect?

A: He wants to know if you have Weather Bureau data at a certain height then how do you get data for different heights. There have been some tables put out on the difference in height. Say you took wind speed measurements at 10 feet. Then, what can you estimate the wind speed to be at 100 feet. About three different tables have been published, and they really don't agree. I talked to a friend of mine who is in meteorology, and he said, for example, between 10 and 100 feet just add 60 percent. Now, I don't know how accurate that is.

Q: My question was about the measurement. Can you do better by particular tables?

A: I'm not sure actually. Once you get a correlation between heights, your Weather Bureau data will give you a good idea of the wind energy potential in that region.

Q: I have a question and a comment. I believe that in the Western part of your region there is quite a bit of high ground there, and, with the speed-up factors on high terrain the British investigations show, I wondered if you were going to get really much in that area.

The second comment: In the Texas area near Dallas there is a high TV tower that has been instrumented. You might do some extrapolations from that as it is one of the tallest instrumented towers on the continent.

A: Yes, I have seen some data from that tower. It is in a region of low wind down there. There is a range of mountains between us and Albuquerque, and we don't expect much wind from that region. In other words, it's only when you get out on the high plain that you get high wind velocity essentially the year round.

Q: I was wondering whether you people had done any work on instrumentation that would measure wind energy directly. There has been some suggestion that the anemometer that measures velocity is not what you're interested in. What you're really interested in is v^3.

A: Some people in England measure wind energy directly.

Q: Is that going to be used?

A-1: We don't know yet. Probably.

A-2: Just to add to your reply, the type of the anemometer that the French used for the wind service during the 1940's and 1950's was an integrated type of meter. It gave out kilometers per meter squared. This has certain characteristics itself. It acts as an energy machine so it doesn't necessarily have the same characteristics. There is a mass of data for France in kilowatt hours.

TABLE 1

MEAN WIND SPEED FOR AMARILLO, TEXAS (1942-72)

Jan.	13.2	July	12.4
Feb.	14.3	Aug.	11.9
Mar.	14.5	Sept.	13.1
Apr.	15.4	Oct.	13.0
May	14.8	Nov. 13.2	13.2
June	14.4	Dec.	13.2

Average = 13.7 mph = 6.09 m/s = 21.9 km/hr

*

*

*

TABLE 2

SPEED OF FASTEST MILE FOR AMARILLO, TEXAS

	mph	km/hr	(Number of Days 50 mph and above)
1968	50	80	2
1969	59	94	3
1970	59	94	2
1971	54	86	1
1972	64	102	2
1973	65	104	3

TABLE 3

ENERGY ($kW-hr/m^2$) IN THE WIND*

Month	1970	1971	1972
1	107	171	179
2	86	272	141
3	180	310	164
4	186	274	240
5	131	277	185
6	150	217	117
7	73	110	129
8	51	102	94
9	120	163	159
10	156	136	137
11	228	133	158
12	184	125	149
Totals ($kW-hr/m^2-Yr$)	1652	2290	1852
$kW-hr/ft^2-Yr$	153	212	172

*Values calculated from 3 hour observations of wind speeds, anemometer at 23 ft., from National Weather Service, Amarillo, Texas.

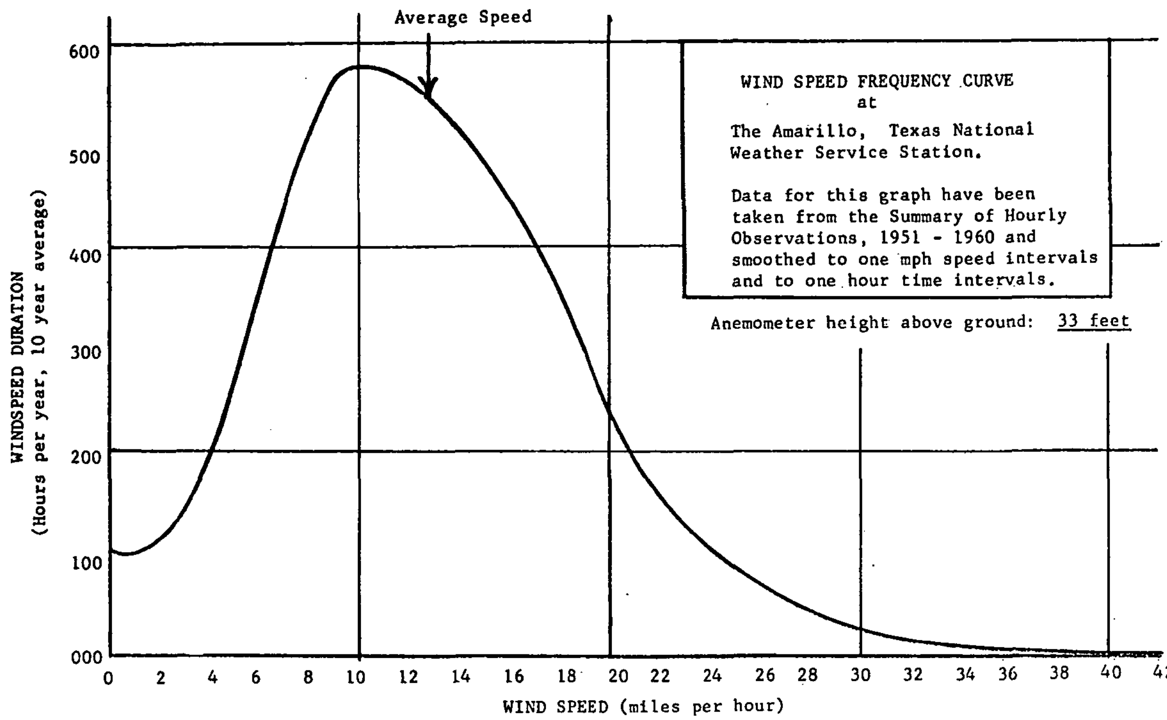

FIGURE 1.

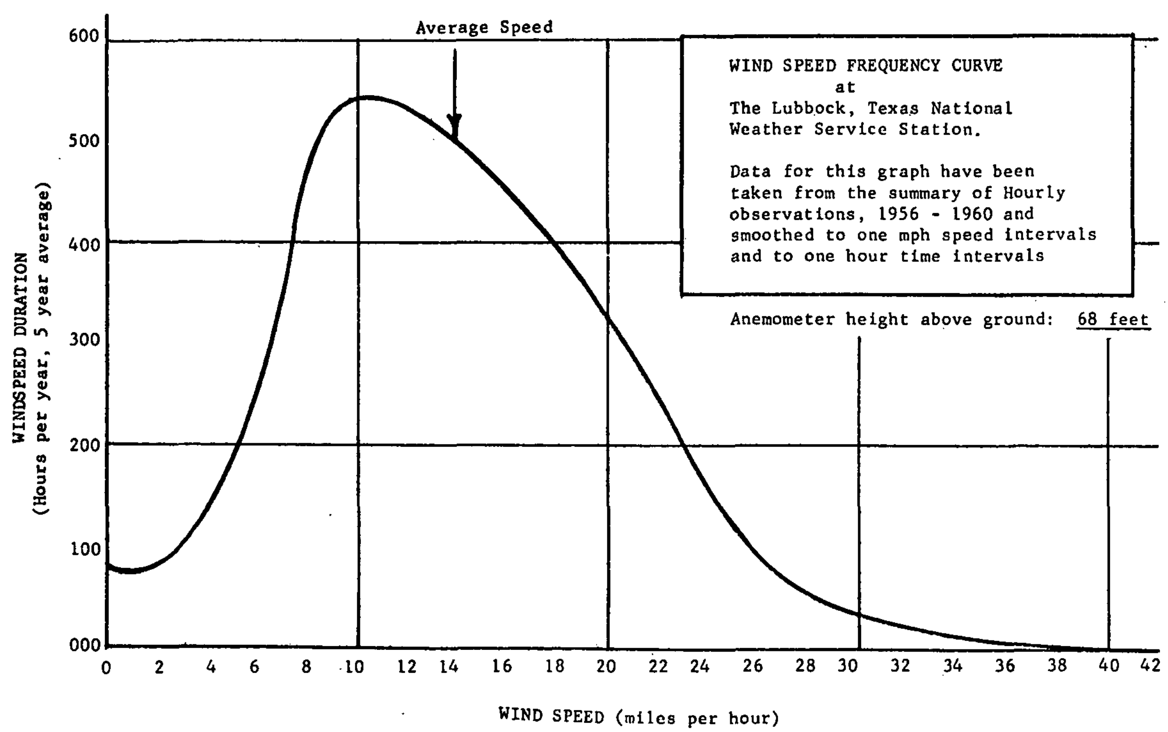

FIGURE 2.

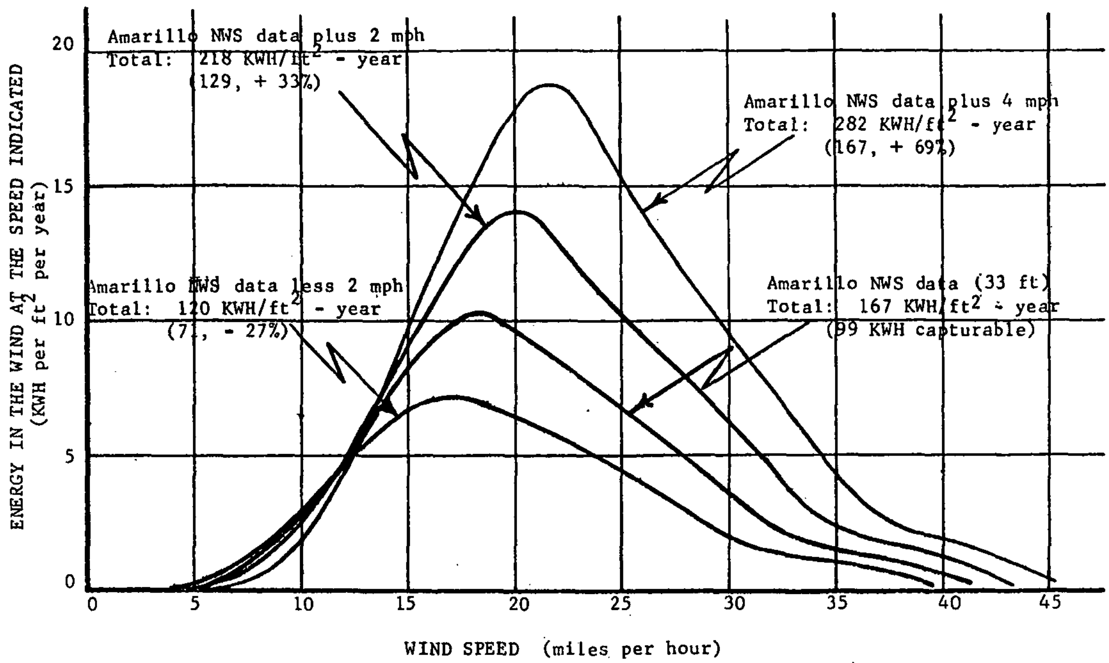

FIGURE 3.

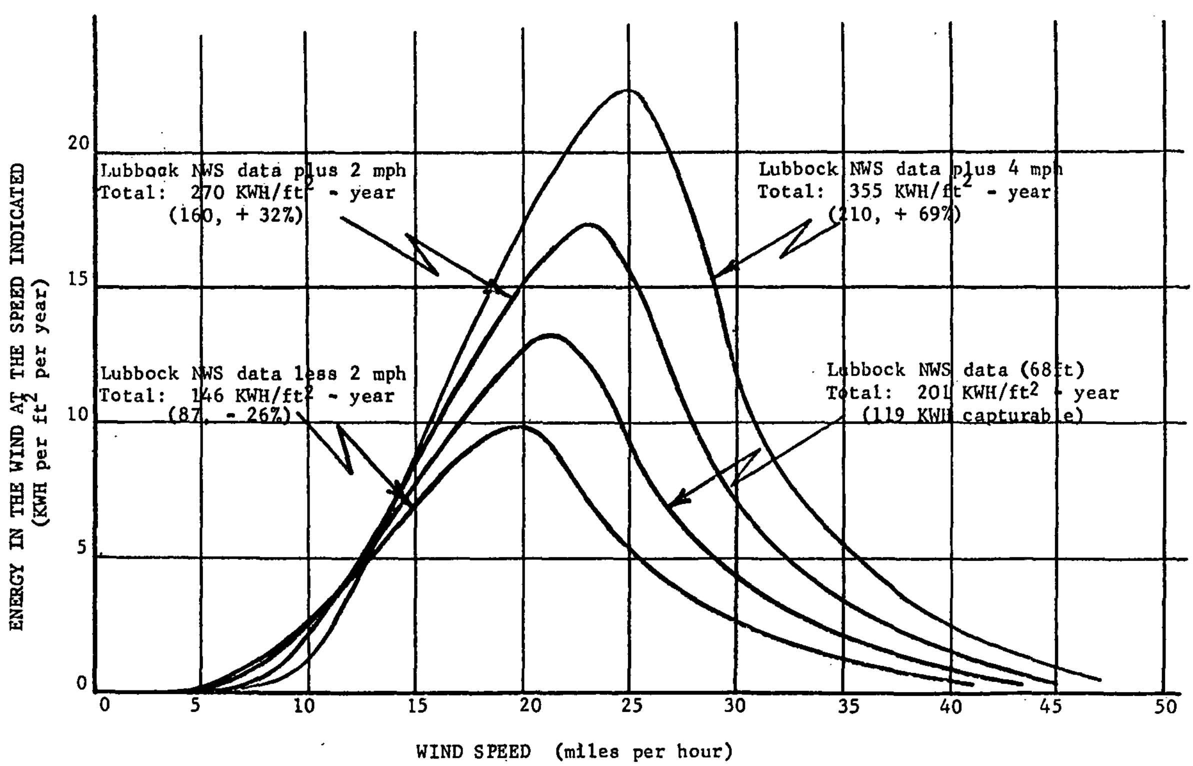

FIGURE 4.

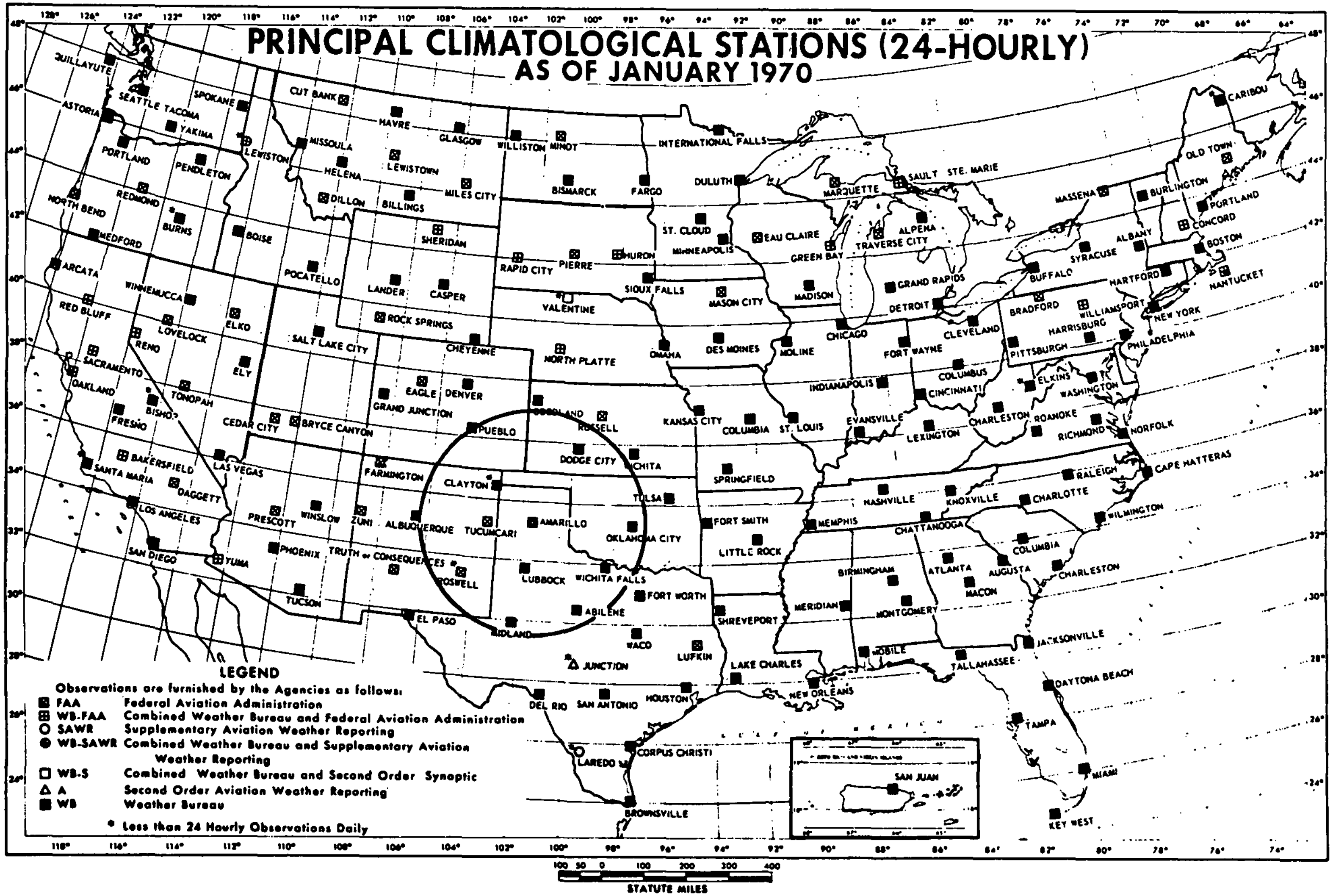

FIGURE 5. Map Taken From The National Climatic Center, NOAA, 1970.

WIND POWER DEMONSTRATION AND SITING PROBLEMS

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I would like to discuss the nature of the work being done at the University of Oklahoma on wind-power generation and on systems associated with the use of nonpolluting energy sources. Our activities are primarily student-oriented programs aimed at specific educational goals. They result from a conviction that wind power represents the most practical way to harness solar energy. The fact that Oklahoma is more than generously endowed with wind is also clearly a factor.

At the same time, we concentrated on the development of a nonpolluting urban car that could use the resulting electrical energy directly. We saw the two programs as being both educational and a contribution to an increasingly critical social problem. We also felt that such programs encourage engineering students to think in terms of social goals, an area which must become increasingly important in engineering education.

In order to insure a general acceptance of alternatives to fossil fuels, research in energy generation and in compatible energy usage must be carried on in parallel. In the long run, there must be alternatives to the "fuel tank" energy economy on which our present transportation systems are based.

Speaking first of the transportation aspect, figure 1 shows the OU Urban Car, a two-seat electric vehicle with an on-board auxiliary generator for extending the range and providing power for heating and cooling. The range of the car is 25 miles on battery power alone and 50 miles with the on-board charger operating. A design goal was to avoid the excessive weight problem which has reduced the performance and efficiency of many electric vehicles. Our test program includes measurements of performance, drag, rolling friction, battery discharge characteristics, and various other technical features. It also includes an operational test program to determine the acceptability of the concept in regular daily use.

The windmill studies have included technical and economic feasibility studies and a hardware program for a small generator that can provide overnight charging for the OU Urban Car. The blades for this mill have a diameter of 12 feet and are coupled through V-belts to a conventional automobile alternator. Under average wind conditions, the mill is capable of completely charging the car batteries in 8 hours.

We have recently embarked on a program of modeling the dynamic response of windmill systems using real wind characteristics and considering variable inertia, aerodynamic characteristics, and energy storage systems. We plan to look both at the short-term response of the system and the long-term energy balance associated with specific demand patterns.

In this connection, OU is fortunate in having the National Severe Storms Laboratory of NOAA located on campus. NSSL has a 44-station recording complex in Oklahoma and Texas, as shown in figure 2 (ref. 1). These stations record wind direction, wind speed, pressure, temperature, and precipitation. The number of stations per unit area is very nearly an order of magnitude greater in the Oklahoma City-Norman area than is currently available in most synoptic data. The purpose, of course, is to provide an accurate portrayal of the surface winds during thunderstorm activities. It is particularly valuable for investigating the siting and performance of wind-power devices.

In addition, NSSL has instrumented the WKY-TV tower to obtain information on the variation of wind characteristics with height. It is located within the area of high-station density for the NSSL surface network. In addition to ground-level measurements, the WKY-TV tower is instrumented at six levels from 146 feet to 1458 feet. Continuous measurements of wind speed, wind direction, and temperature have been recorded since 1966 (ref. 2). The information has been digitized and is available both as annualized velocity and directional distribution and in the form of short-term velocity distributions with intervals of 2 seconds, 10 seconds, and 1 minute. It is these data that serve as one input to our windmill response modeling program.

Since the program is just starting, I believe it is too early to discuss the project in any detail beyond commenting that our goals are to investigate the effect of short-term gusts on the windmill/storage system characteristics and the effect of long-term variations on energy storage requirements with various cut-in speeds and installed capacities.

I would like now to comment briefly on what I see as some of the research needs in the field of wind power.

First of all, I do not believe that we need general concept studies. The concepts exist and, for the most part, the technologies also exist. It seems clear that the development of wind-power systems can be thought of in terms of relatively straightforward engineering programs. The critical element is the willingness of government and industry to make the necessary commitment to policies that will encourage the development and use of wind power. This support need not be expensive, certainly quite inexpensive when compared with AEC funding, for example, and could take the form of development grants and subsidies. Both are consistent with past government efforts to promote the use of emerging technologies. Perhaps even more important, the expression of government interest can have a multiplying effect on independent research carried out by industries and in the universities.

I would like to emphasize particularly the role of practical demonstrations rather than an extensive program of concept and feasibility studies. The subject is old. It has been reviewed and investigated by innumerable competent people over the years and, as Dr. Hutter's presentation showed, the technology itself has reached a high level of development in Germany and in other parts of the world.

As an example of the early recognition of some seemingly-new concepts, I would like to quote J. B. S. Haldane, the eminent British biochemist, writer, and teacher. In 1920, in a small book entitled "Daedalus or Science and the Future," he wrote:

> "Ultimately we shall have to tap these intermittent but inexhaustible sources of power, the wind and sunlight. The problem is simply one of storing their energy in a form as convenient as coal or petrol."

He went on to say that the energy problem would be solved when:

> "...at suitable distances, there will be great power stations, where during windy weather the surplus power will be used for the electrolytic decomposition of water into oxygen and hydrogen. These gases will be liquified and stored in vats, vacuum jacket reservoirs, probably sunk in the ground."

Note the word "intermittent." For the eventual optimization of windmill/storage systems, we need to know how intermittent and we need to know in some detail. The usual velocity information is obtained at relatively wide intervals of time, which permits a comparative, and therefore rational, basis for siting wind power stations. It does not provide the detailed information needed by the designer to fine-tune the optimization process. The point is that detailed wind information is desirable for the long-term applications of wind power, but its lack need not stand in the way of early demonstration programs.

From the purely technical standpoint, we need better information on the performance of windmills in the vicinity of fixed obstacles and when operating in tandem. We need better methods for modeling boundary layers up to 500 feet in a variety of terrains and with relatively few datapoints. We need to develop low-cost blade and tower structures, reliable control systems and efficient storage methods.

Perhaps even more important is the need to consider the matter of social impacts and public acceptance. The appearance of individual mills is important and the siting must be reasonably unobtrusive and based on careful public preparation.

I do not believe the latter point can be overemphasized. Only a few years ago, nuclear power was being hailed as the ultimate source of clean, nonpolluting and inexhaustible energy. Environmental considerations and public objections have essentially halted new construction of nuclear power plants, and the prospects for the immediate future are not bright.

In this connection, a recent study at the University of Texas reviewed the siting problems of a variety of nuclear power plants and compared their public acceptance with the approach taken during their early development. The study found that the successful programs had followed a consistent pattern of full public disclosure, even to the point of announcing where the power plant would be located before completing the plans and buying the land. Although the land costs were higher as a consequence of this policy, the overall costs were considerably less than those associated with strong and well-organized public opposition.

The point to be made here, I believe, is that conventional business wisdom is not necessarily the best guide to decisions that have a strong public impact. In the long run, there would appear to be no substitute for full public disclosure and adequate public discussion prior to a major commitment of funds.

Finally, I would like to address briefly the subject of how development and demonstration of wind power might best be carried out.

I believe that we must avoid the trend toward technological overkill. By this I mean that we should not attempt to do the definitive study in 6 months with 50 people. I recognize that there is often a considerable pressure on funding agencies to come up with early judgments, but if the information is hurried and if the judgments are not mature, it is likely that more harm than good will result.

I make this comment because it seems to me that I have seen a growing tendency on the part of funding agencies to send out RFP's with extremely short response time and high manpower densities. I happen to believe that this is not an efficient way to get at the type of long-term problem which wind power represents. I do not mean that we should neglect certain large or comprehensive studies, but I do believe it is valuable to take advantage of the widespread interest in new power sources by parceling out a relatively large number of small grants. Such grants serve as seed money for other sources of sponsorship and, if issued in the form of student support, for example, have a strong multiplying effect by involving interested faculty members without cost. Furthermore, such programs give the sponsoring agencies a calibration on the interest and competence of the various universities and organizations, which is bound to be helpful when considering commitments to larger or more expensive programs.

It is important to strike a reasonable balance between research, system studies, and demonstration projects.

Aside from the technical programs, we should place a strong emphasis on public policy issues, the effect of the technology on society, and the interaction of State and Federal regulatory actions.

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Figure 1

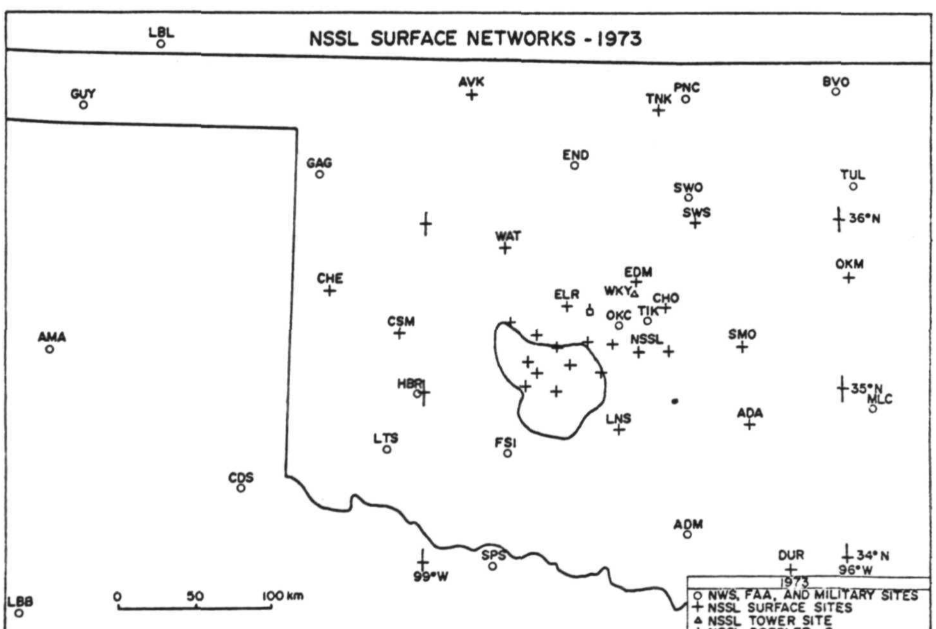

Figure 2

SURFACE WIND CHARACTERISTICS OF SOME ALEUTIAN ISLANDS*

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Our long-range goal is to establish (and, hopefully, exploit) the wind power potential of Alaska, one-fifth the area of the contiguous 48 United States (fig. 1). Important corollary questions are access to promising wind power sites for construction of test or permanent wind machines and shipment of the wind-derived energy. The "packaged" form of the energy must be considered for possible export to the "lower 48" or use in Alaska. Also, the wind regimes involved will dictate windmill design, including, of course, the economics.

A first step is our analysis of near-surface wind data (ref. 1) from some promising sites accessible by ocean transport. We consider a few Aleutian sites (ref. 2) here, to indicate probable velocity[1] regimes and also present deficiencies in available data. Cold Bay and Dutch Harbor are two such wind power sites. (fig. 2, - areas numbered 12 and 15, respectively (ref. 3).)

COLD BAY, ALASKA

Cold Bay has a 5-year average wind velocity of 15.1 knots (17.4 mph). An airstrip accommodating 747's, a harbor permitting 30-foot draft vessels, and a large, wide, unshielded (N and S) plain ideal for a windmill farm all make this area a prime candidate for initial Alaskan large-scale wind power investigations. The monthly average cycle (ref. 4) is shown in figure 3 (more on this later). Figure 4 gives the velocity duration curve averaged for all months. All such curves mask short-term fluctuations, like those of figure 5.

Cold Bay data show surprisingly little wind speed variations with height. Simultaneous measurements at various heights near ground are desirable, as at any site. However, a shift in anemometer height from 88 to 21 feet showed no significant change in monthly velocity distribution curves for comparable months.

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*Supported by State of Alaska funds.

[1]Speed and velocity are interchanged here. Wind direction is not considered, but the winds are cyclonic and, while often from the SW, can shift rapidly in all directions in most areas.

DUTCH HARBOR (UNALASKA ISLAND)

For Dutch Harbor the available wind data (figs. 3 and 6) are disappointing, in view of the fact that it is the best and most sheltered harbor in the Aleutian Chain. These data are a good "horrible" example of data obtained for purposes other than wind power generation. The present values are from an anemometer at the airstrip, which is sheltered on all sides from most strong winds and especially those coming in from the sea, north and south. However, our 1973 on-site inspection indicated that there are at least three areas in the vicinity that seem ideal for windmills; long term weather data should be gathered there.

The Dutch Harbor and Driftwood Bay (also Unalaska Island) monthly mean velocities (fig. 3) illustrate probably typical horizontal differences in the Aleutians for nearby areas. Driftwood Bay is 14 miles northwest of Dutch Harbor. The yearly means are 8.3 and 9.3 knots, respectively (ref. 5).

GENERAL AREA INFORMATION

Table 1 contains data for eight Aleutian sites, including frequencies of selected velocity ranges. The 7- to 21-knot (8 to 24 mph) range covers the cut-in to near peak power speeds for small available generators. In general, in the Aleutians, winds for some degree of power generation are available 77 percent of the time (averages of table 1). Since the data available so far are from sites generally chosen for nonwind power purposes, the values of speed and frequency are probably lower limits for wind power planners.

Wind speeds to 140 mph are reported spasmodically in the North Pacific Ocean - Bering Sea area, but are seldom verified. Peak velocities depend on location. The record at Cold Bay is 73 mph, at Amchitka above 115 mph. At Amchitka winds above 70 mph can last for several hours.

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4. Climatolography of the U.S. #82-49, Decennial Census, Summary of Hourly Observations (for various stations), 1956-60 (GPO 1963); also specific location Local Climatological Data, Monthly and Annual Summary. U.S. Dept. of Commerce, NOAA, National Climatic Center, Asheville, N.C. 28801.

5. Unpublished (generally) data, Air Weather Service, NTC - Asheville, as in ref. 4.

TABLE 1

TIME PERCENTAGE OF SELECTED WIND VELOCITY RANGES IN ALASKA

Location**	Annual Mean, Knots	% of Time at 7-21 Knots	% of Time above 21 Knots
Adak NS (AD)**	13.1 (1942-65)	60.9	16.2
Amchitka AFB (AM)	18.3 (1943-50)	60.1	30.7
Cape Sarichef AFS (11)	13.7 (1952-56?)	57.5	18.5
Cold Bay* (12)	15.1 (1956-60)	64.0	24.0
	14.8 (1965-71)	Data discrepancies need resolution.	
Driftwood Bay AFS (15)	8.3 (1959-69)	56.9	1.9
Dutch Harbor NS (15)	9.6 (1946-47, 1950-54)	53.3	6.9
St. Paul Island* (SP)	16.4 (1972)	68.9	24.2
Shemya AFS (45)	15.1 (1943-53)		
	16.2 (1950-72)	Data discrepancies need resolution.	

*Commercial Airport.

**See Fig. 2.

DISCUSSION

Q: I am interested in the freezing rain potential of your area. Do you think this might come to be a problem?

A: As I see the major problems they are three. Some of them can be checked out early.

One is the mechanical behavior of a large windmill during peak velocities. Can you feather quickly enough? I think the indications are that most of the properly engineered windmills will take above 100 miles an hour. What will they do at 150 miles an hour?

I don't think there is any problem in towers. What I am really concerned about especially in the Aleutians is the prevalence of this high velocity mist they speak about, almost horizontal rains. Experience indicates that in the Aleutians it's almost impossible to seal an electronic device against these winds. If you are going to mount your generators on towers behind the blades, you may have to pressurize the generators to keep them dry.

The problem of icing should be checked out. There are indications in other parts of the world that icing is no problem. It is not particularly cold in the Aleutians, but the snow is quite wet. These are problems that will be faced.

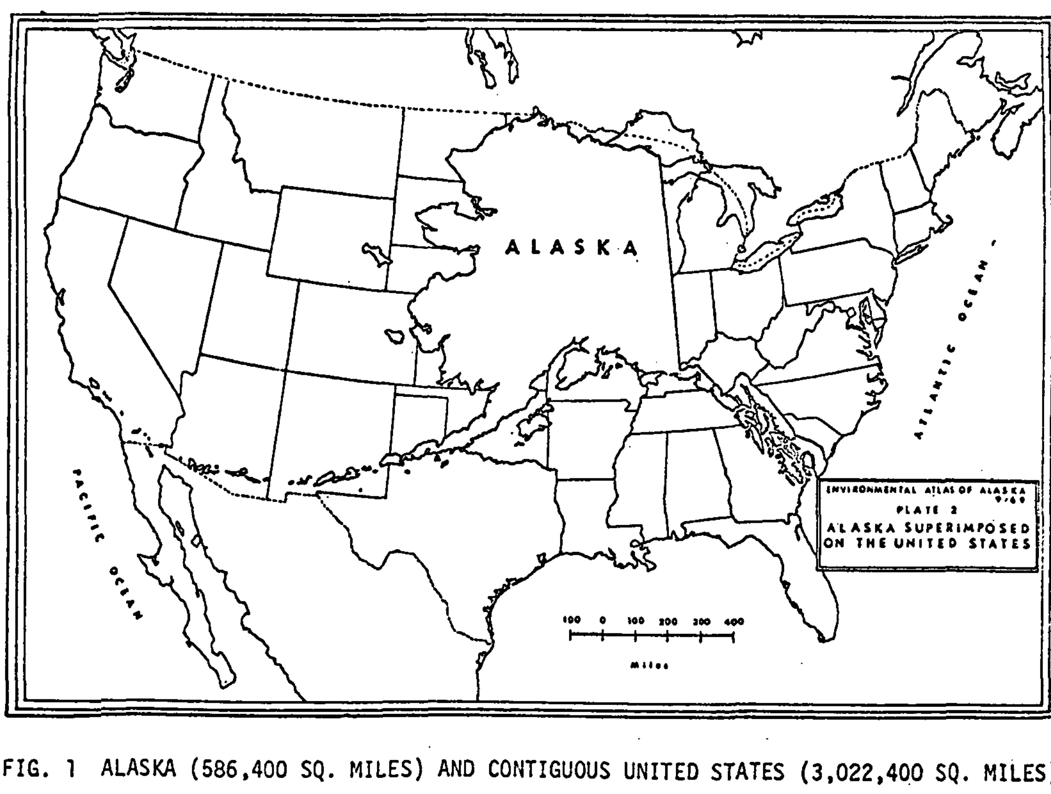

FIG. 1 ALASKA (586,400 SQ. MILES) AND CONTIGUOUS UNITED STATES (3,022,400 SQ. MILES)

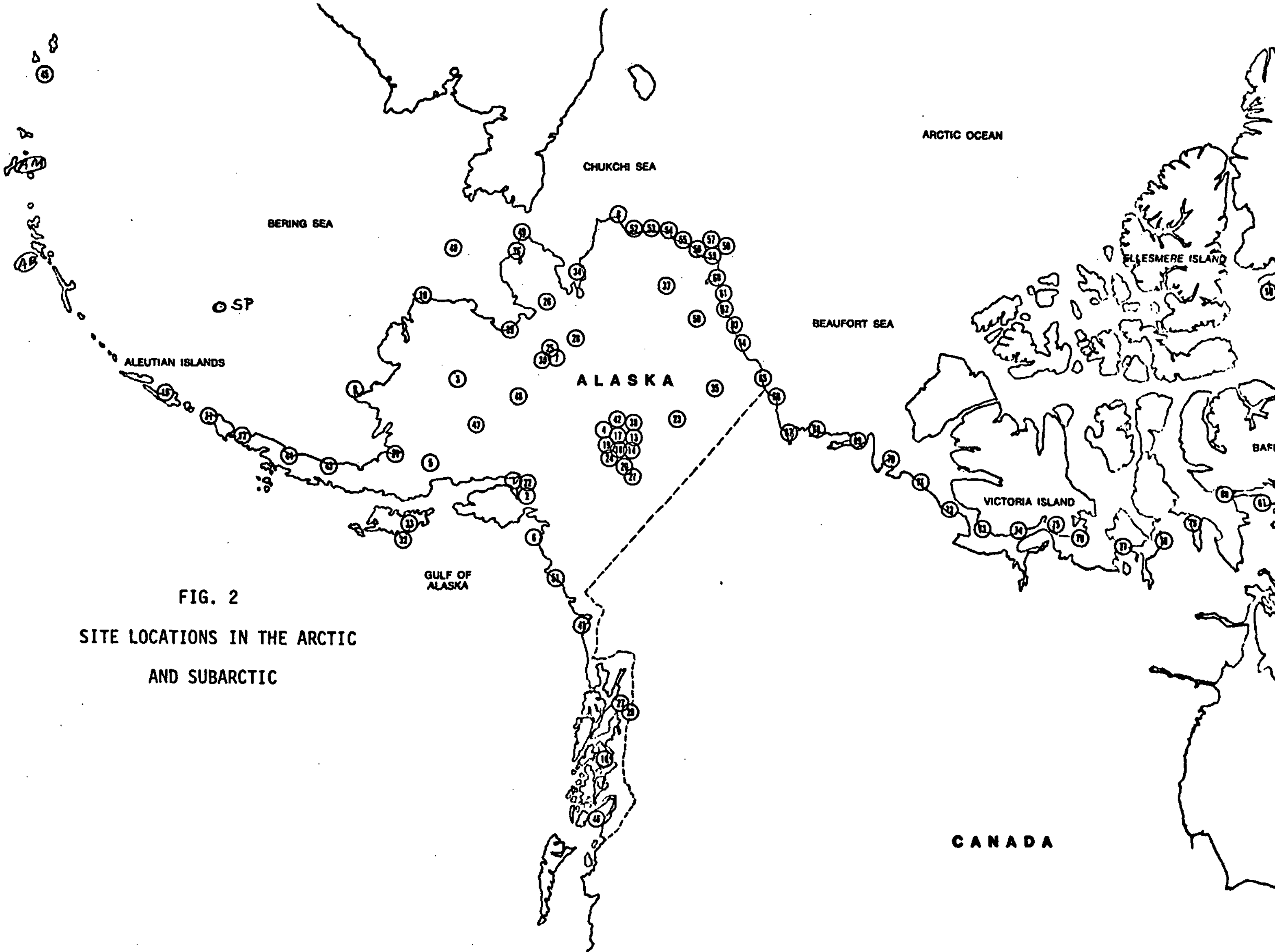

FIG. 2

SITE LOCATIONS IN THE ARCTIC AND SUBARCTIC

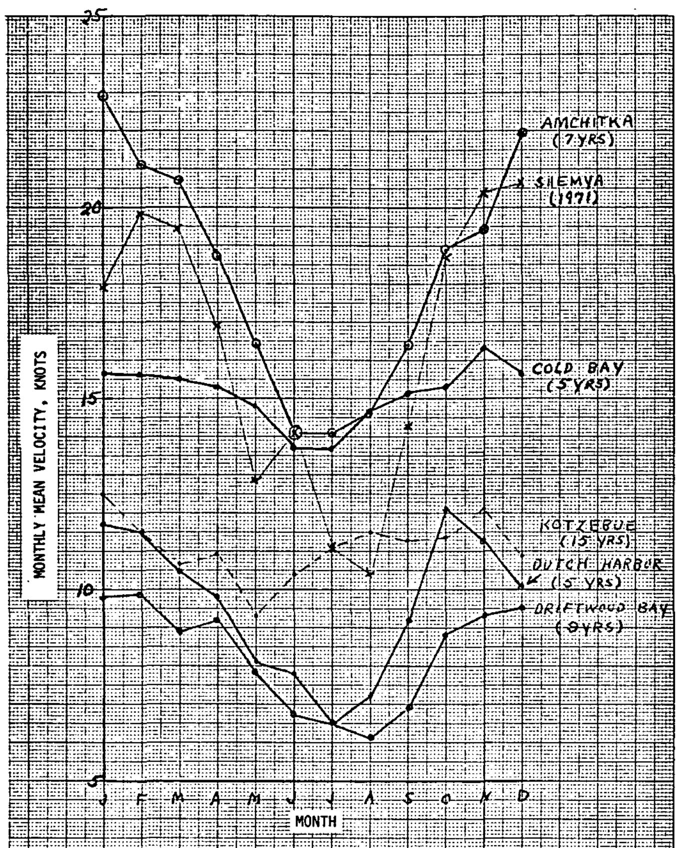

FIG. 3 MONTHLY MEAN WIND SPEEDS AT SOME ALASKAN LOCATIONS

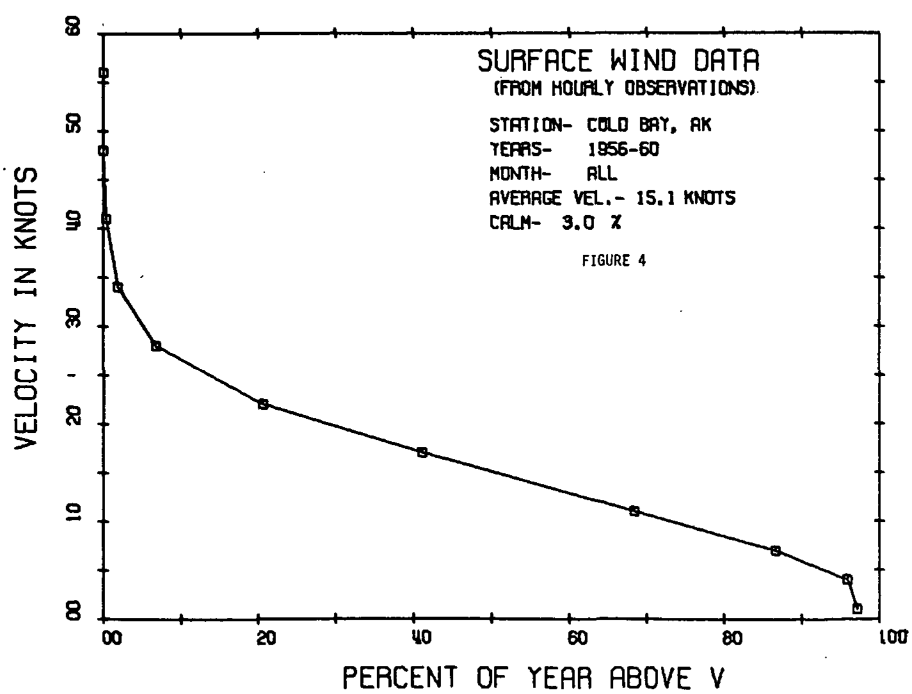

FIGURE 4

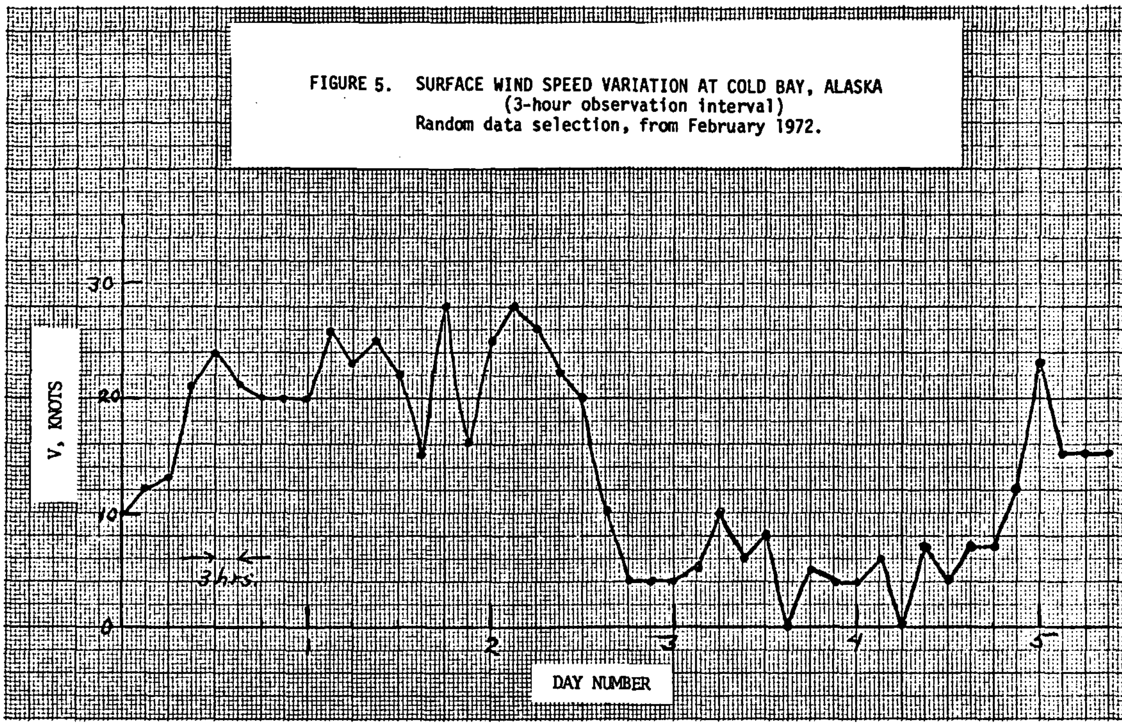

FIGURE 5. SURFACE WIND SPEED VARIATION AT COLD BAY, ALASKA
(3-hour observation interval)
Random data selection, from February 1972.

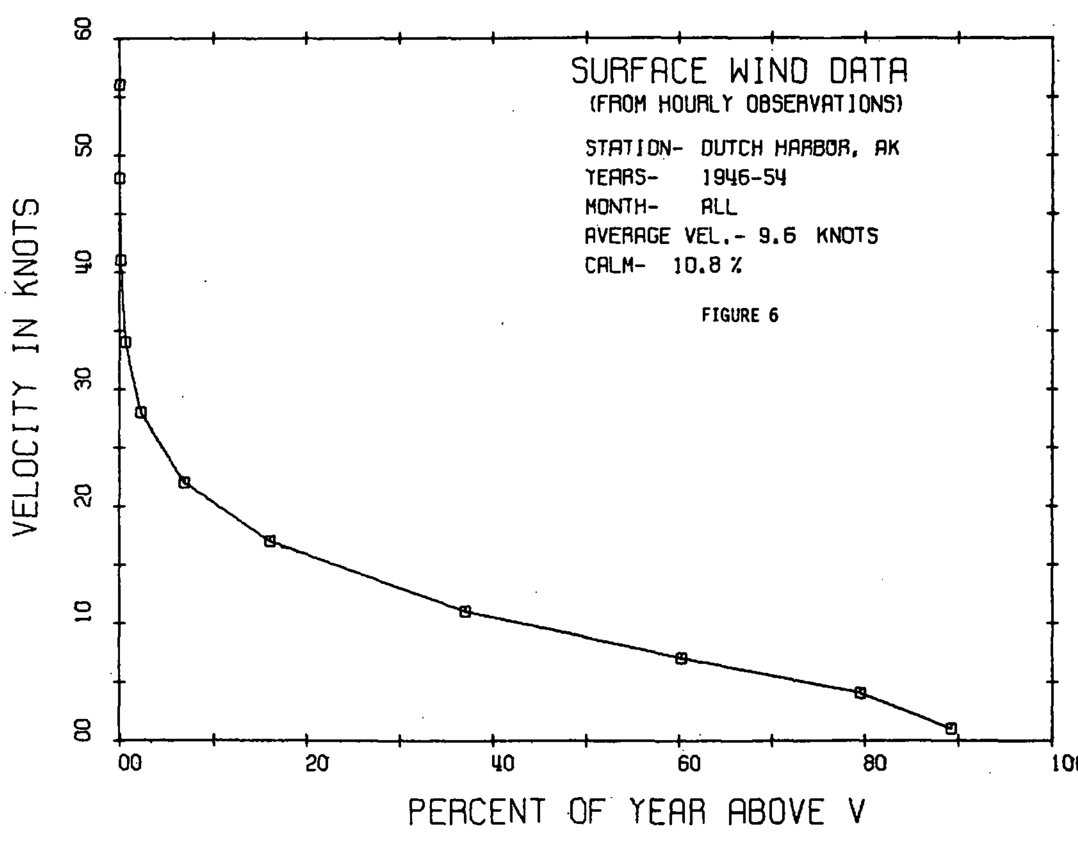

FIGURE 6

WIND POWER RESEARCH AT OREGON STATE UNIVERSITY

E. Wendell Hewson

Oregon State University
Corvallis, Oregon

The program of wind power research at Oregon State University commenced late in 1971 under the sponsorship of four Oregon Peoples Utility Districts, those of Central Lincoln, Tillamook, Clatskanie, and Northern Wasco. The interdisciplinary research team consists of faculty members from the Departments of Atmospheric Sciences, of Electrical Engineering, of Mechanical and Metallurgical Engineering, and of Physics, and from the School of Oceanography.

There have been two primary thrusts of the research effort to date, along with several supplementary ones. One primary area has been an investigation, in a preliminary manner, of the wind fields along coastal areas of the Pacific Northwest, not only at the shoreline but also for a number of miles inland and offshore as well. Estimates have been made of the influence of the wind turbulence as measured at coastal sites in modifying the predicted dependence of power generated on the cube of the wind speed. Wind flow patterns in the Columbia River Valley have also been studied but in less detail.

The second primary thrust has been to substantially modify and improve an existing wind tunnel to permit the build up of a boundary layer in which various model studies will be conducted.

One of the secondary studies involved estimating the cost of building an aerogenerator of the Smith-Putnam type at 1971 prices.

WIND PATTERNS AND SITING PROBLEMS

The wind patterns at a substantial number of coastal sites have been examined. Some of the wind stations were established by the present project, with locations chosen after examining the criteria set forth for the Vermont Smith-Putnam location (ref. 1) and for various coastal sites in Wales and Scotland (ref. 2). The locations of both the older and newly established wind stations are shown in figure 1.

The terrain of the coastal areas of Oregon bears a marked resemblance to that of western Wales and Scotland where a comprehensive wind power survey was conducted a number of years ago (ref. 2). The wind patterns are substantially different, however. The pressure gradients over the British Isles lead to west winds which blow up and over the coastal higher ground. On the other hand, the pressure gradients over the coastal areas of the Pacific Northwest lead to prevailing northwest winds in summer and southwest winds in winter. The High Cascades beyond the Coast Range provide an additional barrier which tends to promote a lower level airflow parallel to the coast rather than perpendicular to it both summer and winter. As a result, the most promising wind power sites appear to be right on the coast or over nearby offshore waters.

Referring to figure 1, our research to date indicates that substantially stronger winds occur at our lower wind stations at Cape Foulweather and at Yaquina Head and at the Columbia Lightship, which is stationed several miles off the mouth of the Columbia River. Relatively high winds also occur over many of the bluffs which extend for several hundred miles along the coast of Washington, Oregon, and northern California.

Another attractive site for wind power development is the Columbia River Valley where limited studies only have been made. Topographic features along a stretch of the river valley east of Portland are illustrated in figure 2. The valley sides rise to heights of 4000 feet mean sea level (msl) to the south and perhaps 1600 feet msl to the north. On September 5, 1972, serial pilot balloon observations were made at three points in the valley, at Cascade Locks, Wyeth, and Viento Park whose locations are shown in figure 2. Balloons were released and tracked at each station at intervals of 1 to 2 hours during the day. The results are presented in figures 3 to 5. Each figure gives isotachs of equal up valley speed in knots. On this September day the winds in the valley appear to average about 20 knots (23 mph; 10 m/sec) if one allows for the tendency of the wind to increase with height. One purpose of these serial pilot balloon measurements was to determine whether or not significant large-scale turbulence occurs in the valley. One such region of turbulence is shown by the hatched area in figure 3 where a strong vertical gust caused the single theodolite method to fail. Future observations in the area will use two-theodolite tracking which avoids this problem. It is obviously important for wind power purposes to determine the magnitude and frequency of the occurrence of such gusts.

Two of the more attractive areas for wind power development are the offshore coastal waters and the Columbia River Valley, as suggested by the power duration curves presented in figure 6. The British aerometric survey referred to earlier showed one of the highest average wind speeds to be 21 knots (24 mph) at Rhossili Down, Glamorgan, Wales at a height of 633 feet (193 m) (ref. 2). The power duration curve for Rhossili Down is shown in figure 6 for comparison with corresponding curves for the Pacific Northwest. A power duration curve for an inland British station at a height of 267 feet (81 m) having limited wind power potential is also shown in figure 6.

The coastal terrain obviously has a substantial effect in slowing down the stronger offshore winds as the comparative data for the Columbia Lightship and Astoria (fig. 1) given in figures 6 and 7 show. The wind records at two of the newly established wind stations, Cape Foulweather and Yaquina Head, do show high winds, but the instruments have not been in operation long enough to permit the establishment of reliable power duration curves. Details of these studies are available (ref. 3).

WIND TUNNEL STUDIES

The purpose of the wind tunnel studies is to develop appropriate simulation methods to the point that it will be possible to locate attractive coastal wind power sites from model studies without the necessity for taking lengthy and expensive on site observations. Analyses of various types of aerogenerators through the use of models will also be undertaken. Work to date has been directed to modifying and improving an existing return-flow wind tunnel to permit the buildup of a boundary layer in which the model studies can be conducted. A 1 to 300 accurate scale model of a portion of Yaquina Head on which one of our anemometers is located has been constructed and is ready for insertion in the tunnel. The enlarged tunnel, with its 5- by 4-foot test section 30 feet long, is shown in figure 8. Other information is also available (ref. 3).

TERRAIN MODIFICATION

One area to be investigated by wind tunnel studies is the possibility that terrain modification may result in appreciably augmented average wind speeds. The concept that will be explored is illustrated in figure 9. The diagram is self-explanatory.

AEROGENERATOR ARRAYS

Another area for exploration is the pros and cons of arrays of aerogenerators, especially of inexpensive, mass produced vertical rotor units. An inexpensive variant of the Savonius rotor is sketched in figure 10. The vertical hemicylinders, in sections of appropriate length, would consist of corrugated steel culverts cut in half. An array of such units is sketched in figure 11. The system of vertical rotors is maintained by guy wires as shown; the only compression members are the vertical shafts of the rotors which are themselves stiffened by the four hemicylinders. Each rotor drives directly, without the need for slip rings, a multipole generator of modern design which is housed below grade in a suitable enclosure.

Although the efficiency of such units is low, this may be more than offset by low cost and the need for little maintenance. Such arrays may be much larger than the one illustrated.

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2. Golding, E. W.: The Generation of Electricity by Wind Power. London, E. & F. N. Spon, 1955.

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DISCUSSION

Q: Professor, with respect to the electric utility industry, would you care to comment with reference to future, what the common objectives are?

A: The Oregon PUD Directors Association allocated $150,000 over three years. At the end of the end of this period they will probably consider a pilot program to get at least one windmill running.

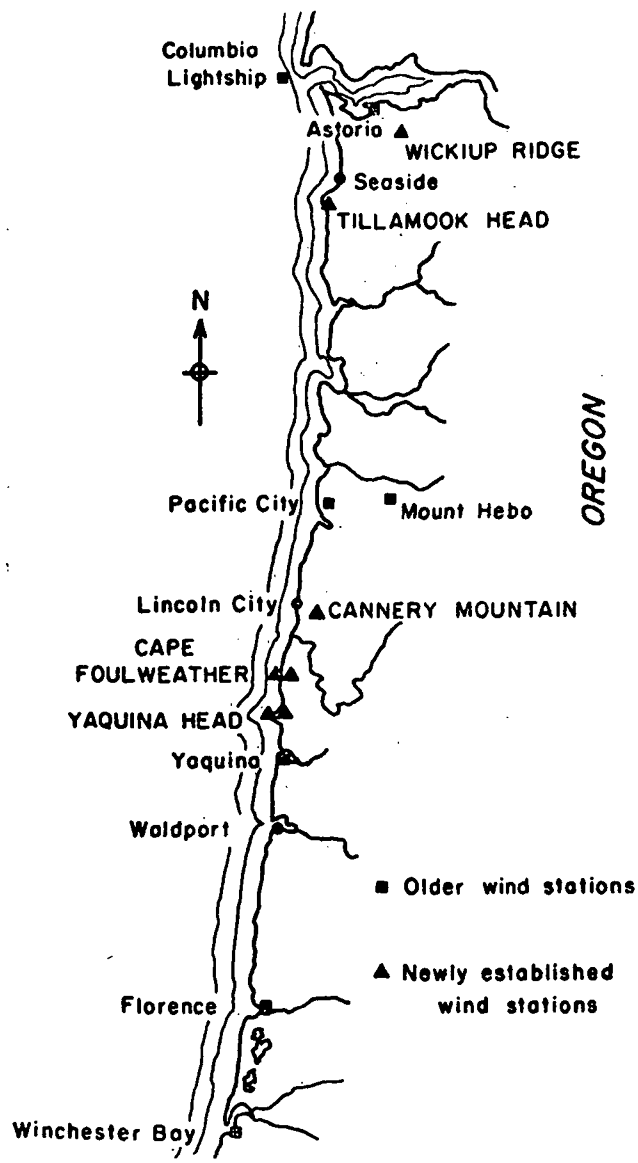

Fig. 1 Wind stations on or near the central and northern portions of the Oregon coast.

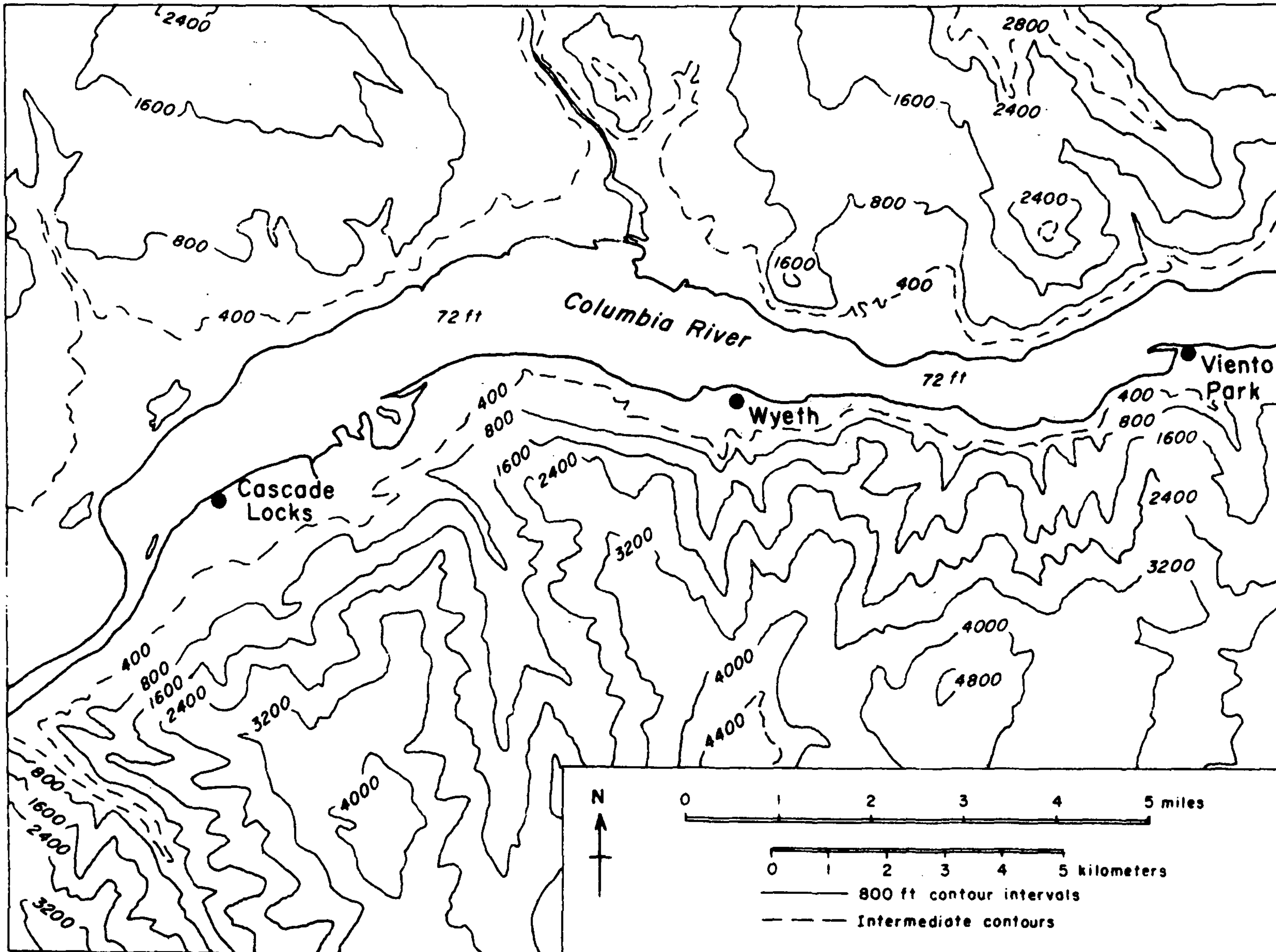

Fig. 2 The Columbia River Valley near Cascade Locks, Wyeth and Viento Park.

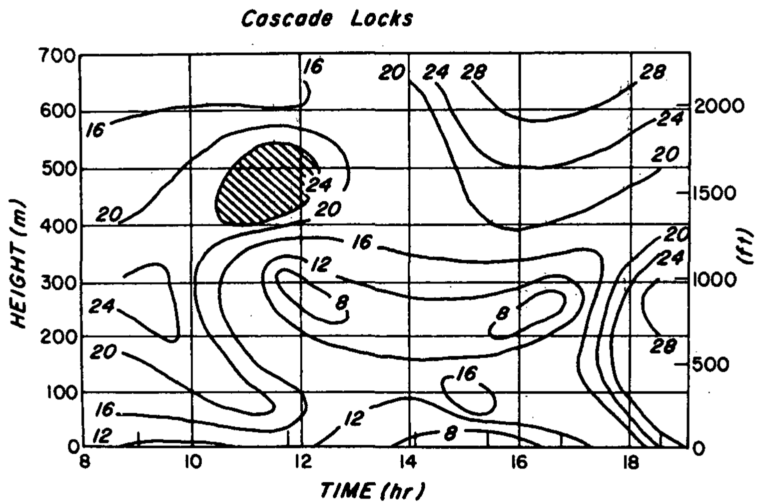

Fig. 3 Isolines of equal up valley wind speeds in knots on September 5, 1972 at Cascade Locks, Oregon

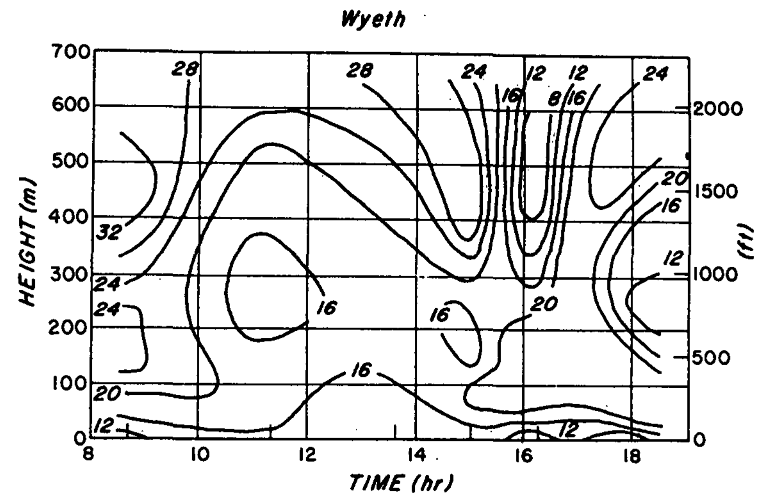

Fig. 4 Isolines of equal up valley wind speeds in knots on September 5, 1972 at Wyeth, Oregon

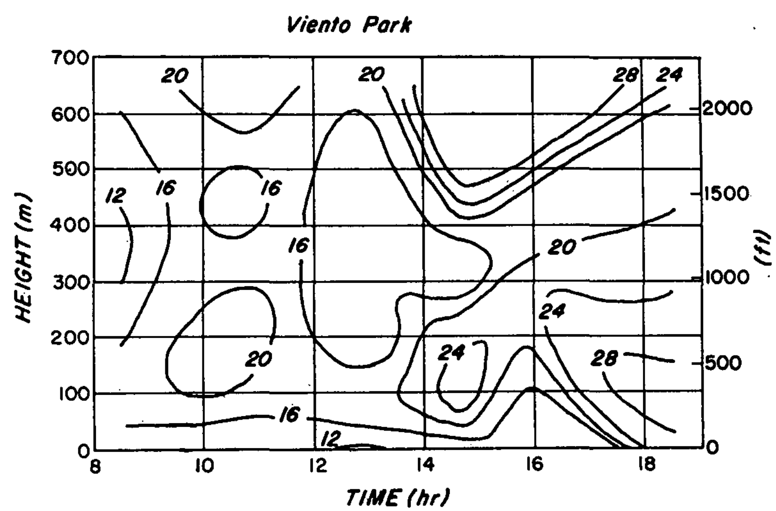

Fig. 5 Isolines of equal up valley wind speeds in knots on September 5, 1972 at Viento Park, Oregon

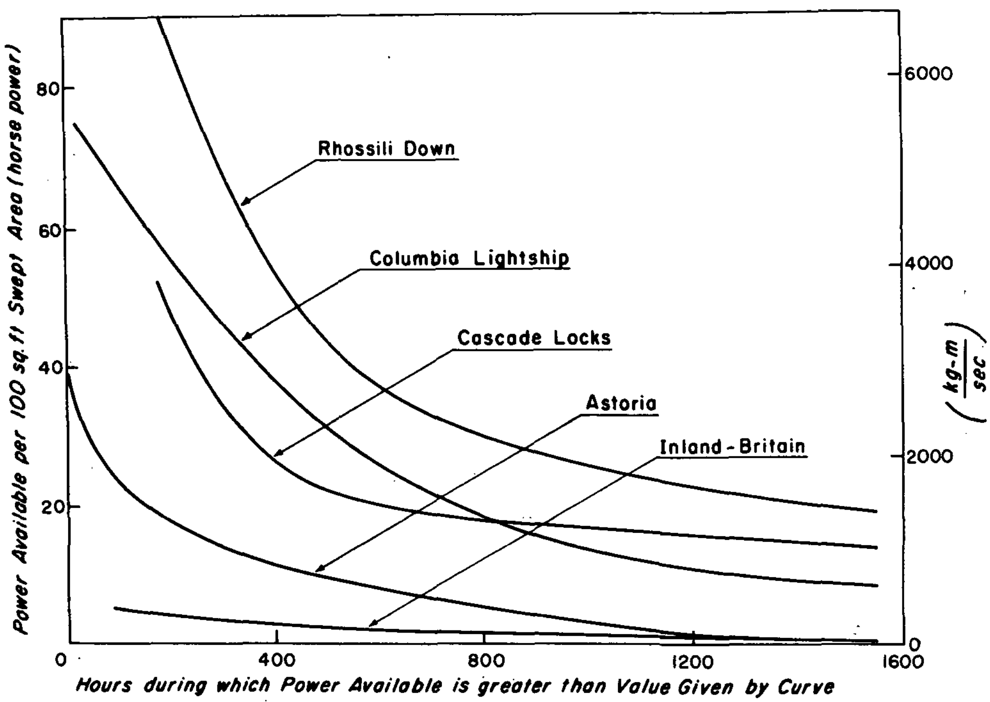

Fig. 6 Wind power duration curves for: Rhossili Down, Wales; the Columbia Lightship off the mouth of the Columbia River; Cascade Locks, Oregon; Astoria, Oregon near the mouth of the Columbia River; and an inland site in Great Britain.

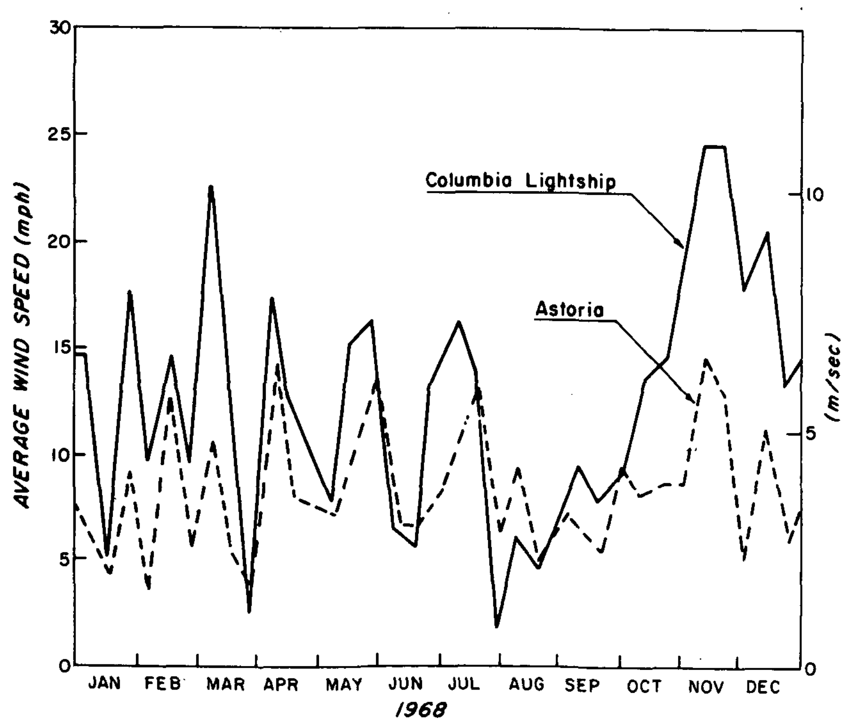

Fig. 7 Comparison of 1968 wind speeds at the Columbia Lightship with those at the nearby coastal station of Astoria

Fig. 8 The exterior of the test section of the wind tunnel; direction of air flow is from left to right.

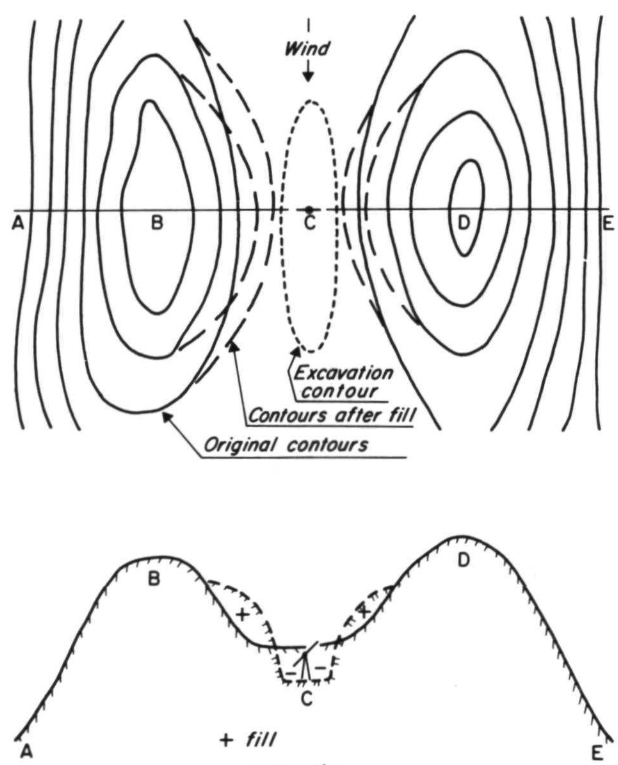

Fig. 9 Proposed type of terrain modification for the purpose of augmenting average wind speeds

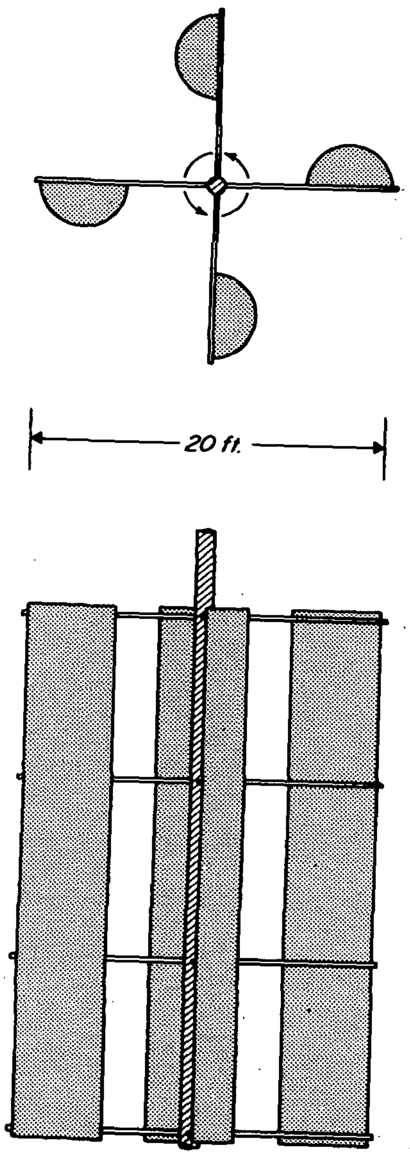

Fig. 10 A variant of the Savonius vertical rotor

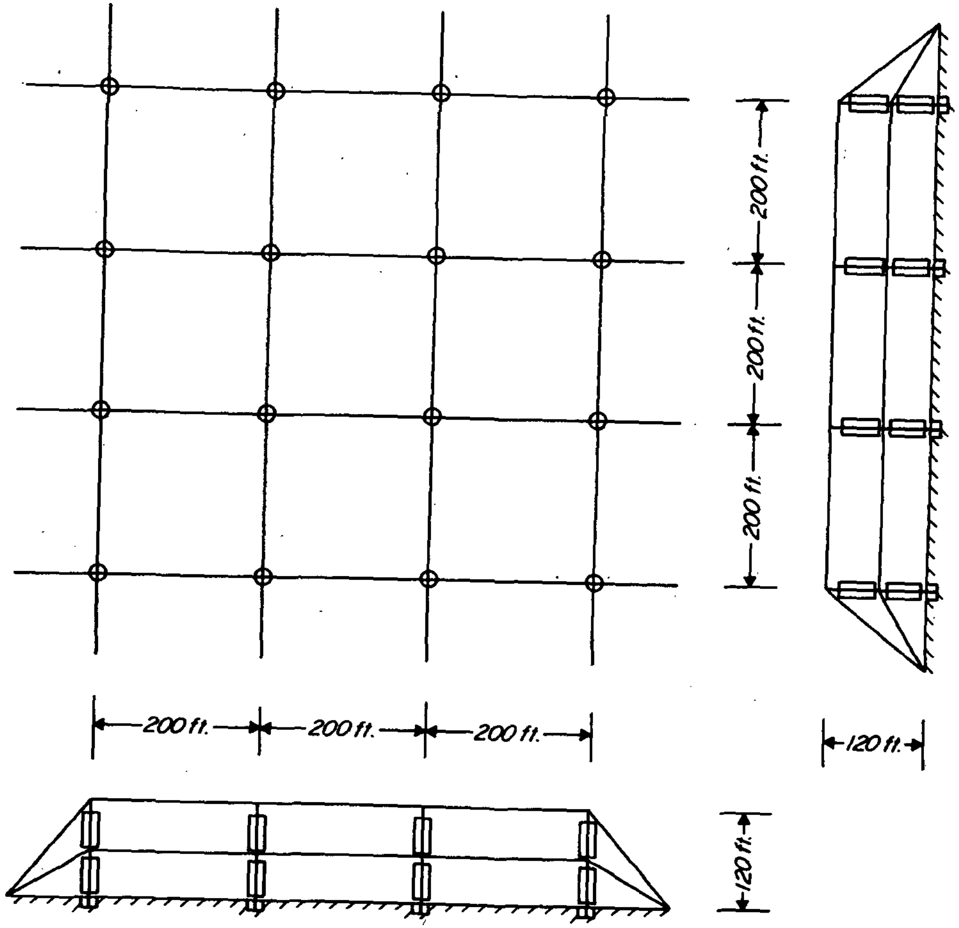

Fig. 11 A guyed array of inexpensive vertical rotor aerogenerators

WIND DATA FOR WIND DRIVEN PLANT

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Surrey, England

To obtain the best performance with any type of machine, it is essential to have a good understanding of the fuel used. It is also necessary, for the broader view, to know where that fuel can most readily be found, the rate at which it can be extracted and used, and the magnitude of the resource. This is as true with wind as with any other fuel, except that this resource does not reduce with use.

What data do we have on wind? We know that of the 1.5×10^{18} kilowatt-hours (kW-hr) of solar energy falling on the Earth annually some 26000×10^{12} kW-hr are converted to air in motion and that a small fraction of what is accessible in the first 100 meters or so above the Earth's surface should provide a resource at least equivalent to the world water power reserves.

Wind is not distributed evenly over the globe, being on the average more plentiful in the temperate and polar latitudes and, almost everywhere, higher in coastal areas than inland for the same type of terrain. (See fig. 1) This same picture is shown in a more local context by the "isovent" map of the British Isles. (fig. 2) This type of map is produced from standard MO (Meteorological Office) data, based on standard MO anemometers, supplemented by spot readings in some sites and by visual observations reported on the Beaufort scale. It relates to open situations in level country at 10 meters above ground. Its use for wind power purposes is to indicate areas that are worthy of further exploration.

Why do we need to explore further? Simply because, if wind regimes much better than those indicated by the isovent map cannot be found, there is no economic case for wind power use at present day fuel prices. What must be found are sites where the specific output of wind-driven plant rated at wind speeds of around 15 meters per second (30 to 35 mph) is between 3500 and 4500 kW-hr/kW. Typical velocity-duration and power duration curves for such sites are shown in figure 3. Analysis of a large number of curves of this type shows that their shape does not differ widely and that there is, for any given rated wind speed, a roughly linear relationship between specific output and mean annual wind speed (fig. 4). It is not, therefore, necessary to use elaborate recorder equipment at each and every potential wind power site.

An adequate, and economic procedure in any geographical area is to make comprehensive measurements, including hourly mean values, at one site and obtain only weekly or monthly integrations of wind at a series of others.

The type of anemometer used is not of particular importance, but it is preferable to use identical types for all the general wind survey work.

How should we choose these sites? All past experience indicates that smooth-shaped hills with all-round exposure provide mean wind speeds well above the average for the surrounding countryside. In temperate and northern latitudes, hills below the normal winter snowline are preferable. It may be that studies of the ecological evidence, as suggested by Putnam, will help in the initial choice of site, but such evidence is not always available. Typical hill sites in the British Isles show average annual wind speeds 35 to 50 percent higher than at lowland measuring stations. Characteristic of the best sites is a slope of about 1 in 3½ (16^{o}) in the final few hundred meters approach to the summit and the absence of a flat top to the hill. Conical shaped hills are preferred to ridges. Another advantage with such hills is the reduction in the vertical wind gradient. In level country of average roughness, and with neutral stability, the exponent of the gradient is about 0.17 (i.e., $\overline{V} \sim h^{0.17}$ where $\overline{V}$ is the mean hourly wind speed and h the height above ground). This is undesirable for aerogenerator operation since it imposes additional cyclic loads on the wind rotor. On ideal sites, because of the compression of the streamlines over the summit, this gradient is reduced, certainly in the first 50 meters, to give values of the exponent of 0.05 or less. For slopes of 1 in 6 the exponent is around 0.10 and for very shallow slopes, it approaches the value for level country.

All of this information can be obtained from hourly mean wind speed data.

To obtain useful data for structural design purposes requires, in the first instance, more detailed information, such as can be provided by sensitive anemometers installed in vertical and horizontal arrays on one or more typical wind power sites. Since the earlier wind power work was undertaken, considerable advances have been made in the collection and analysis of short-term wind data and its use for structural design purposes. The aerogenerator designer can benefit from these advances.

Associated with the period of 1 hour over which means are generally taken, there is a continuous random signal comprising the fluctuations of the wind about that value. These "gusts" need to be described, and to do this the methods developed in communications and control engineering, based on probability theory and statistical techniques, can be applied. By separating the gust vector from the mean, the rms gust speed and intensity of turbulence can be calculated. This leads to the important conclusions that the former is virtually independent of height and that the latter decreases with height (figs. 5 and 6).

Next, for a dynamical approach to wind loading, it is necessary to describe the evolution of gust velocity in time and its variation in space. The time structure of random signals (in this case gusts) can be described by the auto-covariance function, or by a normalised version known as the auto-correlation function. The latter is a measure of the information a gust component at one instant of time gives about the value at a later time. Gust properties can also be described by means of power spectra, an extension of Fourier analysis principles to non-periodic random signals. The power spectrum of a signal can be defined in terms of the contribution to the total variance coming from simple harmonic components in a defined band width of the continuous spectrum centred about a given frequency. It has been shown that the power spectrum of the longitudinal gust component can be fitted into a simple expression having as parameters the hourly mean wind speed at 10 meters and the surface drag coefficient. Typical gust spectra are shown in figure 7.

Results so far obtained confirm that the power spectrum provides a description of the evolution with time of the random gust velocity adequate for many structural loading problems.

Also important are the space average properties of gusts, and these can be obtained from cross-correlations for zero-time lag, which provide a measure of the relationship between simultaneous values of gust components at different points. These can be combined with the time relationships to show correlations at different points for different time lags (see fig. 8). Application of these methods to aerogenerator design could overcome past difficulties of relating wind behaviour to structural performance.

Finally, it is useful to accumulate data on extreme wind speeds in order to assess the likely probability, or return period, of any given value that may be relevant to the machine or tower design. However, because present techniques require the collection of maximum values of wind speed over many years, it will initially be necessary to learn what we can from less windy sites where such information is at present available. The technique is straightforward; the highest values for each year of the period are ranked in order from lowest to highest, a plotting position is calculated, as is the reduced variate (see fig. 9). The results can then be plotted (fig. 9(a)) and confidence limits drawn in. The hourly mean values are immediately meaningful; the gust values are so only if the term "gust" is defined. What may be more useful is to derive the probable values of short-term means from the hourly mean values. For level country inland the following relationships are typical.

	60 min mean	10 min mean	1 min mean	20 s mean	5 s mean	0.5 s mean
V_{max}/V_{mean}	1.0	1.06	1.33	1.36	1.47	1.59

For good wind power sites the ratios of the shorter term means to the hourly means will probably be less than these; a full examination of wind data from such sites is lacking.

The relative importance of extreme wind speeds to wind driven plant has not been established. Under these conditions the plant will be shut down and loading on the rotor and the tower could well be less than under full power conditions. Extreme data for low level sites in the UK are shown in figures 10 and 11.

Summarizing, the use of simple, averaged data will provide information on energy availability, facilitate site selection and enable appropriate operating ranges to be established for wind-driven plant. It will also provide a basis for the prediction of extreme speeds. For structural design purposes the more detailed shorter-term data are required, and more sophisticated methods of analysis must be utilized and applied.

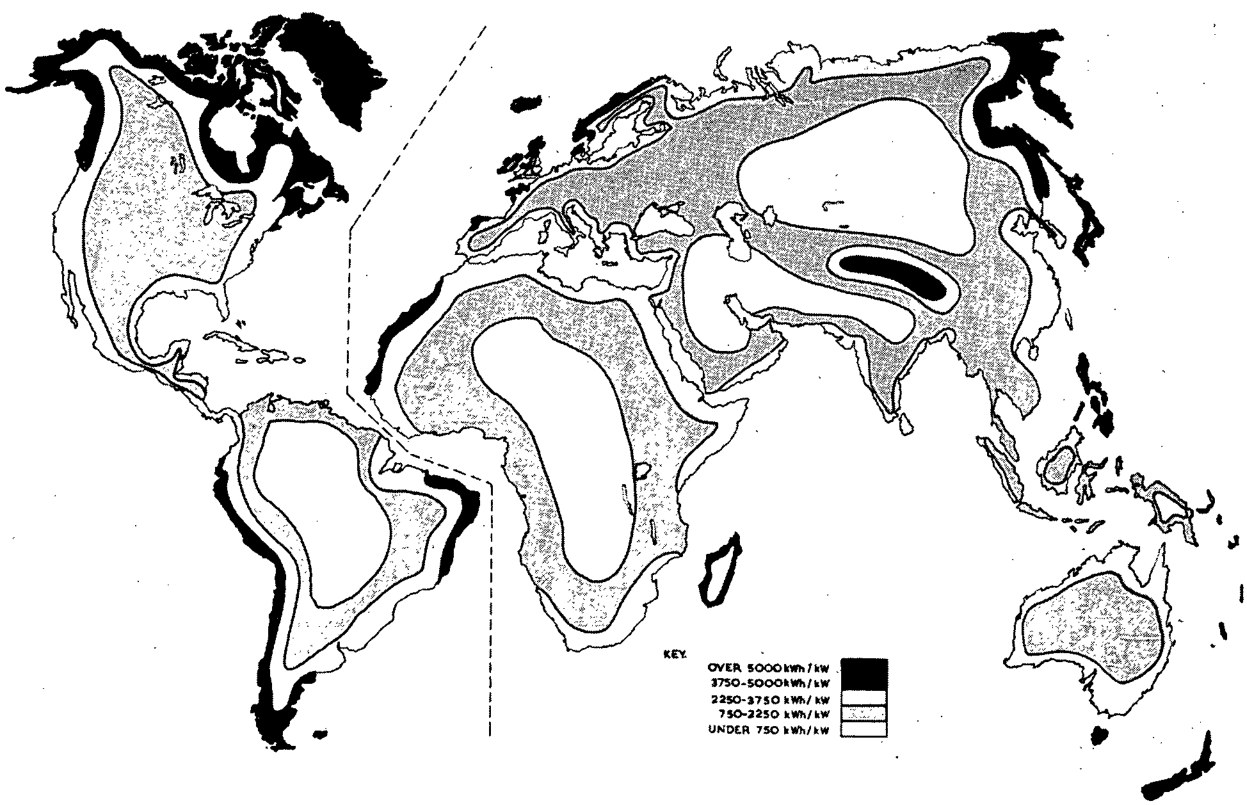

Fig. 1.—**Availability of wind energy**
Annual specific output of windmills rated at 25mile/h

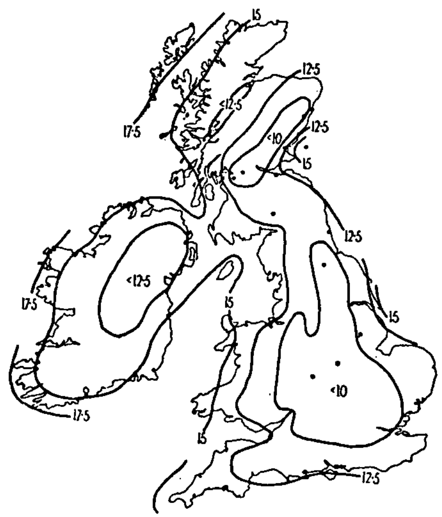

Fig. 2.—Isovent map of the British Isles. Annual mean wind speed given in mph.

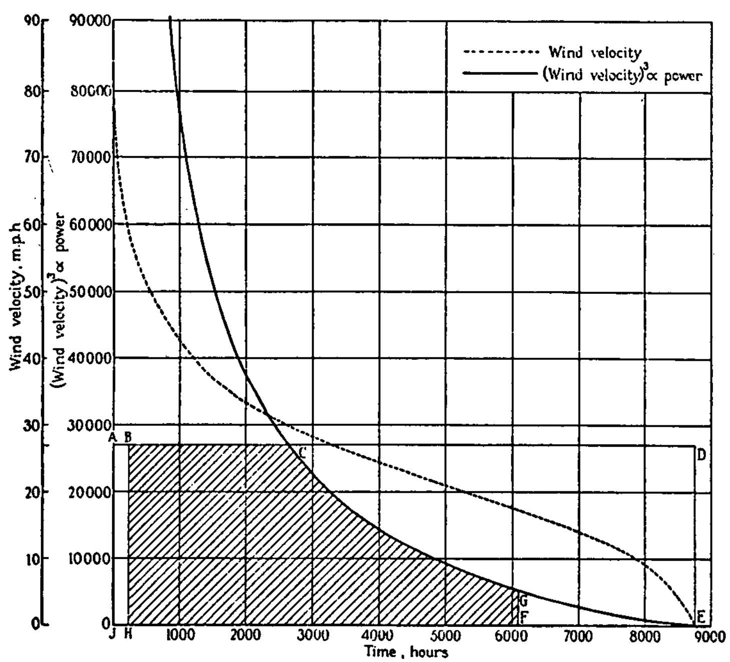

Fig. 3.—Velocity- and power-duration curves typical of an excellent site.

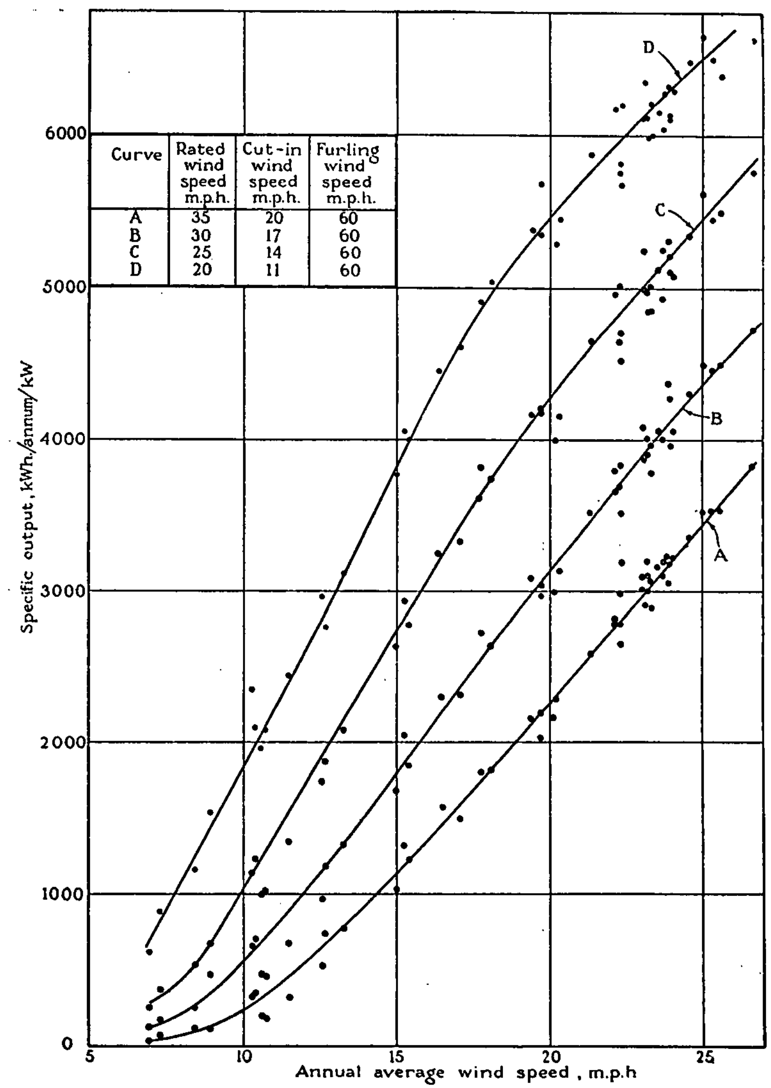

Fig. 4.—Relationship between the specific output and annual average wind speed at sites in the British Isles.

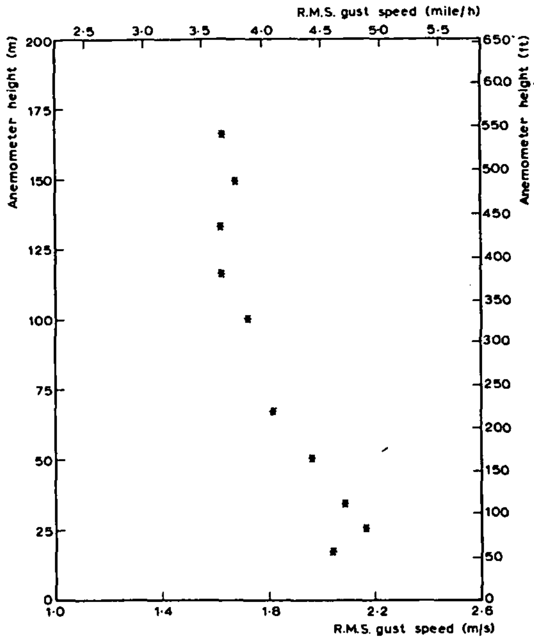

Figure 5 *R.M.S. gust speed measured at Rugby*

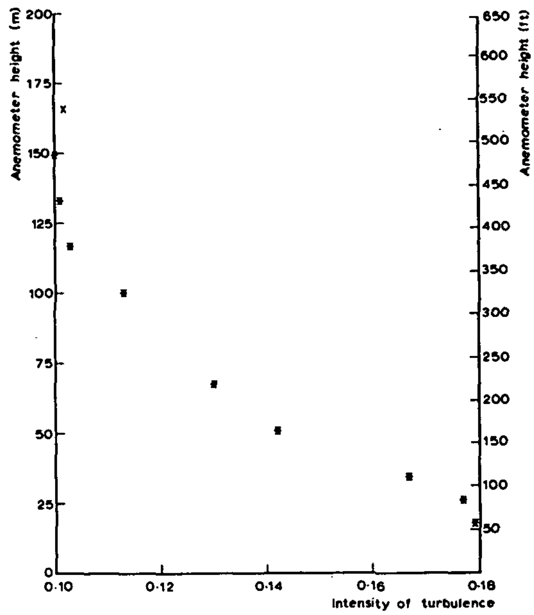

Figure 6 *Intensity of turbulence measured at Rugby*

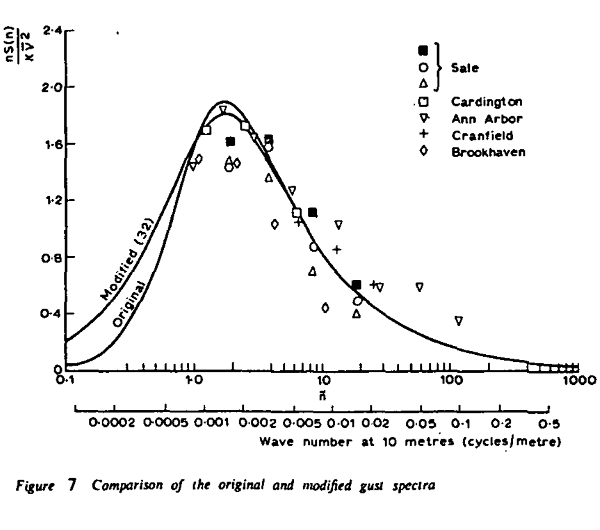

Figure 7 *Comparison of the original and modified gust spectra*

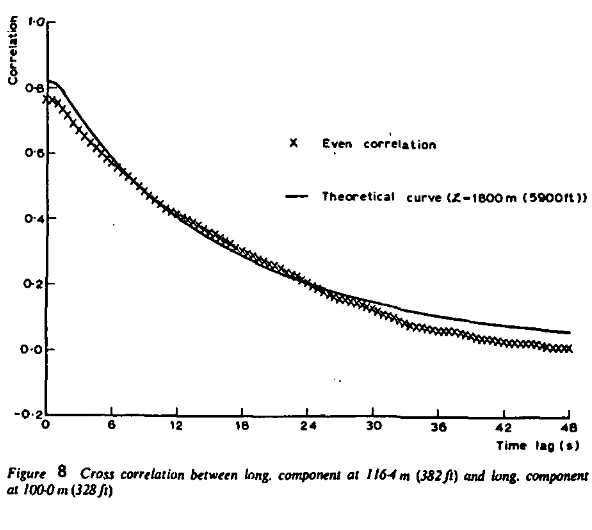

Figure 8 *Cross correlation between long. component at 116·4 m (382 ft) and long. component at 100·0 m (328 ft)*

ANNUAL MAXIMUM WIND SPEEDS (GUSTS) AT CARDINGTON, 1932–54

RANK m	HIGHEST GUST x m.p.h.	YEAR	PLOTTING POSITION $p = \frac{m}{N+1}$	REDUCED VARIATE $y = -\log_e(-\log_e p)$
1	55	1953	0·042	−1·16
2	59	1950	0·083	−0·81
3	60	1941	0·125	−0·73
4	61	1951	0·167	−0·58
5	62	1952	0·208	−0·45
6	63	1937	0·250	−0·33
7	63	1939	0·292	−0·21
8	64	1942	0·333	−0·09
9	65	1933	0·375	0·02
10	67	1949	0·417	0·13
11	68	1948	0·458	0·25
12	69	1945	0·500	0·37
13	71	1940	0·542	0·49
14	72	1934	0·583	0·62
15	72	1944	0·625	0·75
16	76	1954	0·667	0·90
17	78	1943	0·708	1·06
18	78	1946	0·750	1·25
19	81	1932	0·792	1·46
20	82	1936	0·833	1·70
21	86	1938	0·875	2·01
22	88	1935	0·917	2·44
23	93	1947	0·958	3·15

Figure 9

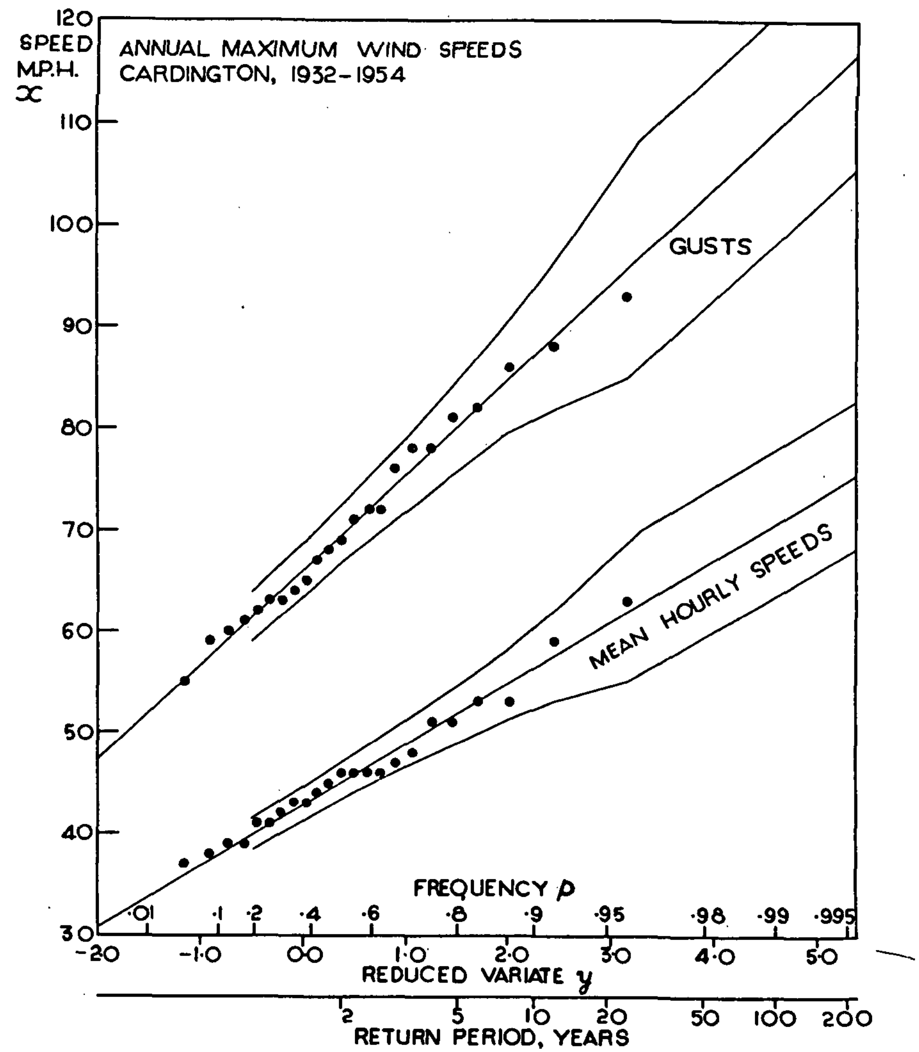

Figure 9(a)

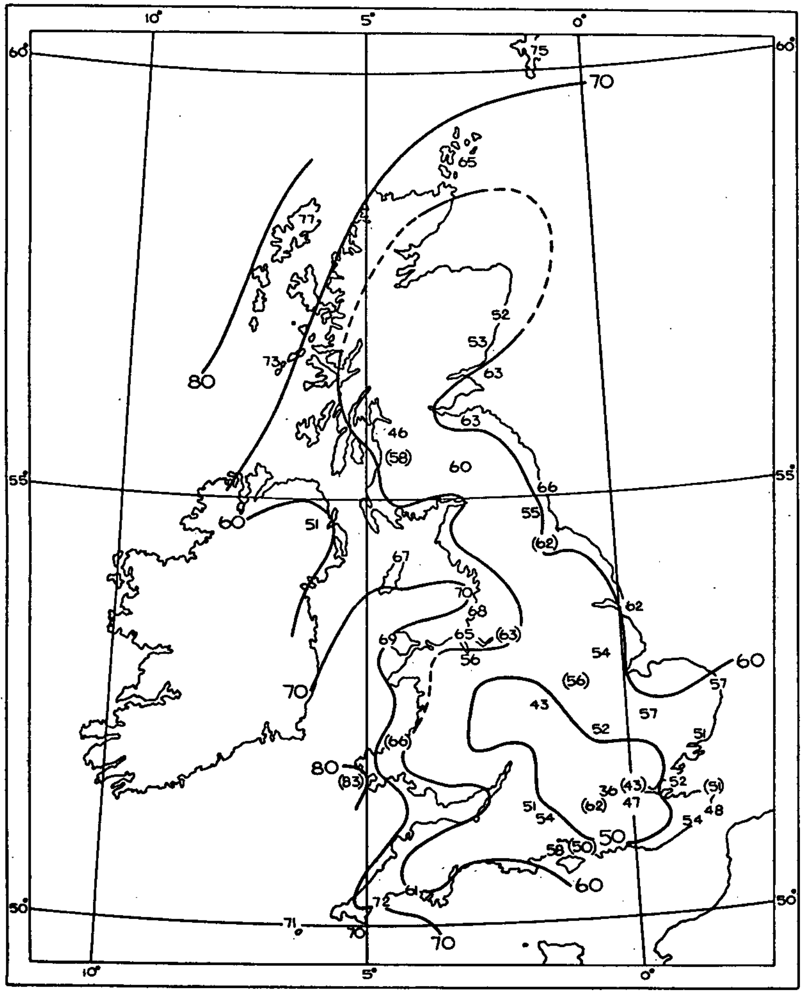

Fig. 10 HIGHEST MEAN HOURLY WIND SPEED AT 33 FT. LIKELY TO BE EXCEEDED ONLY ONCE IN 50 YEARS M.P.H.
(VALUES BASED ON LESS THAN 15 YEARS OF RECORD BRACKETED)

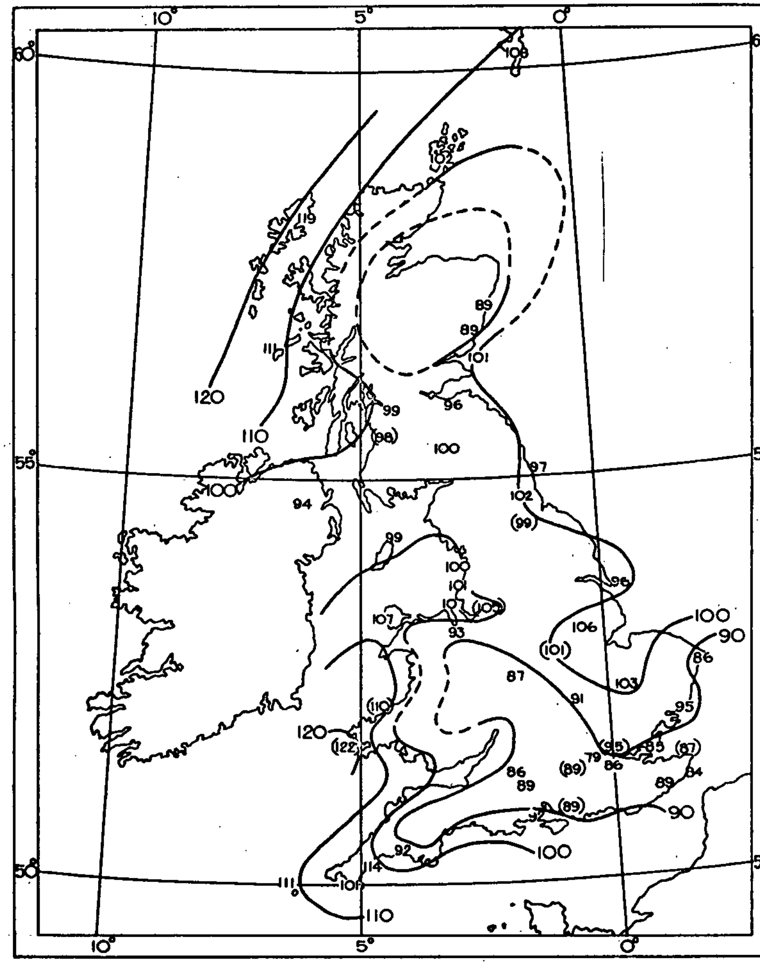

Fig. 11 HIGHEST GUST SPEED AT 33 FT. LIKELY TO BE EXCEEDED ONLY ONCE IN 50 YEARS M.P.H.
(VALUES BASED ON LESS THAN 15 YEARS OF RECORD BRACKETED)

AN INTRODUCTION TO THE PRINCETON SAILWING WINDMILL

T. E. Sweeney and W. B. Nixon

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Generally discussed is the Princeton University interest in a wide range of wind machines. Specifically discussed is one example of the work - the Sailwing windmill. The aerodynamic characteristics of the Sailwing itself are presented in condensed form and its natural application to the wind machine is discussed. Past and present Sailwing windmill configurations are shown and their relative merits are compared. A section on a future promising configuration is presented and its compatibility to advanced technology electrical machinery is briefly discussed. Also included is a short bibliography.

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DISCUSSION

Q: What is a reasonable size for one of these sails? Could you get up to 100 feet or so?

A: Possibly, but there is a crossover point. We had studied it in reference to the entry body back when we were talking about Skylab: fixed wing versus something you could fold up. If you send up heavy big loads, the structure get so heavy, that you lose your whole weight advantage. So we're pretty sure we're good at 25, and I would bet 50. When you get to 100 I'm going to leave.

Q: What sort of loadings do you use in a sail application?

A: For the airplane type of application, 10, 12, up to 15 pounds per square foot, rather light.

Q: On the aerodynamic comparison between the solid and the sailcloth type of configuration, the difference there is that you built the solid rotor the same as the sail one. If you did, it should have the same characteristics.

A: Yes, the characteristics would be the same if a conventional metal wing could crinkle and bend the way a sailwing does. The advantage of the sailwing is its flexibility.

L.E. = Leading edge
T.E. = Trailing edge

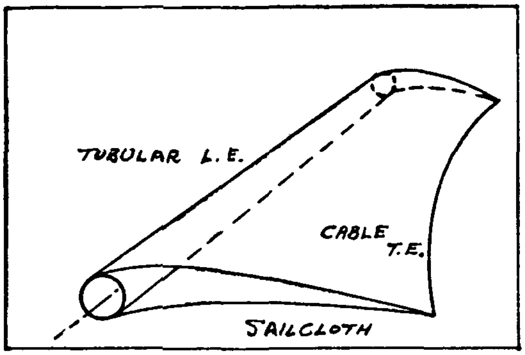

Fig. 1

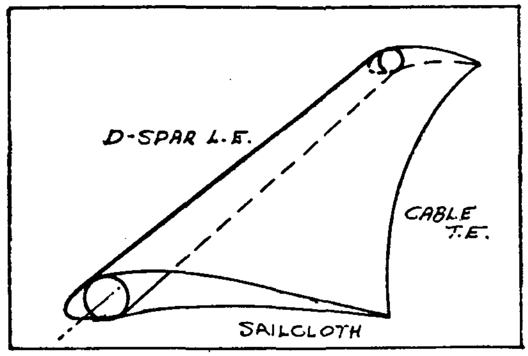

Fig. 2

Sail wing types of blade

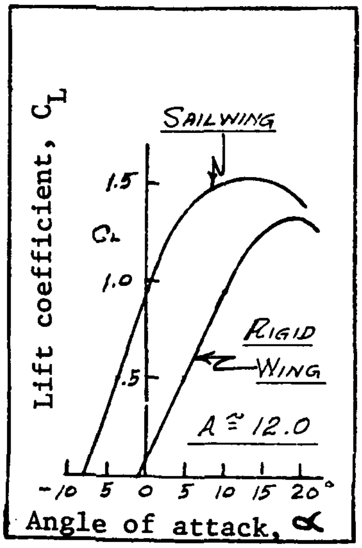

Fig. 3a

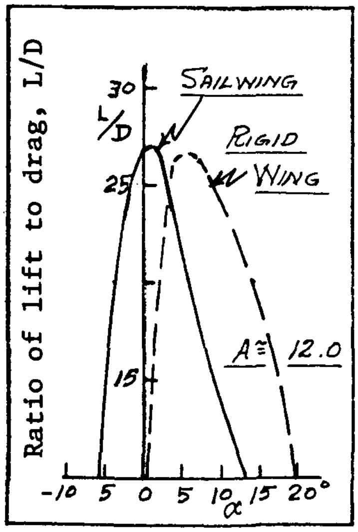

Fig. 3b

Aerodynamic characteristics of sail-wing airfoil

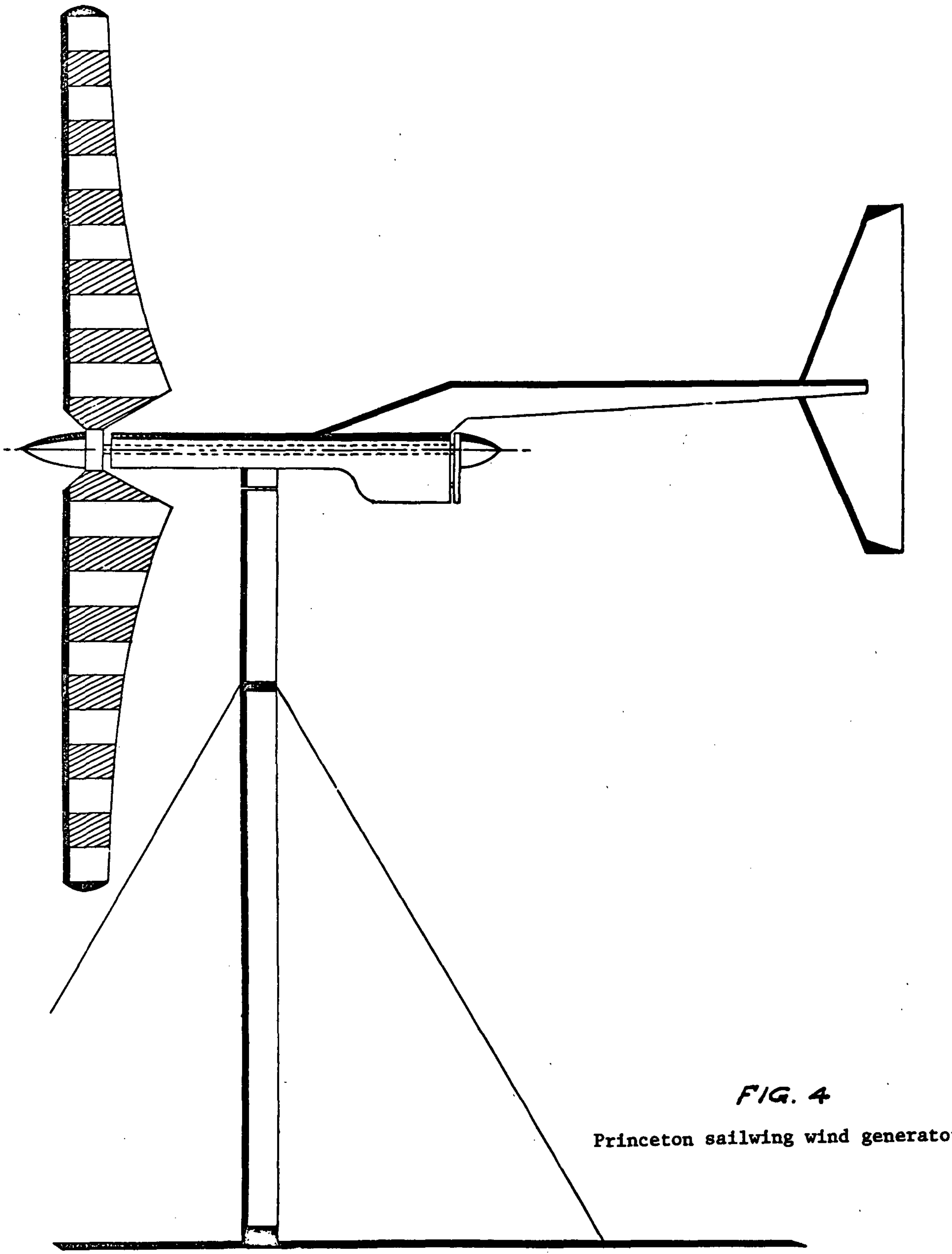

FIG. 4

Princeton sailwing wind generator

THE USE OF PAPER HONEYCOMB FOR PROTOTYPE BLADE CONSTRUCTION

FOR

SMALL TO MEDIUM-SIZED WIND DRIVEN GENERATORS

Hans Meyer

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Windworks, under the sponsorship and direction of R. Buckminster Fuller, began working on wind energy conversion systems in 1970. It was decided, in view of the high cost per kilowatt output and the relative difficulty of construction of conventional or existing wind plants, that the first area of emphasis should be in making wind more accessible for experimentation and use.

With this in mind, we began working with paper honeycomb for the construction of conventional, propeller-type, windmill blades. Using fairly simple techniques and conventional power tools, it is possible to shape both simple foils (NACA 4415) and more complex foils (Wortmann FX-60-126 and FX-72-MS-150A) with or without tapered plan forms with or without varying profile. Still more complex geometries can be developed using router techniques developed by Hexcel Corporation.

For blade diameters up to 30 feet, typical costs are as follows:

Honeycomb	$ 0.14/ft^2 of blade
Fiberglass/resin	.90/ft^2 of blade
	$ 1.04/ft^2 of blade
Construction time	8 to 12 hr/blade
Tolerances:	
Paper	± 1/32 in.
Aluminum	± 1/100 in.

The first step of the process is to cut out the blade blank. A block of honeycomb, in its compressed form, is mounted on a wedge and run through a bandsaw with the table at an appropriate tilt angle. It is the combination of the wedge angle and the table angle that gives the tapered plan form and profile shape.

Next the honeycomb is expanded on the shaft and jigged to give the desired angles of attack. With the honeycomb fixed in position, the blade is covered with a fine weave fiberglass cloth. Any surface quality can then be achieved with filling and sanding.

The process, being both simple and low cost, lends itself particularly to prototype work and tool making. In encouraging individuals to use and experiment with wind energy, we hope to increase the support for wind utilization which will be necessary for the acceptance of large-scale developments in this country.

DISCUSSION

Q: In any of your units do you have any feathering mechanisms or do you keep the angle constant?

A: No. But we do have feathering. We have two types: we have Popular Science typical coning -- incidentally, in the U.N. report there's a Japanese windmill for which are shown test results for absolute constant rpm with a mildly sophisticated feathering system. It's a cone windmill running downwind with variable pitch, and they have been able to run that at constant speed regardless of wind velocity.

We've worked on two different types: the coning straightaway, which is an umbrella structure working against a spring with damping, and the flyball governor wherein as the blades move out they rotate. When the windmill shuts down, the blades go into a partial coning position, which increases the starting torque. As it starts up, the blades begin to rotate into maximum power, and then they rotate further into full feather.

Q: What kind of increase in power did you get with the Venturi prototype?

A: We designed for a 50 percent increase in windspeed. We got about a 35 percent increase.

Q: What was the area ratio, minimum and maximum?

A: It had a 6-foot opening, a 5-foot diameter, a 7-foot exit, and an 80-foot length from entrance to exit.

THE SAIL WING WINDMILL AND ITS ADAPTATION FOR USE IN RURAL INDIA

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New Alchemy Institute
Woods Hole, Massachusetts

A 25-foot diameter sailwing windmill was built in 1973 in a small village near Madurai, Tamilnadu State, India. This windmill is the result of design research conducted in the U.S.A. at the New Alchemy Institute--East (refs. 1 and 2) and in India at the Indian Institute of Agricultural Research (refs. 3 and 4) and the Wind Power Division of the National Aeronautical Laboratory (ref. 5). It is to be used mainly in light winds during the dry winter months for irrigating small fields, watering dairy cattle and supplying water for domestic use.

In many parts of India there are adequate supplies of ground water which are unavailable to farmers during the dry season because of inadequate power resources for pumping. Three to eight horsepower diesel pumps are frequently used, but they are expensive to operate because of the high cost of imported oil and often must be taken out of service for costly and time-consuming repairs. Efficient 5-horsepower electric pumps are being used more and more as rural electrification proceeds, but only well-to-do farmers can afford to buy and maintain them. Recently in South India there has been a 75 percent power cut to the rural areas due to heavy use in the cities and to overexpansion of the power grid without a corresponding increase in supply. This power shortage means that there are only 4 hours of electric pumping per day. This situation is expected to worsen for the next 4 to 5 years until the Indian Government begins operation of atomic power plants in South India. At the present time bullock operated pumps remain the most common and reliable source of irrigation water for subsistence farming. Water for domestic use is usually hand-lifted with a rope and bucket from open wells.

During the early 1960's the Wind Power Division of the National Aeronautical Laboratory in Bangalore, Mysore, developed, tested, and produced two hundred 12-bladed fan-type windmills which demonstrate the feasibility of using wind power to pump water to South India (ref. 6). Several types of imported European and American multibladed windmills have also been used to harness India's abundant wind energy resources. However, due to lack of public awareness of the subject and the unavailability of an even simpler and less expensive device, wind power remains only occasionally exploited.

Cloth sails with a wooden framework have been used for hundreds of centuries for transforming the useful energy of the wind into labor saving mechanical work, especially grinding grain and pumping water. The use of windmills spread from Iran in the seventh century A.D. to coastal China where the application of the art of sailmaking significantly improved the sophistication of windmill construction (ref. 7). Heavy rigid wood windmill blades surfaced with cloth were increasingly used throughout northwestern Europe so that by the seventeenth century the Netherlands became the world's richest and most industrialized nation, largely as a result of extensive exploitation of windpower with ships and windmills. Cloth was a natural choice for windmill sails because of its acceptance and wide use in sailing ships. It is lightweight, easy to handle, readily and cheaply available, and most importantly it forms a strong uniform surface for catching the wind when firmly supported at three or more points.

In the Mediterranean region flour-grinding and oil-pressing mills were rigged with six to twelve triangular cloth sails set on simple radial spars. A three-dimensional array of guy ropes radiating from a central spar projecting out along the axis of the main shaft suspended the sails in position, rather than a heavy grid of wood as was used in the traditional Dutch-type windmills. This sailboat jib type of rigging was a significant improvement in windmill design which encouraged the spread of windmills throughout the deforested Mediterranean countries. The wind capturing area of these windmills was controlled by wrapping each cloth sail around its spar. Though requiring daily rigging adjustments and occasional replacement of tattered sails, the efficiency and simplicity of these windmills resulted in their widespread use in Rhodes, the Black Sea coast, the Aegean Islands, and Greece. In Portugal their use was accompanied by the sound of whistles attached to the rigging, an audible indicator of the wind at work. In the West Indies large sailing windmills were commonly used for crushing sugar cane (ref. 8). Many handcrafted windmills with eight triangular jib sails are presently pumping irrigation water in the Plain of Lassithi, Crete (ref. 9). In Japan four-bladed jib sail windmills are used to operate reciprocating pumps which supply water to vegetable gardens. A high-speed aerodynamic, two-bladed sail wing is being developed (refs. 10 and 11). Further construction simplifications may make it applicable to use in lesser developed countries.

A windmill with four self-adjusting cloth sails was developed for rural markets in less industrialized regions (ref. 12). Its relatively complex design is limited because of the difficulty in connecting it to a deep well pump. Unfortunately, it cannot be manufactured by hand using local materials. Those people who are in a situation to most benefit from a windmill are also those least able to pay for it. If the critical moving parts were separately available, a small farmer could purchase the remaining materials needed and assemble the windmill in his own village using local skills and labor. This way a major portion of the money spent would remain in the village.

The 8-meter-diameter prototype sail wing windmill recently erected on a small peanut and sesame farm in a dry hilly region in South India lifts 300 pounds to a height of 20 feet in 1 minute in a 10 mph wind. This is accomplished by a rope passing over a 6-inch pulley on the main drive shaft. This lift is used to lift soil and rock from the well being hand dug below the windmill. The windmill will be set up to operate a modified paternoster or chain pump like those used to drain mines in England many years ago. Recently chain pumps have been rapidly replacing the traditional square-pallet pump and the noria water lifting wheel throughout China. A chain pump, easily and cheaply built, is more efficient than most types of pumps. Most importantly, it operates well with a low-speed, variable power source.

This sail wing windmill is made of a 1-meter-diameter bullock cart wheel to which three bamboo poles are lashed in a triangular pattern with overlapping ends. Each bamboo pole forms the leading edge of a wing, and a nylon cord stretched from the outer tip of the pole to the rim of the wheel forms the trailing edge. A stable and lightweight airfoil results from stretching a long narrow triangular cloth sail over that bamboo-nylon frame. This wing configuration, a hybrid of low-speed eight-bladed Cretan sail wings and high-speed two-bladed aerodynamic sail wings, produces high starting torque at low wind speeds. The bullock cart wheel is attached at the hub to the end of an automobile axle shaft which rotates in two sets of ball bearings. The shaft and bearing assembly is mounted horizontally on top of a turntable. The turntable consists of two circular steel plates separated with a raceway of ballbearings and held together with a ring of eight bolts which encircle the bottom plate. A 1-foot diameter hole through the center of the turntable will allow the chain and gaskets of the chain pump to go up and around the "squirrel cage," which is mounted at the center of the automobile axle. If a reciprocating, deep-well piston pump were desired, the reciprocating rod, rather than a chain, would go through this hole and the crankshaft rather than an axle shaft would be mounted on top of the turntable. Since the blades have a slight built-in coning effect and the axle or crankshaft is mounted slightly off center from the centerline of the turntable, the blades act as their own tail, trailing in the wind. Because the blades are downwind from the tower, there is no danger of the bamboo poles bending in a monsoon wind and hitting the tower. The tower is made of five 25-foot long teak poles set in concrete at the base and bolted at the top to five angle irons welded at a slight flaring angle to the bottom of the turntable. The tower tapers in towards the turntable at the top from a 7-foot diameter at the base. It has cross bracing and a ladder.

It is hoped that other persons will continue to refine and adapt this windmill to their own needs and materials. Please send all inquiries, operating experience, and suggestions for improvement to: Marcus M. Sherman, New Alchemy Institute--East, Box 432, Woods Hole, Mass. 02543.

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THE SAIL WING WINDMILL
AND ITS ADAPTATION FOR USE
IN RURAL INDIA

Figure 1

ROTOR DYNAMIC CONSIDERATIONS FOR LARGE WIND POWER GENERATOR SYSTEMS

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Practical large-scale wind power generating systems must be competitive in terms of energy cost. Low available wind energy per unit area demands efficient aerodynamic design, a location with high mean wind velocity, and proper integration with established power grids. Also essential for low initial and operating costs are reliable, lightweight, mechanically simple designs requiring a minimum of maintenance. To a large extent, these qualities depend on the dynamic loads and vibratory stresses of the rotor/tower structure that, for very large wind turbines, will probably constitute the ultimate design constraints.

In many respects the dynamic properties of large wind turbines will be similar to helicopter rotors where cost, reliability, vibration, etc., are also of primary importance. Although some differences exist, much of today's helicopter rotor technology is applicable to the design of wind power systems. Based partly on this experience, the following comments are offered to provide some understanding of the dynamic properties of large wind turbines and suggest some possible design concepts.

DETERMINATION OF VIBRATORY LOADS

Vibratory loads and stresses result from unsteady aerodynamic, inertial, and gravitational forces which act on the rotor/tower structure. If this structure is ideally rigid, vibratory loads and stresses can be easily determined from known applied forces. For real flexible structures, elastic deformations contribute additional aerodynamic and dynamic forces, and the determination of vibratory stresses is considerably more difficult. If exciting forces occur at frequencies near the natural frequencies of the structure, resonance may seriously amplify dynamic loads.

Principal Structural Deformations

The elastic deformations of the rotor blades and tower structure are shown schematically in figure 1. In this example the blades are shown cantilevered to the rotor hub, but similar deformations occur for articulated (hinged) blades. Structural deformations include flap and lead-lag bending of the blade perpendicular and parallel to the plane of rotation, respectively, blade torsion or elastic twist, vertical and horizontal bending of the rotor shaft (not shown in fig. 1), and bending and torsion of the tower structure. The importance of these elastic deformations will be dependent on the degree of flexibility of the rotor/tower structure.

Rotor Blade Frequencies

The vibratory loads and stresses of a rotor system depend to a large extent on the natural frequencies of the structure. Some understanding of the dynamics of a single rotor blade can be obtained from the linear bending-torsion equations (ref. 1) that determine the rotating natural frequencies.

Flap: $$-(\underline{Tw'}) + EI_y w'''' + m\ddot{w} = L_z$$

Lead-lag: $$-(\underline{Tv'})' + EI_z v'''' + m(\ddot{v} - \underline{\Omega^2 v}) = L_y$$

Torsion: $$-GJ\phi'' - \underline{k_A^2(T\phi')'} + mk_m^2\ddot{\phi} + \underline{m\Omega^2\left[k_{m_2}^2 - k_{m_1}^2\right]}\phi = M_\phi$$

where $T' = -m\Omega^2 x$.

Flap and lead-lag deflections are given by w and v, respectively, and torsional deflection by ϕ (See fig. 1.) The effects of centrifugal tension and stiffening due to rotational velocity Ω are underlined. The remaining terms are due to bending stiffness (EI) or torsional rigidity (GJ) and inertial forces due to blade mass m. The forces and moment L_z, L_y, and M_ϕ applied to the blade are caused by aerodynamic, inertial, and gravitational forces. When these applied forces are not retained, the homogeneous equations define the blade natural frequencies and mode shapes. Rotor-blade frequencies are typically displayed in dimensionless form as a function of the normalized rotor speed. A typical example is sketched in figure 2. The frequencies and rotor speed are normalized by the nominal or rated operating speed Ω_o. The frequencies correspond to the fundamental and higher modes of bending and torsional deformations and they increase with rotor speed because of centrifugal stiffening. Also shown on this plot are frequencies of the applied blade forces which occur at integer multiple harmonics of the rotor speed (such as one per revolution, twice per revolution, ..., or, 1P, 2P, ..., for short). These applied forces will exist whenever the rotor blade is not uniformly loaded around the azimuth, for example, nonaxial wind components, gravity forces, rotor disk tilt, or shaft precession. Generally, the applied forces diminish with increasing harmonic number.

The significance of this figure is that resonance and severe vibratory stresses may occur when a blade natural frequency is close to the frequency of an applied force. Therefore, the rotor blade must be designed to avoid such resonances to achieve low fatigue stresses and long life. One difficulty is that during operation below rated speed, or with ungoverned wind turbines, it is virtually impossible to avoid a resonance at some speed. This may preclude operation at that speed if severe vibratory stresses result.

DYNAMICS OF LARGE ROTORS

The importance of flexibility for vibratory loads and stresses depends partly on the degree of flexibility of the structure. Therefore, the proper questions in discussing wind turbines are:

(1) what parameter best characterizes blade flexibility, and
(2) how does this parameter vary as a function of rotor size?

Perhaps the most appropriate parameter is the dimensionless fundamental blade natural frequency, which depends on the ratio of blade bending stiffness to centrifugal forces $\bar{\omega} \equiv \omega/\Omega \sim \sqrt{EI/M\Omega^2R^4}$.

This parameter establishes the condition for dynamic similarity for a wide variety of rotor blades having large differences in size, stiffness, mass, and rotational speed. It does not, however, account for gravitational forces. The blade natural frequencies are also a good measure of the importance of flexibility on dynamic loads. For very high stiffness or frequency, only low-energy, higher integer harmonic forces will be available to cause resonant vibratory stresses. The low frequency forces will then act on the structure much as static loads. Lowering the blade stiffness and frequencies will tend to relieve high "static" loads but will increase the importance of dynamic response.

It is interesting to compare expected wind turbine blade fundamental flap and lead-lag frequencies with conventional rotor and propeller blade frequencies as shown in figure 3. The conventional fully articulated rotor has very low fundamental frequencies because of the blade hinges. The teetering helicopter rotor with a single hinge has a low flap frequency and a moderately high lead-lag frequency. Other systems include the cantilevered hingeless helicopter rotors and conventional propellers which are relatively stiff. Structural information for large wind turbines are nonexistent and therefore only estimated frequency values can be shown. The lead-lag bending frequency is assumed relatively high in view of the typical low operating speeds of wind turbines, and the need to stiffen large rotor blades against gravitational stresses. Three possible wind turbine configurations are shown:

(1) a teetering or coning hinge design to relieve aerodynamic thrust and hub moments,
(2) a hingeless design to relieve blade root stresses with elastic flap bending, and
(3) a stiff design to withstand aerodynamic loads directly.

These fundamental frequency values must be more precisely known before it will be possible to accurately compare the dynamic load characteristics of large wind turbines with other types of rotor systems.

Scaling Effects for Large Rotors

Sizing trends for wind turbine properties may be deduced from dimensional analysis considerations. For purposes of comparison, a constant level of aerodynamic efficiency at a given wind speed is assumed which in turn constrains the blade tip speed $R\Omega$ to a constant value. For geometrically similar construction then, the rotor parameters will vary with size, or radius R, in the following manner:

Parameter	Proportional to -
Rotor speed	R^{-1}
Blade mass	R^3
Centrifugal force	R^2
Solidity	R^0
Power	R^2
Thrust	R^2
Centrifugal stress	R^0
Aerodynamic stress	R^0
Gravitational stress	R
Dimensional natural frequencies	R^0

These relationships show that the important aerodynamic and centrifugal stresses are independent of rotor size, but that gravity stresses increase in proportion to the radius. The dimensionless natural frequencies remain constant, however, which means that dynamic response and resonant characteristics will not be influenced by rotor size. Interestingly, the power output increases with the square of the radius but blade weight increases with the cube. This is an example of the "square-cube law" that will eventually limit wind turbine size because of diminished power to weight ratio. This factor as well as aerodynamic efficiency trade-offs will alter the ground rules of geometric similarity and constant tip speed as a basis for establishing trends for dynamic properties of large rotors. For example, power losses due to aerodynamic profile drag can be reduced by increasing the rotor solidity and reducing tip speed, but only at the expense of increased blade weight and cost. Improvements in airfoil lift/drag ratio will permit reduced solidity and higher tip speeds. Increased tip speeds would be advantageous for reducing the capacity of the speed-increaser gear needed to step-up the low rotor shaft speed to the electrical generator speed. Although these trade-offs are complex, it will probably be necessary to sacrifice some aerodynamic efficiency to reduce blade size and weight of large wind turbines. Therefore, thinner blades operating at higher tip speeds will tend to reduce the dimensionless natural frequencies and so increase dynamic response and the effects of flexibility for large rotors. And, inevitably, gravitational stresses will be important for large wind turbines.

ROTOR CONFIGURATIONS

The choice of a specific rotor configuration can strongly influence the mechanical complexity, vibratory stresses, reliability, and maintenance cost of wind turbines. Therefore, the attributes of different rotor concepts must be carefully weighed. Important configuration properties include the number of blades, blade to hub articulation, pitch control mechanisms, etc. Before discussing the dynamic characteristics of several rotor systems, the various forces contributing to blade vibratory stresses will be described.

Rotor Blade Forces

These include aerodynamic, inertial, and gravity forces. The major aerodynamic loads are generated by the unsteady nonuniform wind environment. The mean axial wind component generates thrust forces which deflect the blades equally downwind (coning). Gradients in axial velocity (the vertical gradient of the ground boundary layer for instance) produce a tilting of the rotor disk with respect to the shaft. Velocity components perpendicular to the rotor axis also produce disk tilting as well as higher harmonic loadings. Nonuniformities in velocity peculiar to the wind turbine location, the tower wake, and atmospheric turbulence will produce important unsteady loads. Additional unsteady loads, though probably small, will be induced by the rotor wake vorticity that itself results from unsteady blade loadings. Inertial blade loads include centrifugal tension due to rotation, lead-lag, and flapping loads due to Coriolis forces arising from blade oscillations, and gyroscopic forces due to precession of the rotor shaft to maintain alinement with the wind velocity vector. The primary lead-lag Coriolis loads result from tilting of the rotor disk (flapping deflections). Finally, gravity loads may produce significant lead-lag bending stresses for large rotors as noted above.

Hub Configurations

The importance of minimizing cost by reducing mechanical complexity favors the use of a minimum number of blades and the elimination of unnecessary articulation (blade attachment hinges) at the hub. Usually, however, some articulation is required to reduce blade stresses, due to aerodynamic loads, and blade flapping motion. Several types of rotor hubs found on helicopters are shown in figure 4. The simplest two-bladed teetering rotor is typical of current helicopters and allows simple flapping freedom (disk tilting) to relieve 1P aerodynamic loads. The teetering hub does not provide individual blade flapping (coning) to relieve thrust forces due to wind gusts. The coning hub relieves these forces with an additional hinge, but these hinges must support the full centrifugal force load as well as the lead-lag bending moments. A hub configuration found on helicopters with three or more blades eliminates individual blade flapping hinges by attaching the blades to a gimbaled hub. This would not provide coning freedom for a wind turbine, but it does provide relief for inertial lead-lag bending moments. The common fully articulated helicopter rotor hub provides nearly complete relief for the major blade loads by using individual flap and lead-lag hinges for each rotor blade. However, this system is complex and, again, the hinges must carry the full centrifugal load of the blade. The last configuration shown in figure 4 is the hingeless rotor system in which hinges are replaced by flexible spars that deflect elastically to relieve applied loads. Because flap bending moments are transmitted to the shaft, two bladed hingeless rotors would not be practical unless the tower structure could withstand 2P vibratory hub moments due to rotor disk tilting. With three or more blades, only steady hub moments due to disk tilting are transmitted to the shaft. Although hinged rotor hubs are currently in wide use, the hingeless rotor has definite advantages in terms of reduced complexity and improved reliability; and with continued development it is gaining acceptance for helicopter applications. Suitability of the hingeless rotor for wind turbines remains to be established and would require detail design and feasibility studies aimed particularly at reducing vibratory loads and stresses. Especially attractive is the use of molded composite materials to reduce fabrication costs and optimize the blade structural properties.

Each of the rotor hubs in figure 4 requires additional bearings to permit blade pitch changes for regulating power and feathering the rotor in extreme wind conditions. A possible extension of the hingeless rotor concept might permit the elimination of the pitch change bearing for maximum simplicity. A conceptual sketch in figure 5 shows the flexible cantilevered spar with bending flexibility to relieve stresses and with torsional flexibility accommodating blade pitch changes. This twisting may not be sufficient to fully feather the blade, however, and alternate means for dealing with extreme wind velocities might be necessary.

AEROELASTIC STABILITY

Practical rotor systems, including both helicopter rotors and wind turbines, must avoid aeroelastic instabilities. These may stem from several different but related physical mechanisms. Perhaps the best known is classical bending torsion flutter encountered on fixed-wing aircraft. This type of flutter occurs when relatively high-frequency unsteady aerodynamic forces couple with the elastic flap bending and torsion of the rotor blade to produce negatively damped oscillations. This is generally precluded by proper mass balance. Another type of instability, although less well known, can occur for cantilever (hingeless) rotor blade configurations. This type of instability involves both flap and lead-lag elastic bending as well as torsional deformations. It is primarily due to the strong structural coupling between bending and torsion that is characteristic of cantilevered rotor blades and can be avoided by proper tailoring of the bending and torsional stiffness distributions. A typical example of stability boundaries for a helicopter rotor of this type operating in hovering flight is shown in figure 6. These boundaries show that instability will be encountered above a certain pitch angle θ for configurations having various dimensionless torsional $\bar{\omega}_{\phi}$ and lead-lag $\bar{\omega}_{V}$ natuaral frequencies. This figure, taken from reference 1, is only indirectly representative of specific wind turbine configurations. But it does indicate that aeroelastic stability should be considered in the design of large rotor systems.

CONCLUSIONS

Successful large, reliable, low-maintenance wind turbines must be designed with full consideration for minimizing dynamic response to aerodynamic, inertial, and gravitational forces. Much of existing helicopter rotor technology is applicable to this problem. Compared with helicopter rotors, large wind turbines are likely to be relatively less flexible with higher dimensionless natural frequencies. For very large wind turbines, low power output per unit weight and stresses due to gravitational forces will be limiting factors. The need to reduce rotor complexity to a minimum favors the use of cantilevered (hingeless) rotor configurations where stresses are relieved by elastic deformations.

REFERENCES

1. Hodges, D. H. and Ormiston, R. A.: Stability of Elastic Bending and Torsion of Uniform Cantilevered Rotor Blades in Hover. Paper No. 73-405, AIAA, Mar. 1973.

DISCUSSION

Q: You say a helicopter rotor is apparently designed for much higher frequency?

A: Yes. You couldn't take a helicopter rotor and turn it sideways and have an efficient wind turbine. In principle there are many similarities, but in terms of detail characteristics there are many differences.

Q: I have one question and one comment. You did not in your presentation state the difference of material. Materials have natural frequencies. The natural frequency is divided by the density. Perhaps this will be used to evaluate rotors. Did you investigate this?

A: Well, we haven't done any work on that, but I have made that point in my written comments. There is a tremendous potential for using glass fiber components or epoxies or whatever kind of molding materials, to tailor not only the aerodynamic configuration but the structural characteristics as well. This is extremely important in terms of aeroelastic characteristics, the blade frequency, vibration, and so forth. It's a tremendous potential for a rotor, any type of rotor. And it makes for much simpler construction. I think the work that Professor Hutter has done is a good example of that, and from what I've seen it looks a very good way to go.

The hingeless rotor I mentioned has no bearings or hinges, is made with composite materials and, is quite simple. They are nothing like typical rotors that we have nowadays.

COMMENT: There are problems of vibration, that would increase beyond limits we have so far heard on the tests. Therefore, I see that vibration would be most serious in the development of some windmills. It would be very difficult to erect these machines because a vertical rotor can't have downhanging rotors.

A: I think you are referring to gravitational loads under static conditions? Yes, that's going to be a problem. You don't have to go too much higher in size before just the static deflections get to be a problem.

In helicopter rotors, the plane of the rotor is normal to the gravity field so the blades all drop evenly. The rotor can start up and gain centrifugal stiffening, and the blades can be made much more flexible. But for wind turbines, they have to start vertically. It could be a real problem.

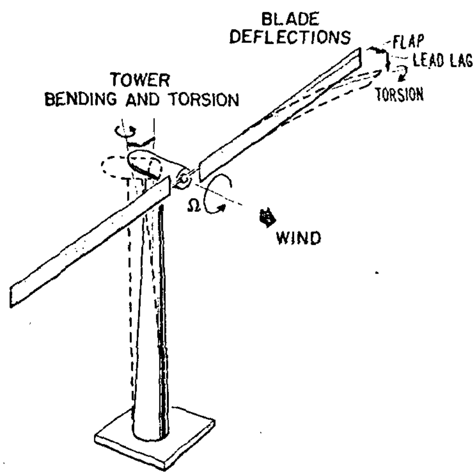

Fig. 1 - Elastic deformations of rotor/tower structure.

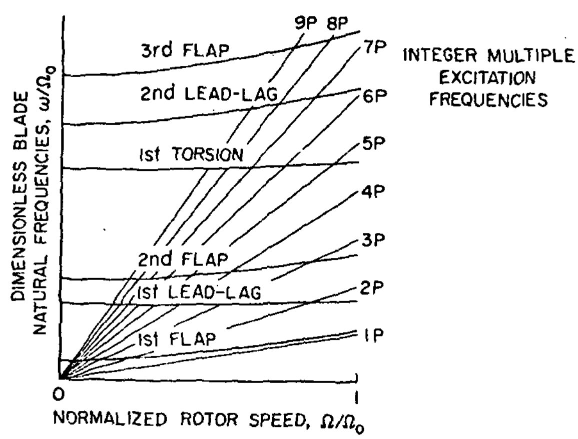

Fig. 2 - Variation of rotor blade natural frequencies and excitation frequencies with rotor speed.

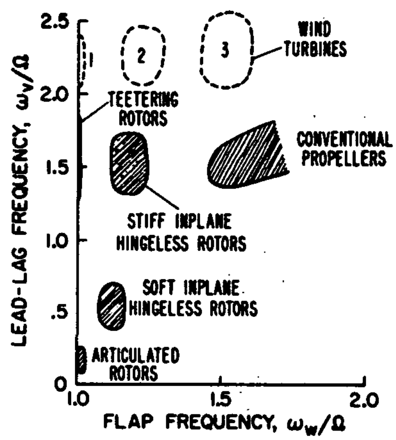

Fig. 3 - Comparison of rotor systems according to dimensionless bending frequencies.

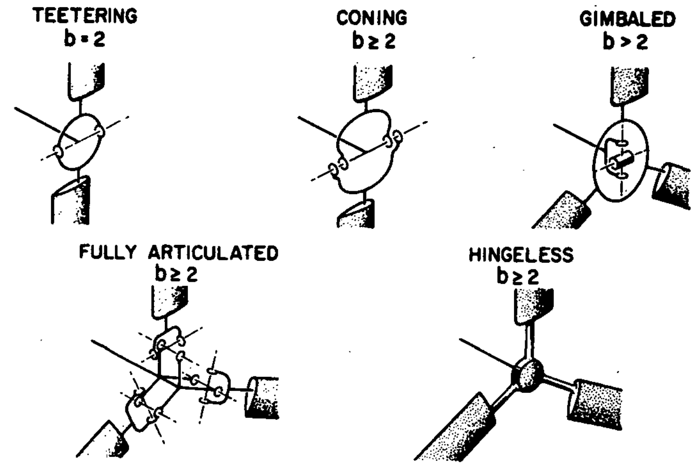

Fig. 4 - Typical rotor hub configurations.

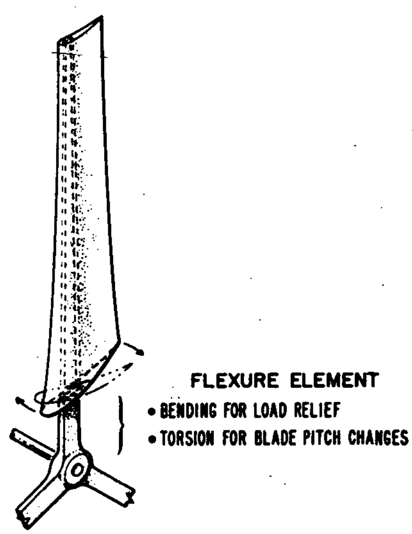

Fig. 5 - A hingeless rotor concept of simplified design.

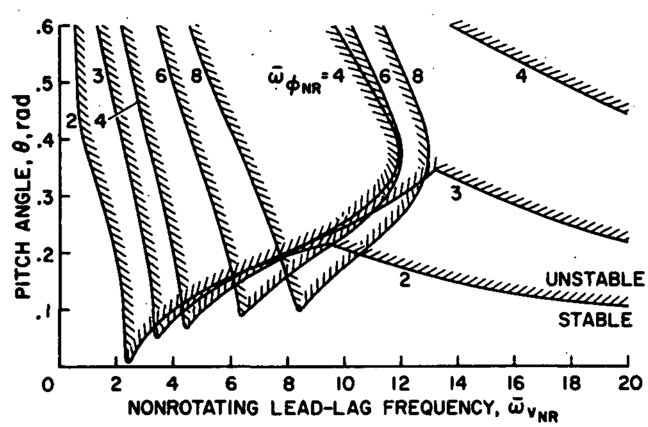

Fig. 6 - Aeroelastic stability of hingeless helicopter rotor blades in hover.

THE EFFECT OF AERODYNAMIC PARAMETERS ON POWER OUTPUT OF WINDMILLS

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SUMMARY

This paper reports the aerodynamic results of a study on wind power generation the Boeing Vertol Company has conducted during this past year. Windmill power output is presented in terms that are commonly used in rotary wing analysis, namely, power output as a function of drag developed by the windmill. Effect of tip speed ratio, solidity, twist, wind angle, blade setting and airfoil characteristics are given.

INTRODUCTION

Several papers have been written on the performance of windmills, but none, to the author's knowledge, have systematically examined the effects on power output of the various aerodynamic parameters. Therefore, the Boeing Vertol Company formulated a theory and computer program to accept the various parameters that can be studied such as tip speed ratio, solidity, twist, wind angle, blade angle, airfoil characteristics, etc. The purpose of this paper is to present the effect of such variations on power output of a windmill. All combinations possible are not the intent of this study, but it is believed that an initial understanding of how these parameters effect power can be obtained from the data herein.

METHOD OF ANALYSIS

The program used is our SR1BR Rotor Research Program which calculates 10 points along the blade at 12 evenly spaced positions of rotation and sums the individual points to give the usual rotor parameters such as thrust, drag, lift and power. The program is set up to calculate induced velocity based on the disk loading at the particular point of calculation and thus uses a nonuniform downwash program. The data resulting from these calculations are all referenced to the product of wind dynamic pressure, wind velocity, and windmill rotor solidity ratio.

SYMBOLS

d diameter of rotor, ft

P power output

q wind dynamic pressure, $(1/2)\ \rho V^2$

R blade radius, ft

V wind velocity, ft/sec

X rotor drag, lb

α_S stall angle of airfoil

$\alpha_{0.90}$ aerodynamic angle of attack at blade element at 0.90 blade radius

C_{D_o} profile drag coefficient of blade at blade angle of attack = 0^o

θ_t blade twist (linear)

$\theta_{0.70}$ blade incidence at 0.70 blade radius

ρ air mass density

σ solidity, ratio of blade area to disk area

μ tip speed ratio, ratio of wind velocity to rotational tip velocity of rotor (V/WR)

ω angular velocity of rotor

RESULTS

Comparison with Test Results

Figure 1 shows that the SR1BR Program calculations compare very favorably with the power output measured values published by the Brace Research Institute for their 32-foot-diameter, three bladed windmill.

Effect of Blade Angle

Figure 2 shows how power output P and drag X vary with blade angle at 0.7 of the blade radius for the baseline windmill chosen for this paper. This baseline[1] performance is based on a blade airfoil section that stalls at a 14^o angle of attack, a tip speed ratio of 0.30, and a solidity ratio of 0.20. It will be noted that there are two values of blade pitch where the power is zero. Point (A) is where the relative velocity is in line with the blade elements. Point (B) is where the blade elements are fully stalled as will be noted by the value of angle of attack

[1]Baseline parameters were arbitrarily established for example only. They should not be accepted as optimum parameters. Future studies should be conducted to determine optimum aerodynamic parameters for specific applications.

at the blade tip of 19.3°, which is beyond the 14° stall angle of the airfoil. The maximum power output P occurs at a blade angle of 16°, but the important item to note is that at maximum power the blade angle of attack at the 0.90 radius point is 11.4° - about 3° less than the stall angle. Point (C) is maximum efficiency point (that where the power for a given drag is greatest). However, windmills should operate at Point (D) because that is where the power output is greatest. The tower structure must be designed for the drag at Point (B), unless great care is expended in developing a drag limiting governor.

Effect of Blade Twist

Figure 3 shows that, for the baseline windmill operating at a tip speed ratio of 0.30 with solidity of 0.20, the best linear blade twist is 30°. Such twist will produce 25 percent more power than an untwisted blade. It should be noted that optimum twist[2] will vary with tip speed ratio.

Effect of Solidity

Figure 4 shows that power output normalized to $(qVd^2\sigma)$ decreases with solidity, but figure 5 (based on the maximum power line of fig. 4) shows that power output is maximum at a solidity between 0.20 and 0.40 for the baseline conditions of $\theta_t = 30^\circ$, $\alpha_s = 14^\circ$, and $\mu = 0.30$.

Effect of Wind Velocity

Figure 6 shows drag and horsepower output for a 100-foot-diameter windmill using the Points (A) and (B) design values from figure 5 for solidity = 0.20. It will be noted that a 45-foot per second wind will generate 800 horsepower or 0.10 horsepower per square foot of rotor swept area.

Effect of Airfoil Section

Figure 7 shows that if the airfoil stall angle is doubled without any other changes, that the power output increase over the baseline configuration with $\alpha_s = 14^\circ$ is 20 percent while the windmill drag force X is increased 25 percent at maximum power output. The maximum drag that can be developed is almost doubled so windmills with high life airfoils will necessarily have to be provided with stronger towers at an increase in cost.

Effect of Wind Angle

Figure 8 shows that output power decreases rapidly if the wind angle with respect to the shaft is very much greater than 12°. Thus, windmills must be provided (as they have through the ages) with some means to point into the wind for maximum power generation.

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[2]Not shown in this paper.

Effect of Tip Speed Ratio

Figure 9 shows that power output is dependent on tip speed ratio and that for each operating tip speed ratio there will be an optimum solidity to produce maximum power output. Boeing studies are continuing in the effort to quantify such effects.

CONCLUDING REMARKS

(1) Boeing SR1BR Program gives results that compare favorably with test data.

(2) Maximum power output of windmill occurs when a blade-element angle of attack near tip of blade is about 3° less than airfoil stall angle for the baseline case considered.

(3) Selection of the proper blade twist will increase power output.

(4) For a given blade twist, airfoil and tip speed ratio, there is a range of solidity ratios that will produce nearly the same power.

(5) Power output varies approximately as the cube of the wind velocity. Drag of the windmill varies as the square of the velocity

(6) Higher lift airfoils for windmills will increase the power output, but greatly increase the design drag value for tower design.

(7) Windmills should be designed such that shaft should point into wind with tolerance no greater than $\pm 12^{\circ}$ for good power output.

(8) Solidity will vary with operating tip speed ratio to produce maximum power output.

DISCUSSION

Q: In your computer program can you use that blade element theory?
A: Yes, it is very similar to the vortex theory or ones that are developed on helical vortex analysis.

COMMENT: Certainly you have the solution where you have the slow rotating shaft speed into a high speed by putting some small rotors on the tip of the blades. This is the only position of application where you have rated the towing efficients. If you have a fixed wing on an aircraft, you want to give out from the resistance or the drag of the wind the maximum power. This is your efficiency. This efficiency is in another sense involving the ordinary windmill. But the towing efficiency is important for the transformation of speed.

FIG. 1 COMPARISON OF BRACE INSTITUTE WINDMILL POWER TO VALUES CALCULATED BY SRIBR

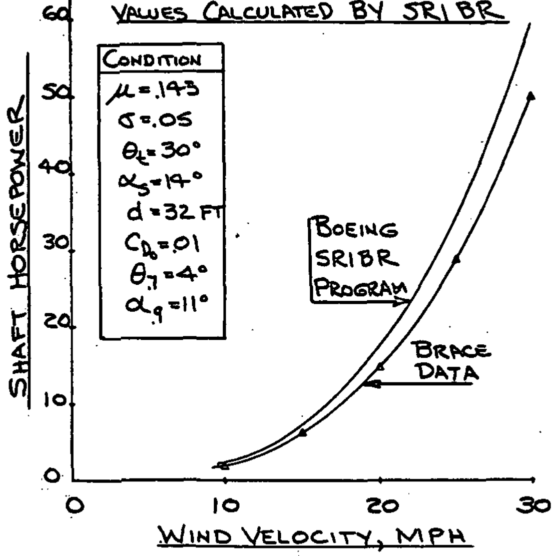


FIG. 2 EFFECT OF BLADE PITCH ON WINDMILL POWER OUTPUT AND DRAG

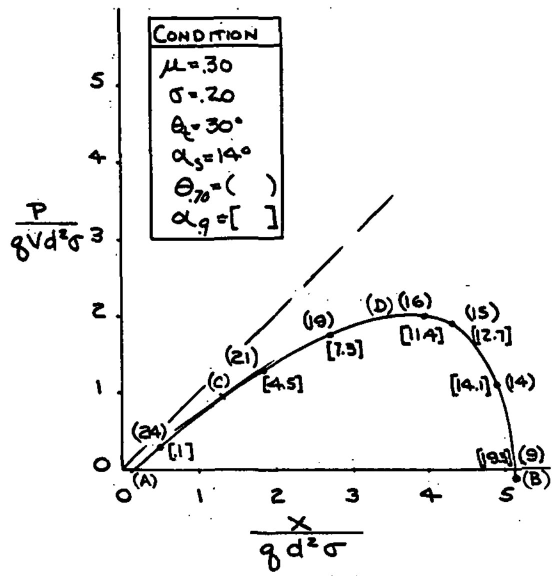


FIG. 3 EFFECT OF BLADE TWIST ON WINDMILL POWER AND DRAG

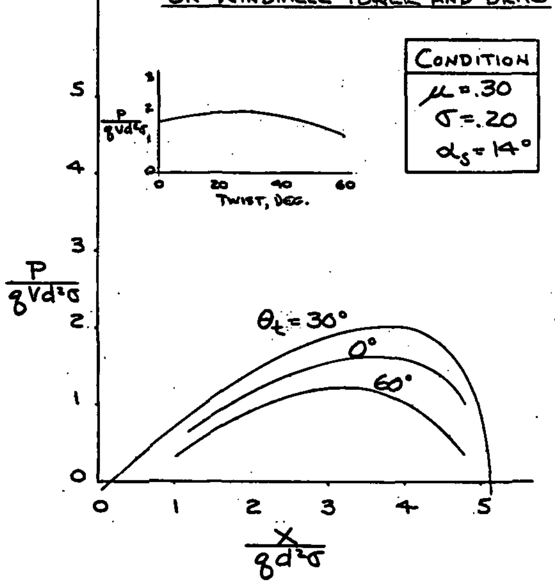


FIG. 4 EFFECT OF SOLIDITY ON WINDMILL POWER AND DRAG

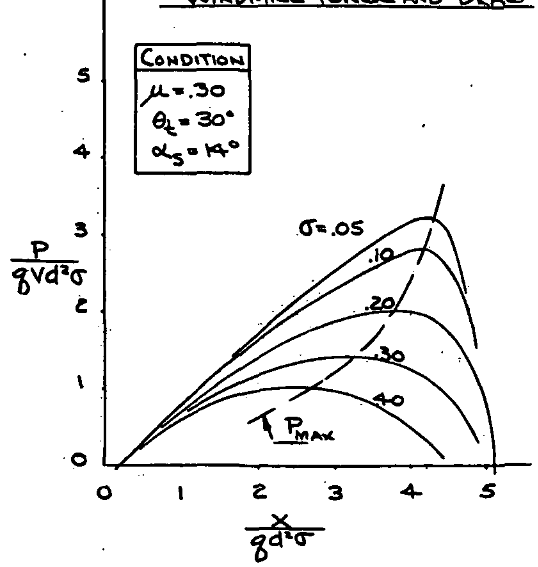


FIG. 5 EFFECT OF SOLIDITY ON POWER, DRAG AND DRAG EFFICIENCY

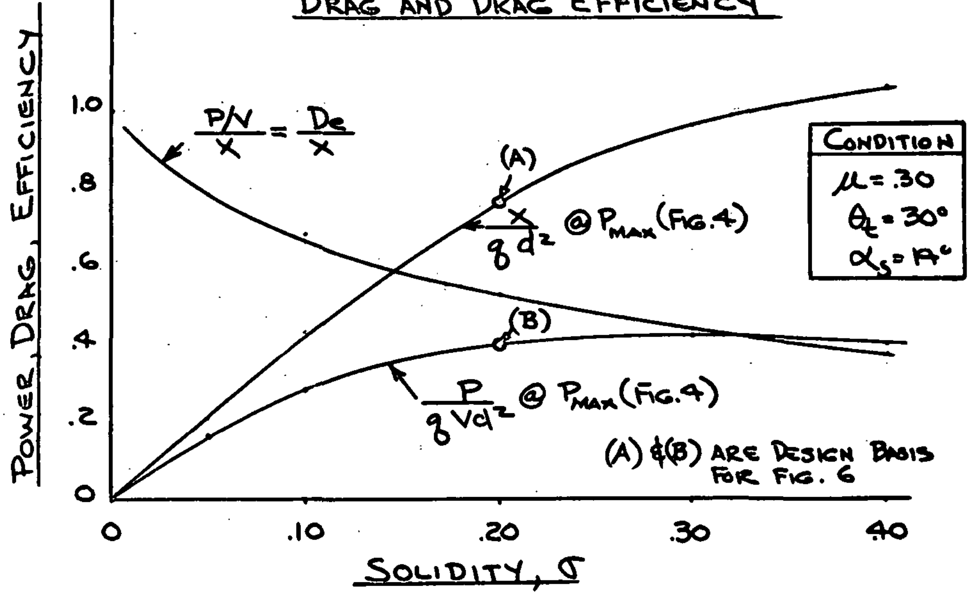
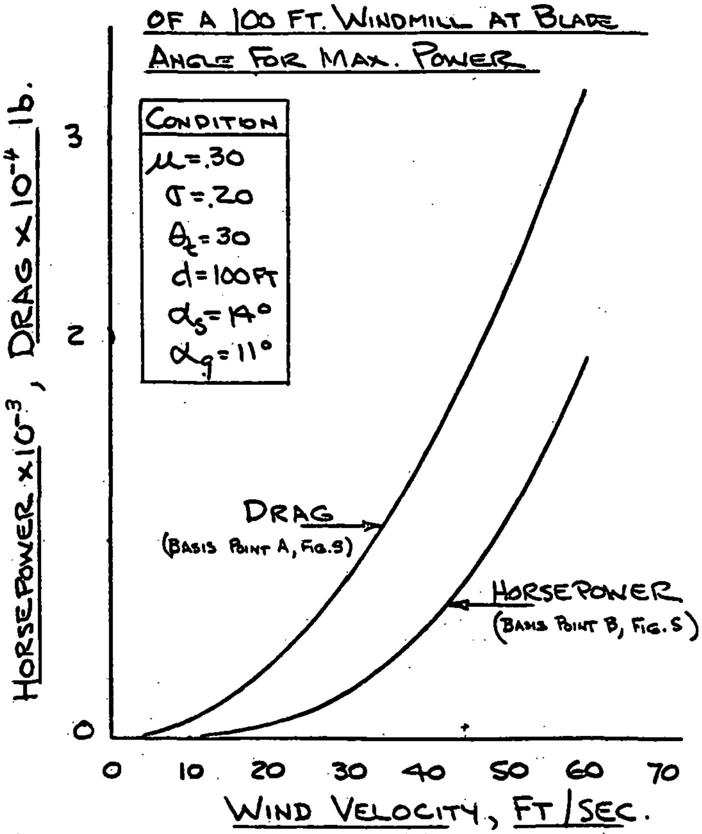


FIG. 6 POWER OUTPUT AND DRAG OF A 100 FT. WINDMILL AT BLADE ANGLE FOR MAX. POWER



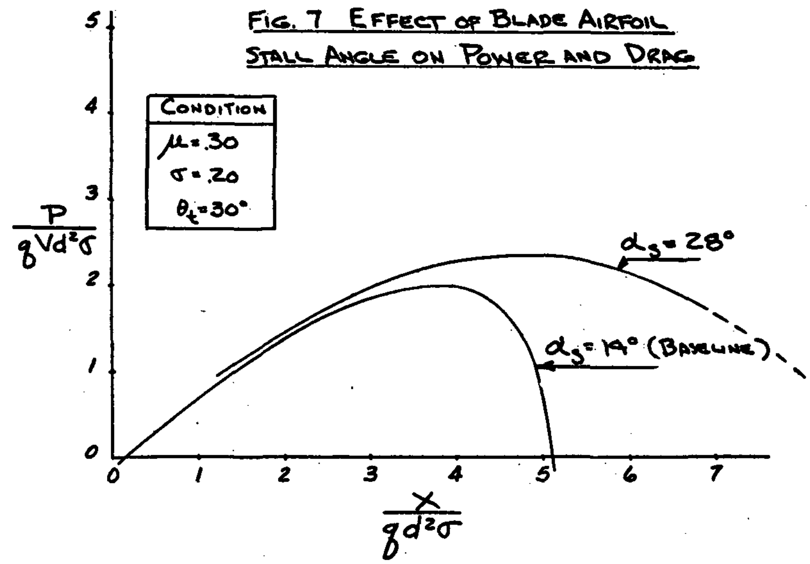


Fig. 7 Effect of Blade Airfoil Stall Angle on Power and Drag

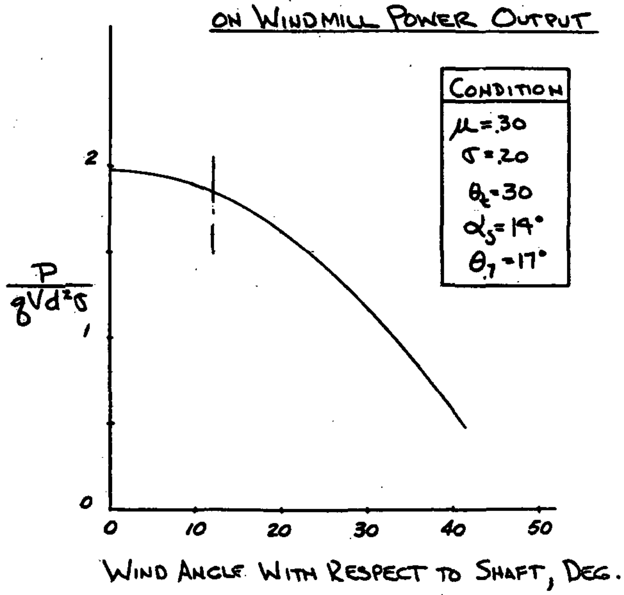


Fig. 8 Effect of Wind Angle on Windmill Power Output

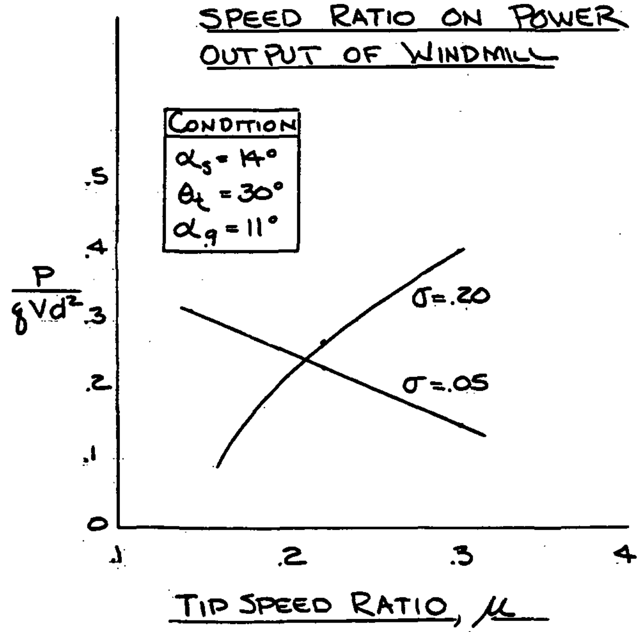


Fig. 9 Effect of Tip Speed Ratio on Power Output of Windmill

VERTICAL AXIS WIND ROTORS - STATUS AND POTENTIAL

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Except for a rather inventive period in the 1920's, the approach taken to extracting power from the wind has been that of using blades or vanes rotating about a horizontal axis with the plane of the blades essentially perpendicular to the wind velocity vector. The two devices shown in figure 1 were patented almost 50 years ago and have as a common element a vertical axis of rotation. The first device, patented by Msr. G. J. M. Darrieus in 1931, has received some recent study by the National Aeronautical Establishment in Canada; the second was developed and patented by Mr. S. J. Savonius in 1929. These rotors share a performance characteristic which differentiates them from the horizontal axis wind rotors, namely, their ability to operate equally well regardless of the direction of the wind. This characteristic is important because it permits the rotor to extract the energy of a given wind or gust instantaneously regardless of any rapid changes in wind direction. Considering that the energy available from the wind is proportional to the cube of the velocity, the feature of not having to take time to head the machine into the wind may well provide additional energy extraction capability over that of a horizontal axis rotor. It is also likely that the elimination of a heading control and servosystem will tend to reduce acquisition and maintenance costs and improve reliability.

Although a number of applications were developed for the vertical-axis rotor, the concept never became popular. Horizontal axis machines were improved over the years and have received substantial attention, perhaps largely due to the availability and advance of propeller theory. We believe that the time is right to take a hard look at the vertical axis machines to see if recent advances in aerodynamics, structures, and materials technology might not place these concepts individually (or perhaps in combination) in a favorable light in comparison with the horizontal axis wind rotors.

To maintain brevity, we will concentrate on the S-rotor for the remainder of the presentation. The configuration of the original S-rotor shown in figure 2 resulted from some 30 or more wind tunnel and field tests conducted by Savonius wherein he varied some of the parameters of the rotor.

Essentially, the device operates (at least during part of its rotation) as a two stage turbine wherein the wind impinging on the concave side is circulated through the center of the rotor to the back of the convex side, thus decreasing what might otherwise be a high negative pressure region. The flow is indicated in figure 2.

Savonius applied his wind rotor to water pumps, ship propulsion, and building ventilators, all with some success. In addition, he also showed the feasibility of using the energy in ocean waves to drive the rotor. This last application was developed subsequentially as an ocean current meter and is available commercially. Very good current measurement capability exists in a region of from 0.05 to 5 knots.

In reviewing the work that has been done on vertical axis rotors, we have concluded that there are a number of development alternatives that should receive some attention from the standpoint of both test and analysis. Figure 3 indicates some of these alternatives. The effects of aspect ratio (the ratio of rotor height to diameter) and the number of vanes will be discussed in detail below. The issue of the profile of the rotor has not been investigated, at least in terms of large (50 ft high or greater) machines. Questions have arisen concerning whether more of the area of the rotor should be at the top to catch the higher wind speeds or whether the area should be at the bottom to provide a more uniform torque distribution along the height. The rotor camber and thickness distribution also need to be optimized. Our own limited amount of test data have indicated that the amount of venting between the rotor vanes has a very significant effect on the rotor speed for a given wind speed.

Figure 4 presents some of the results of a preliminary analysis of the impact of rotor aspect ratio on rotor acceleration. Most of the rotors in use have relatively low aspect ratios (refs. 1 to 3). If we look at the rotor's ability to accelerate as defined by the ratio of the torque on the rotor to its polar inertia, it can be shown that this characteristic improves in proportion to the square root of the aspect ratio as aspect ratio increases. Clearly, there must be limits to this trend due to structural or other considerations. Furthermore, constant-speed performance may impose other requirements.

Test data are shown in figure 5, which indicates the static torque obtained for the two- and three-vaned rotors shown as a function of wind direction. The torque diagram for the two vaned S-rotor has a considerable irregularity that could make it difficult to start under some orientations. The addition of the third vane smoothes the torque diagram to some degree and apparently increases the torque per revolution, but also increases the polar inertia of the rotor, which may offset the increased torque when starting under low wind conditions. Whether two or three vanes will be optimum remains to be resolved. It is also likely that the torque diagram for a rotating rotor may be considerably different from that of the static case described.

The S-rotor may be located in any area where a horizontal axis rotor might be sited. However, the nondirectionality of the S-rotor may be put to use more effectively on sea coasts where the diurnal variation of the wind could be readily accepted. In considering this basic application, it occurred to us that it might be possible to generate an artificial on-shore breeze through the appropriate use of solar energy in the desert. Figure 6 shows a concept of such an artifice. A set of S-rotors are placed circumferentially around a circular area whose surface is made such that the air over it is heated to a higher temperature than the air outside of it. A flow will be established from outside of the heated area to replace the rising heated air. By locating the rotors in the throats of suitably contoured areas, it may be possible to extract considerable energy from the resulting accelerated air. It is recognized that this is an ambitious concept. In essence, we are trying to produce our own wind in sufficient quantities to make a cost-effective power system. Analysis and test techniques must be developed to verify the feasibility of this system concept.

Another application of S-rotor might be in remote areas such as the one depicted in figure 6. In the Arctic and many other places in the world, empty oil drums might be used for rotor vanes. In some underdeveloped countries it may be possible to construct the rotor from indigenous materials. The actual siting of the rotor in a village or base camp would depend on knowing where strong winds persisted without regard to their direction. This simplification coupled with low costs (for the rotor) might make the S-rotor a valuable asset to the community. It should also be noted that vertical axis rotors might be of considerable value in meeting instrumentation and power needs for research on the surface of other planets.

In conclusion, we believe that the potential of vertical axis rotors has not been exploited in recent years and that a comprehensive program including design, analysis, and test could yield devices of equal (if not better) cost-effective performance than that of horizontal axis rotors. We further believe that applications of these rotors should be considered simultaneously with their development to ensure the practical utility of the wind machines.

DISCUSSION

COMMENT: There are two units currently being manufactured in Switzerland which use this principle. One is a 50 watt unit; the other is a 250 watt unit. The design is a slight variation of the Savonius rotor principle. The larger unit has been in production now for about 5 years. They are being used very successfully, particularly on top of radio towers where a little power is needed for a booster amplifier to take the signal down to the house. They worked very well for that purpose.

COMMENT: The company, Electro GMBH Company, also produces the 6-kilowatt standard generators. The man that runs that company is very interested in vertical axis design. He has experimented a lot with them. He has come up with, it seems, a quite successful unit for a small-scale, very simple in design and virtually no maintenance whatsoever, and no problems with regulations in high wind, and so on. There has been one built as a matter of fact, out in the Scripps Institute of Oceanography not too far north of where we are.

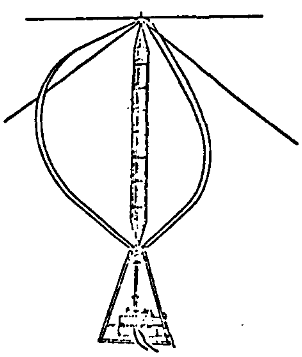
Q: You speak of one of these machines being 100 feet high. What is the largest model you know about?
A: I haven't heard of any near that size. An important question is whether this type of rotor be scaled up to larger sizes? My answer is: I don't know.

Q: How big you have seen any size.
A: About 15 or 20 feet high.

Q: In the thirties one about 100 feet high was constructed in New Jersey.

VERTICAL AXIS WIND ROTORS

DARRIEUS ROTOR



BACKGROUND

PATENTED IN 1931 (US AND FRANCE)

CURRENTLY UNDER STUDY AT NATIONAL AERONAUTICAL ESTABLISHMENT, OTTAWA, CANADA

CHARACTERISTICS

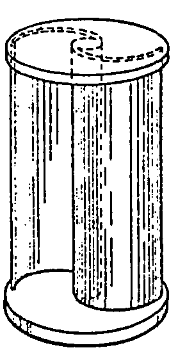
EFFICIENCY ~ 35%

TIP SPEED TO WIND SPEED ~ 6 TO 8

POTENTIALLY LOW CAPITAL COST

CURRENTLY NOT SELF STARTING

S-ROTOR



BACKGROUND

PATENTED IN 1929 (US AND FINLAND) BY S. J. SAVONIUS

CURRENTLY USED AS AN OCEAN CURRENT METER

OTHER APPLICATIONS SHOWN FEASIBLE

CHARACTERISTICS

TIP SPEED TO WIND SPEED ~ .8 TO 1.8

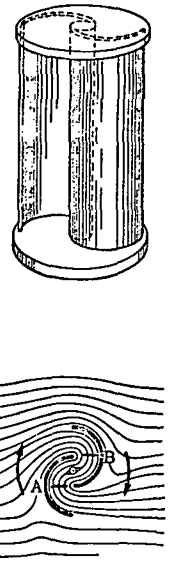
EFFICIENCY ~ 31%

SELF STARTING

VERTICAL AXIS ROTORS OPERATE INDEPENDENTLY OF WIND DIRECTION AND THUS HAVE A POTENTIAL FOR HIGH EFFICIENCY IN CHANGING WINDS

FIGURE 1

S-ROTOR DEVELOPMENT



CONFIGURATION

- END PLATES PROVIDE
  - STRUCTURAL MEMBERS
  - CONDITIONS FOR 2 DIMENSIONAL FLOW
- COMMON ASPECT RATIOS < 3
- SHEET METAL VANES

FLOW CONDITIONS

- PERFORMS SOMEWHAT LIKE 2 STAGE TURBINE
- FLOW TO BACK SIDE OF ADVANCING VANE REDUCES NEGATIVE PRESSURE
- SUBSTANTIALLY CONSTANT AREA FOR AIR FLOW

DEMONSTRATED APPLICATIONS

- WIND DRIVEN WATER PUMP
- WIND DRIVEN SHIP PROPULSION
- BUILDING VENTILATORS
- OCEAN WAVE DRIVEN WATER PUMP
- OCEAN CURRENT METER

FIGURE 2

DEVELOPMENT ALTERNATIVES

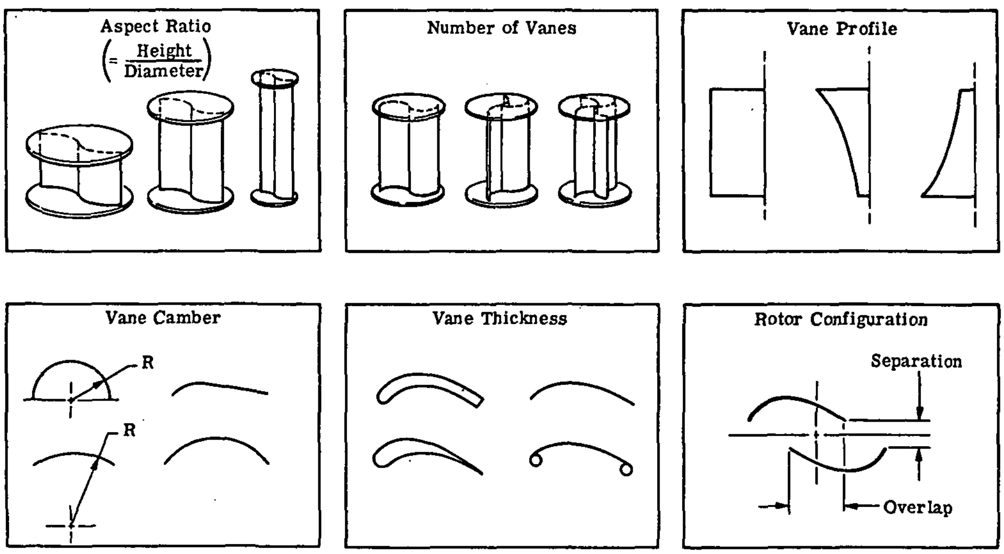


FIGURE 3

EFFECT OF ASPECT RATIO ON ROTOR ACCELERATION

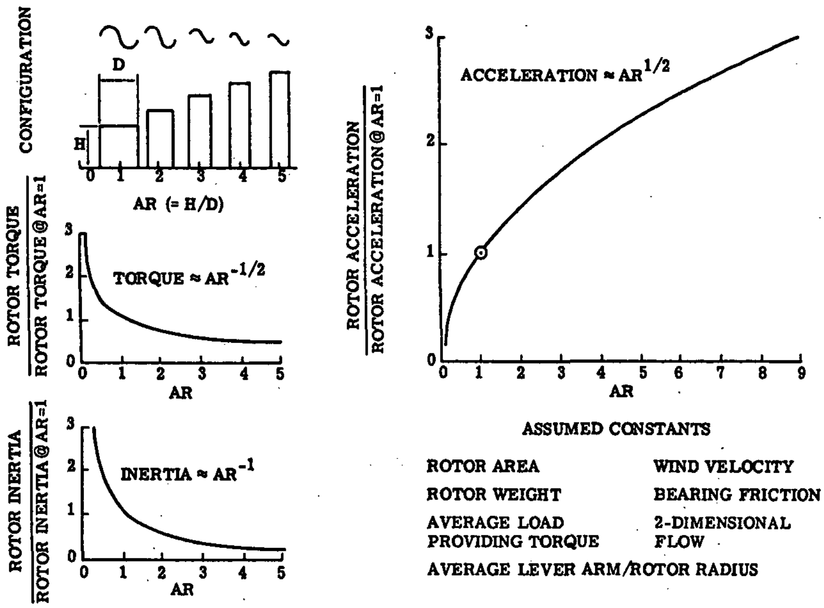


FIGURE 4

STATIC TORQUE PROFILE

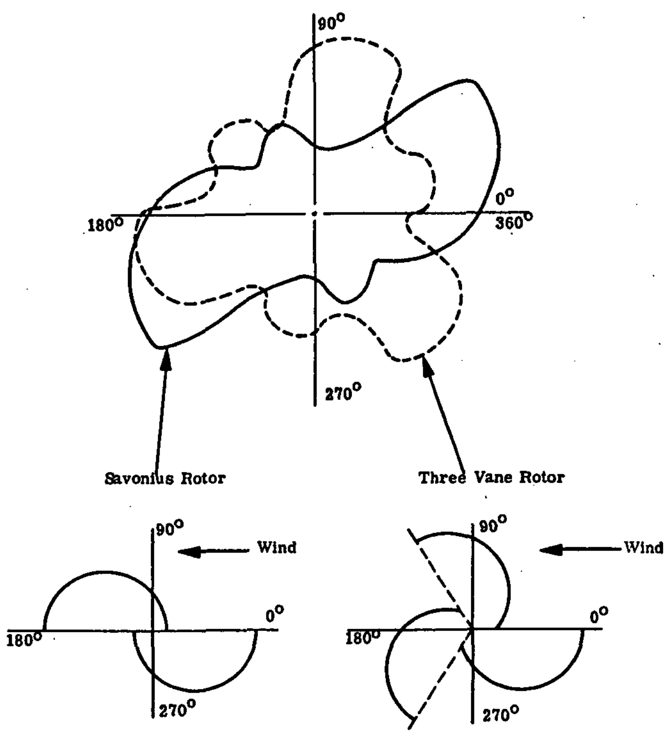
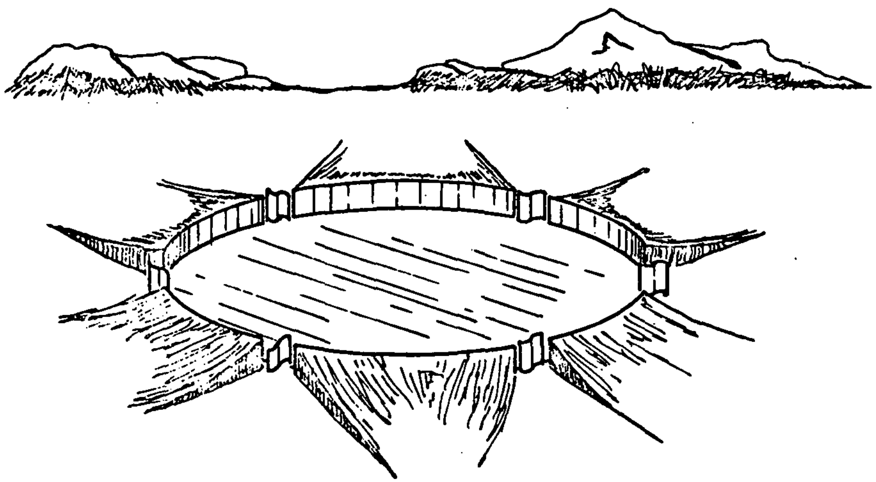


FIGURE 5

POTENTIAL IMPLEMENTATIONS



SOLAR/WIND CONCEPT

- LARGE RADIATING SURFACE TO HEAT AND RAISE AIR
- S-ROTORS ARRANGED TO EXTRACT ENERGY FROM INCOMING REPLACEMENT AIR
- FOR EQUILIBRIUM FLOW:

$$V_x \simeq \frac{\text{AREA OF RADIATING SURFACE}}{\text{(NUMBER OF ROTORS) (ROTOR DIAMETER)}} V_y$$

- POTENTIAL HYDROGEN PRODUCER

REMOTE AREA CONCEPT

SIMPLE VANE REQUIREMENTS PERMIT CONSTRUCTION USING
- OIL DRUMS
- INDIGENOUS MATERIALS

SITING REQUIREMENTS SIMPLIFIED
- DEPENDS ON WIND SPEED -
- NOT DIRECTION

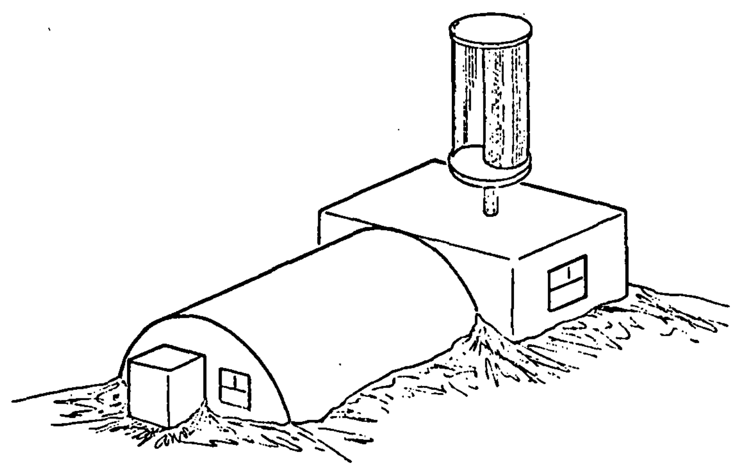


FIGURE 6

ADVANTAGES OF THE DIFFUSER-AUGMENTED WIND TURBINE

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The fact that substantial performance advantages can be realized by the use of a shroud and diffuser on a wind turbine was recognized in the 1950's. The work of Lilley and Rainbird (ref. 1) indicates that diffuser-augmented turbines can produce up to twice the power of unshrouded turbines of the same diameter, and our independent analysis indicates the same range of performance improvement. Even more attractive is the potential for operational flexibility afforded by the diffuser, enabling useful power generation at lower and higher wind velocities, and simpler control features.

Figure 1 shows an artist's conception of a diffuser-augmented wind turbine. The basic function of the diffuser is to convert the kinetic energy of the flow downstream of the rotor into a pressure rise. This lowers the pressure level behind the rotor, and makes it possible for the rotor to capture airflow from a free stream tube area that is greater than that of the rotor itself. The inlet area need not be large, as the stream tubes will converge naturally to the inlet if the diffuser is sufficiently effective. The optimum conditions for such a system are very significantly different from the familiar ideal optimum for an unshrouded rotor (cf. Glauert, ref. 2). The flow velocity through the rotor is typically 20 to 60 percent greater than the free wind velocity as opposed to 67 percent less than the free wind for the unshrouded case. In addition to offering more output per unit rotor area, this fundamental change in stream tube configuration enables practical rotor designs to operate even at very low wind speeds. The presence of the diffuser also offers the opportunity to accommodate to very high wind speeds without the need for variable pitch in the rotor blades. These large performance and operational advantages may be sufficient to overcome the cost of the large diffuser, especially in applications for which storage is a significant cost factor.

Our one-dimensional analysis differs from that of Lilley and Rainbird in that the drag of the shroud does not enter explicitly into the performance prediction. Figure 2 shows that stations used in the analysis, and indicates schematically that the upstream capture area is greater than that of the rotor, but smaller than that of the rotor stream tube far downstream of the diffuser exit. We define the ideal power coefficient $C_{P_i} \equiv \Delta p_{23} V_2 / (1/2)\rho V_o^3$, which through Bernoulli's equation, continuity, and a statement of losses in inlet and diffuser can be expressed as

$$C_{IP_i} = \Big[1 - K_i - C_{p_4}\,\varepsilon - (1 - \eta_D)\varepsilon^3 - \eta_D\varepsilon^3\lambda^2$$

where $\varepsilon = V_2/V_o$, K_i is the inlet loss coefficient, η_D is diffuser efficiency, $C_{p,4} = (p_4 - p_o)/(1/2)\rho V_o^2$, and $\lambda = A_3/A_4$.

The optimum velocity ratio and the corresponding ideal power coefficients are shown in figures 3 and 4, while the off-optimum performance is shown in figure 5, all for $K_i = -C_{p,4}$. Because of the very low exit velocity, viscous entrainment downstream of the exit should make it possible to operate with slightly negative $C_{p,4}$, increasing ideal performance beyond that indicated. It is to be understood that no real turbine could achieve these ideal figures, but the relationship between shrouded and unshrouded systems should be at least as favorable to the diffuser-augmented type as that shown. The effect of the shroud in reducing tip losses is not accounted for in this analysis, nor is the reduced swirl loss due to radial expansion in the diffuser and the reduced optimum disk loading of the diffuser system ($\Delta p_{23}/(1/2)\rho V_o^2 = 2/3$ versus 8/9 for the unshrouded optimum).

The relative advantages of a diffuser-augmented wind turbine will be sensitive to the type of application; that is, the size of unit, the economic value of a broader operating range, and the local wind spectrum. Technical issues that need better definition are the relationships between diffuser efficiency and diffuser geometry with a turbine exhaust as input flow, the range of $C_{p,4}$ that can be achieved with a practical external contour as a function of V_4, diffuser and support construction costs, optimization of λ for given applications, and trade-offs for rotor design factors such as pitch control and disk loading as affected by the diffuser.

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2. Glauert, H.: The Elements of Aerofoil and Airscrew Theory. Second ed., Cambridge University Press, 1948.

DISCUSSION

COMMENT: Our calculations show very similar results. One point, though, which I am sure the speaker is aware of is that a ducted rotor is never better than a free rotor that has an area equal to the area of the duct exit.

A: Right. The equivalent rotor would be between the two. It can be better in that it can have a very much lower wind velocity cut-in speed.

That could be more important than the power per unit size.

Q: Did the speaker ever consider actually making the duct rotate with the rotors? What might the losses be in a system like that?

A: On what axis?

Q: Just fasten the rotor tips to the duct itself, so that you removed all your clearance and mechanical problems, and have the duct go round.

A: I think the bearing problem would bother us more than the tip losses at the wall would.

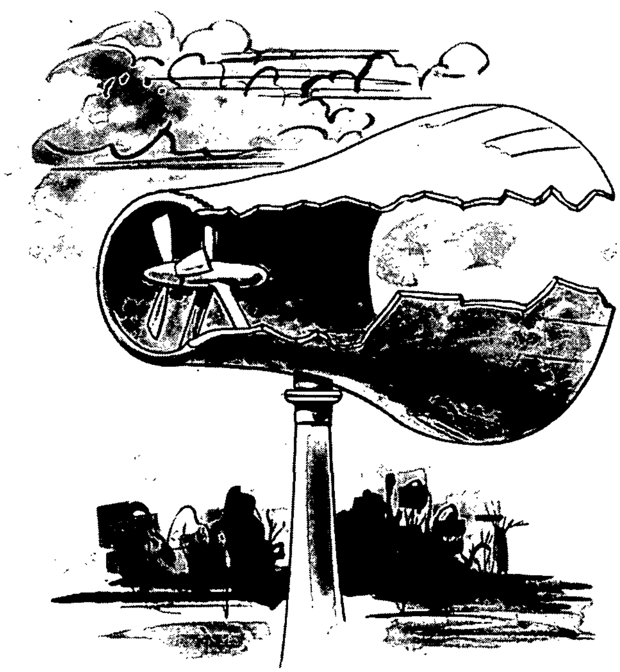

Figure 1

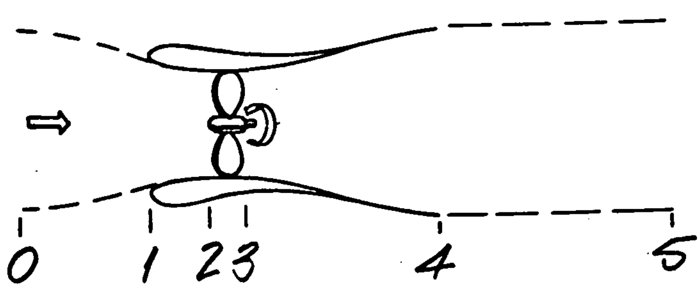

Figure 2

OFF-DESIGN PERFORMANCE

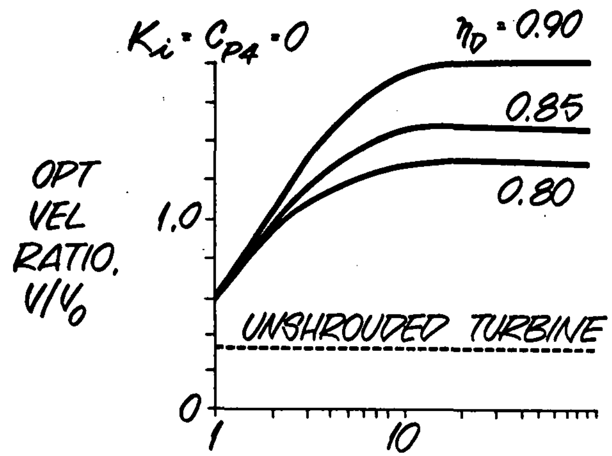

Figure 3

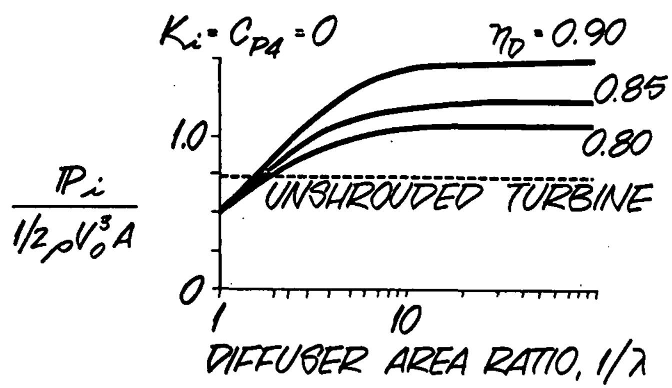

Figure 4

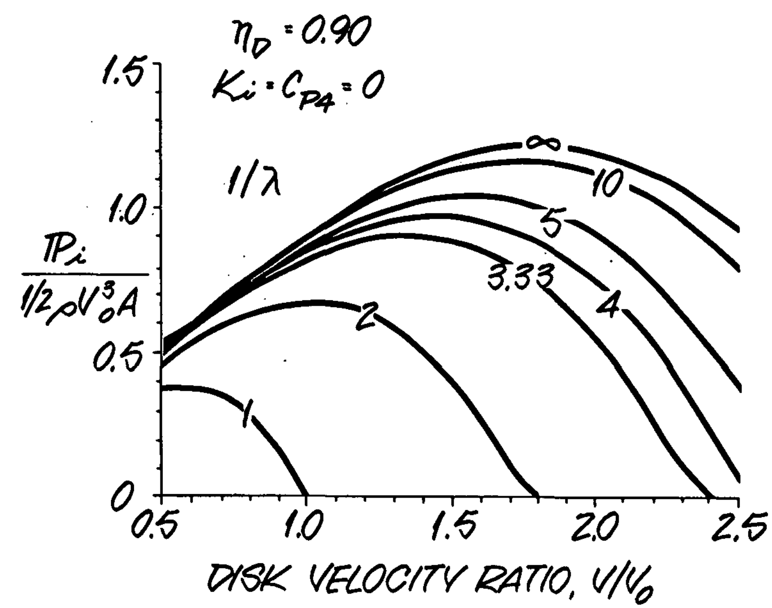

Figure 5

BUCKET ROTOR WIND-DRIVEN GENERATOR

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and

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One of the common types of impellers for moving large volumes of air at low velocity is the bucket rotor. Perhaps we have overlooked the possibility of using this design in reverse for the extraction of power from the wind.

To get some preliminary feel for this, a unit with rotor 4 feet in diameter and 4 feet long has been built (see figure 1). It has deflectors on the top and bottom to guide the wind into the top half. The lower deflector also shields the back side of the bucket from the wind, thus reducing the reversing wind force. The present rotor is fixed in direction facing the predominant wind; it may also be mounted and installed with a tail boom to follow the direction of the wind.

Mounted on a trailer towed by an automobile, this unit has been tested at wind speeds from 15 to 40 mph. The mechanical energy produced was measured using a rather crude dynamometer. The maximum power at 40 mph was measured to be 0.14 horsepower. Further improvements in the configuration design will undoubtedly improve the performance.

As compared with the ordinary propeller-type rotor, the bucket rotor is limited in rotational speed since the tip rotor speed can never exceed the wind speed. However, it does not present the blade fatigue problem that the ordinary rotor does, and it perhaps causes less sight pollution. The deflector vanes also provide a venturi passage to capture greater wind flow. The bucket rotors can be strung together end-to-end up to thousands of feet long to produce large amounts of power.

DISCUSSION

Q: This is simply a Savonius rotor on its side with a couple of vanes out front to direct the flow. The disadvantage is that it's directional.

A: It is directional, certainly, but because it is directional, the vanes here have the Venturi effect that simply improve the efficiency of the thing.

Q: Right, but, if radial vanes are mounted on a Savonius rotor it captures the wind from all directions, the effect is the same.

A: But the Savonius rotor has a vertical axis. However, if you are free of directional influence, you cannot put in those guide vanes.

Q: You could put them in as part of your supporting structure. They would hold the upper bearing of the vertical axis. I don't see how your rotor is any improvement over the Savonius rotor with guide vanes.

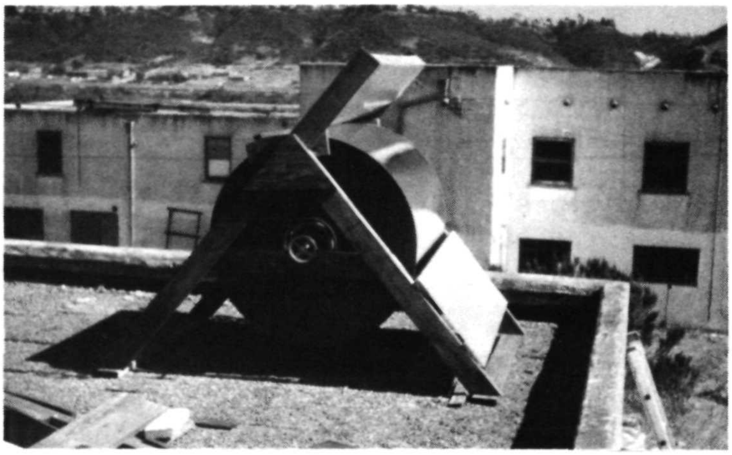

Figure 1

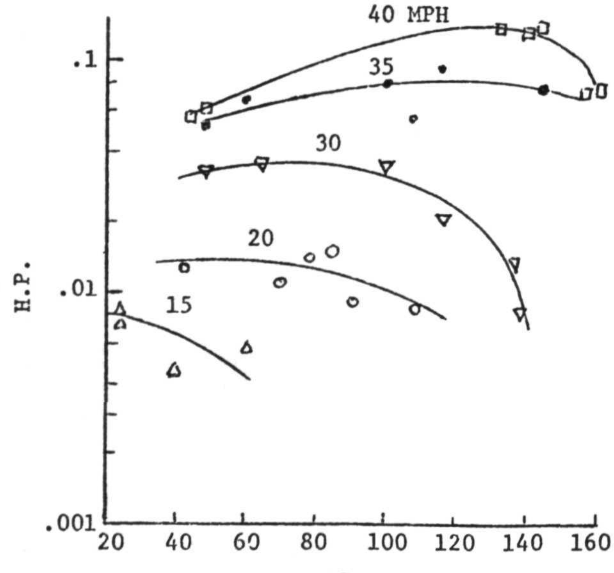

Figure 2. - Test results of the bucket rotor wind-driven generator.

WIND-POWERED ASYNCHRONOUS AC/DC/AC CONVERTER SYSTEM

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The two asynchronous ac/dc/ac systems shown in figures 1 and 2 are in the process of being modelled at the University of Wisconsin. The figures contain the main information and are somewhat self-explanatory such that only a brief explanation is contained herein. The system of figure 1 can use a variable or constant Hertz alternator drive such as can be provided by wind power. The system of figure 1 generates (ref. 1) variable Hertz ac, rectifies this with a frequency independent three-phase two-way, six-pulse bridge-rectifier (see inset) operating with constant current control, and parcels this constant I_R among pumped-storage, dc loads, and the high-capacity 60-hertz bridge inverter, also operating usually under constant current control (C.C.C.). The 60-hertz bridge inverter comprises a stable link to the power company to either supplement them from wind energy, storage, or from a combination of both at a preset desired current. In that the rectifier and inverter are identical, they are "converters" and can operate in either mode depending on the silicon-control-rectifier (SCR) firing angle α. Thus, if needed, the inverter can go over into rectifier mode and pump back into storage. Tests were run at a wide range of wind-bus hertz and with rectifier C.C.C. set at higher and lower levels than the inverter C.C.C. - storage taking up the slack. The system is not "sensitive" in that, for given C.C.C. settings, Sw3 can be opened and closed at will - suddenly - activating or cutting off the inverter current to the 60-hertz power company bus. The system is presently modelled as a three-phase ac generation/dc/three-phase 60-hertz inversion, but a single-phase 60-hertz C.C.C. inverter will be built also.

The system of figure 2 employs the same rectification but from a 60-hertz alternator arrangement (refs. 2 to 4). This system is missing the high-power 60-hertz inverter tie to the large backup supply of the power company, and it is thus meant to be a self-contained electric supply. System 2 has the option of mainly dc output, some sinusoidal 60-hertz from the wind bus and some high harmonic content 60 hertz from the 800-watt inverter. Work is presently under way to do some wave shaping on inverters of this type to investigate the harmonic tolerance of various appliances (ref. 5).

Figures 3 to 8 are mostly self-explanatory and show the instantaneous waveforms of voltage found at the indicated places in figure 1. Of note are the following:

(1) "Zero" voltage exists during conduction of an SCR.

(2) The "safe" negative, but large, voltage exists across a rectifier SCR during its off period.

(3) The potentially troublesome large positive voltage (shown in fig. 7) exists on an inverter SCR during its off time.

(4) The harmonic content in the bridge voltages increases in all cases when both the SCR firing angle and commutating angles are greater than zero.

(5) The firing angle of an inverter SCR must be such that the conduction period ($120^{o} + \mu$) is over soon enough to allow the deion angle γ or a commutation failure will occur. This is the reason for the build-in inverter constant extinction angle control (C.E.A.), which will override the inverter C.C.C. when necessary.

(6) Every commutation between a pair of SCR's momentarily results in a direct short circuit on one of the line-line voltages (fig. 8). For example (see inset, fig. 1), a commutation from SCR#1 to SCR#3 causes a short on line-line voltage E_{ab} for a duration of μ. The firing order of the converter shown is 1, 6, 3, 2, 5, 4.

Figure 9 shows the input and output of a six-pulse bridge-rectifier as supplied by a 100-percent field-modulated alternator (refs. 2 to 4). Pertinent operation is evident or noted directly on figure 9.

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2. Bernstein and Schmitz: Variable Speed Constant Frequency Generator Circuit Using a Controlled Rectifier Power Demodulator. AIEE, Paper No. CP60-1053, San, Diego, Calif., Aug. 1960.

3. Allison, Ramakumar, Hughes: A Field Modulated Frequency Down Conversion Power System. IEEE Industry Applications Meeting Philadelphia, Pa., Sept. 1972.

4. Lindsley, E. F. and Luckett, H.: New Alternator Delivers 60-Cycle Power at Any Speed. Popular Science, Jul. 1973, page 38.

5. Grateful acknowledgment to the Sperry Univac Corp. and the Univ. of Wisconsin Research Committee for their encouragement and support to continue this project.

DISCUSSION

Q: With the rectifiers you were describing, is it possible to charge two frequencies?

A: No. I had a little 14-pole generator; 14 poles develops 60-cycles at 514 rpm. I ran it over 5000 rpm and operated it with no delay and with delay. The rectifier is independent of the frequency. It will pump into storage constant current control. All solid state controls will operate at that frequency.

Q: We found the converters were extremely expensive.

A: They are expensive, but I would like to add that this inverter-converter scheme, this particular graph's type bridge, is what's used in the present-day, large-scale dc power links. There are a dozen or so operating within the world, and there is practically no limit on the size of these converters. With the present state of the art, this rectifier and this inverter can be built for 3000 megawatts.

Q: I believe this solves the problem of the variable at one speed.

A: The rectifier is independent of the frequency. The inverter will operate strictly at 60 cycles and tie right onto the existing supply.

Q: Is that generally cheap in a system - are there any hydraulic variations?

A: I'm assuming that somebody can supply the proper wind generator, and I take it from the electrical end.

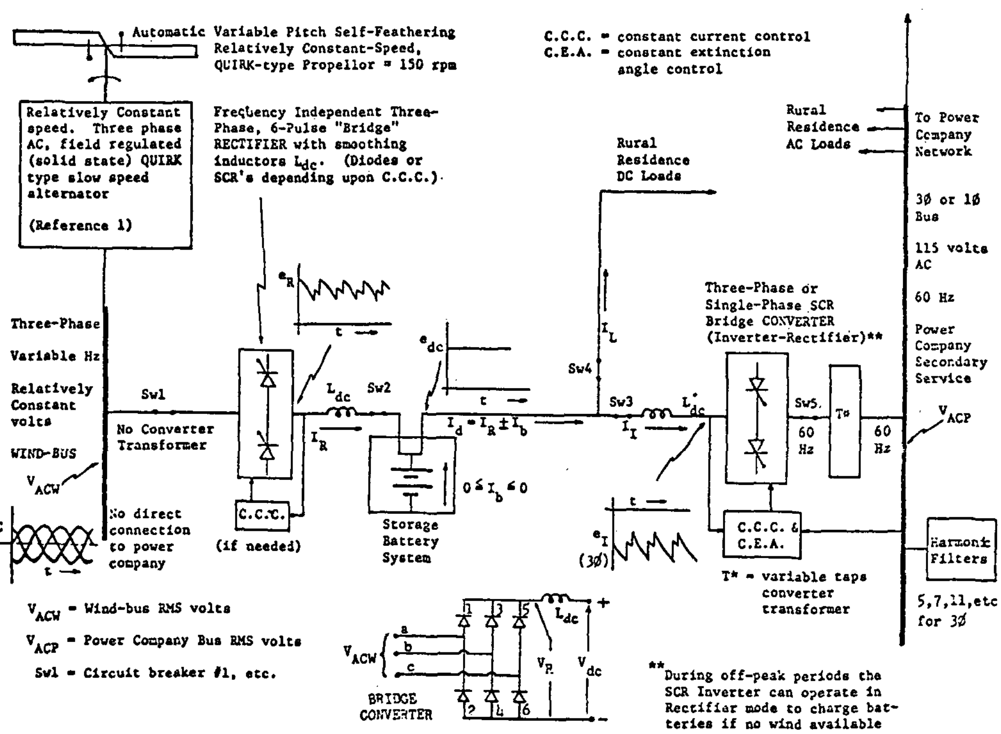

FIGURE 1. Non-Synchronous AC/DC/AC Pumped and Pumpback Storage Wind-Energy System to Supplement Rural Power Company Supply

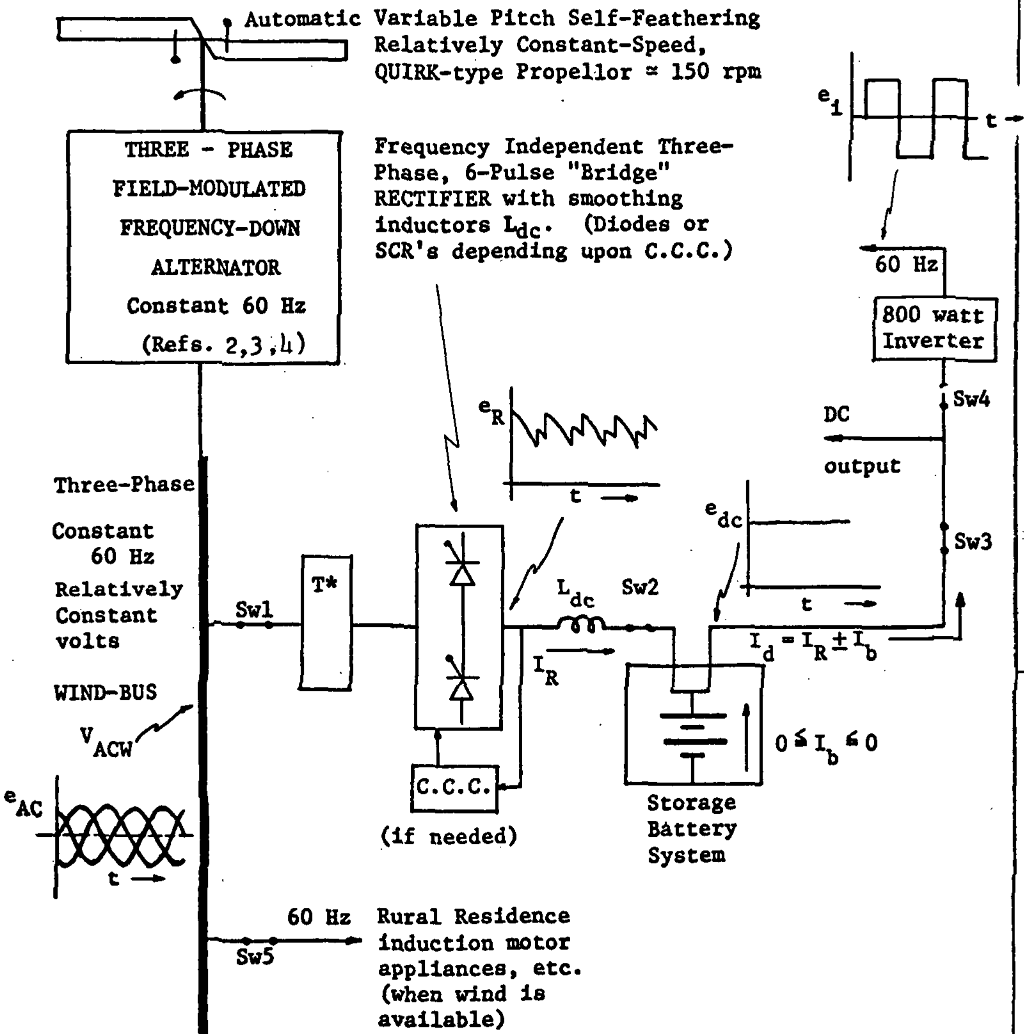

FIGURE 2. Non-Synchronous AC/DC/AC Pumped Storage Wind-Energy System for Electrically-Isolated Rural Residence

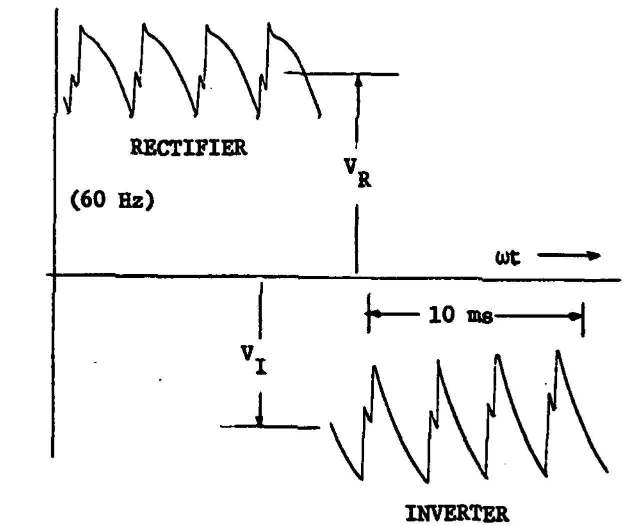

FIGURE 3. Full-Load Converter Bridge-Voltage

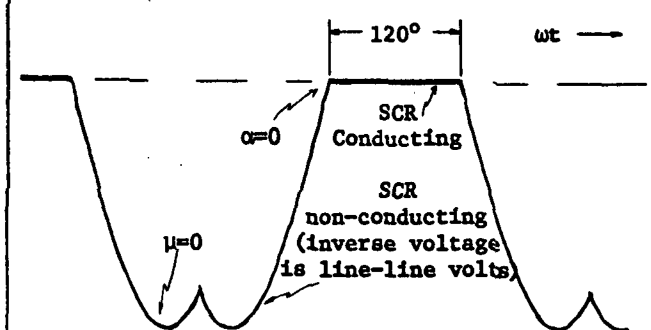

FIGURE 4. No-Load Rectifier SCR Voltage

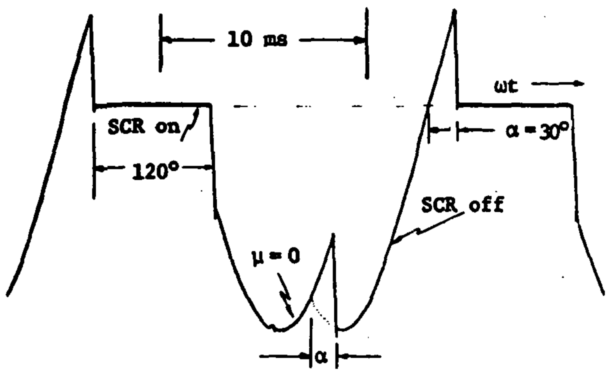

FIGURE 5. No-Load Rectifier SCR Voltage $\alpha \neq 0$

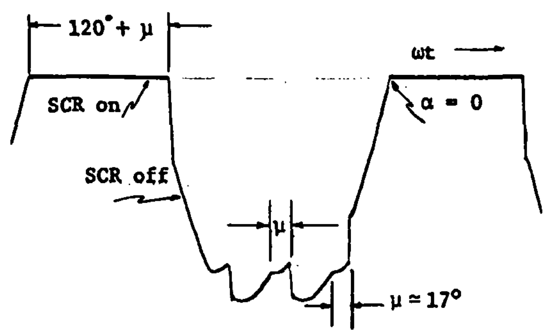

FIGURE 6. Full-Load Rectifier SCR Voltage
$\alpha = 0 \quad \mu \approx 17°$

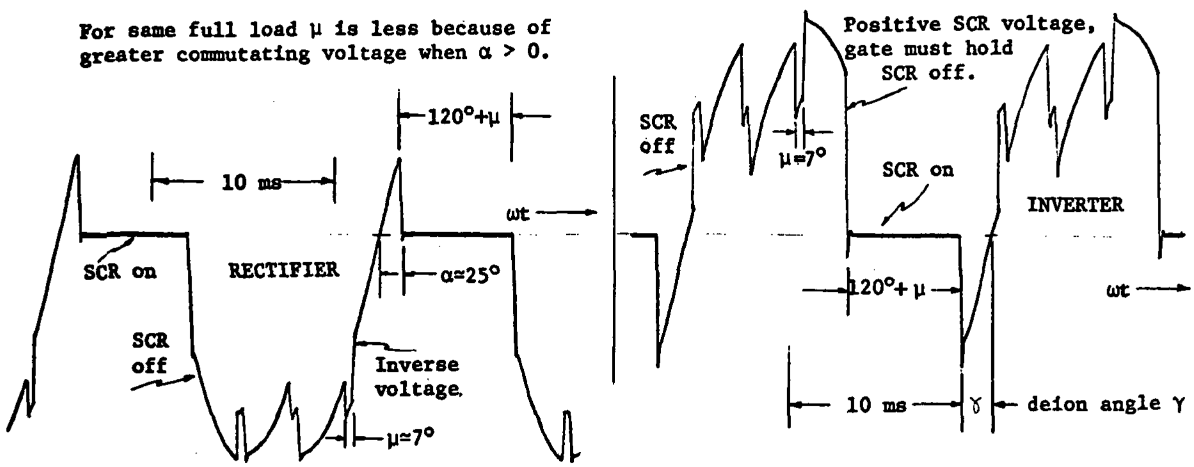

FIGURE 7. Full-Load Converter SCR Voltage — $\alpha \approx 25°$, $\mu \approx 7°$

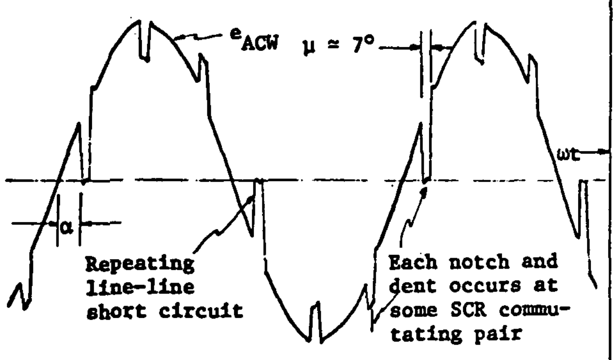

FIGURE 8. Full-Load Line-Line Voltage V_{ACW}

Remarks: 1. The system of Fig. 1 operates in a normal manner with rated V_{ACW} on the wind-bus and rated V_{ACP} on the Power Co. bus, for any level of Storage Battery System bus voltage from 10% to 100% of normal. The operation for lower Storage bus voltages merely changes to larger firing angle α and a different C.C.C. setting for the same constant current.

2. For low Storage bus-voltage (due to temporary partial outage) the harmonic content increases, the SCR voltages go lower and shift to the left in all the above figures, and the volt-ampere-reactive requirement of both AC busses unfortunately increases. This would be a temporary situation, usually.

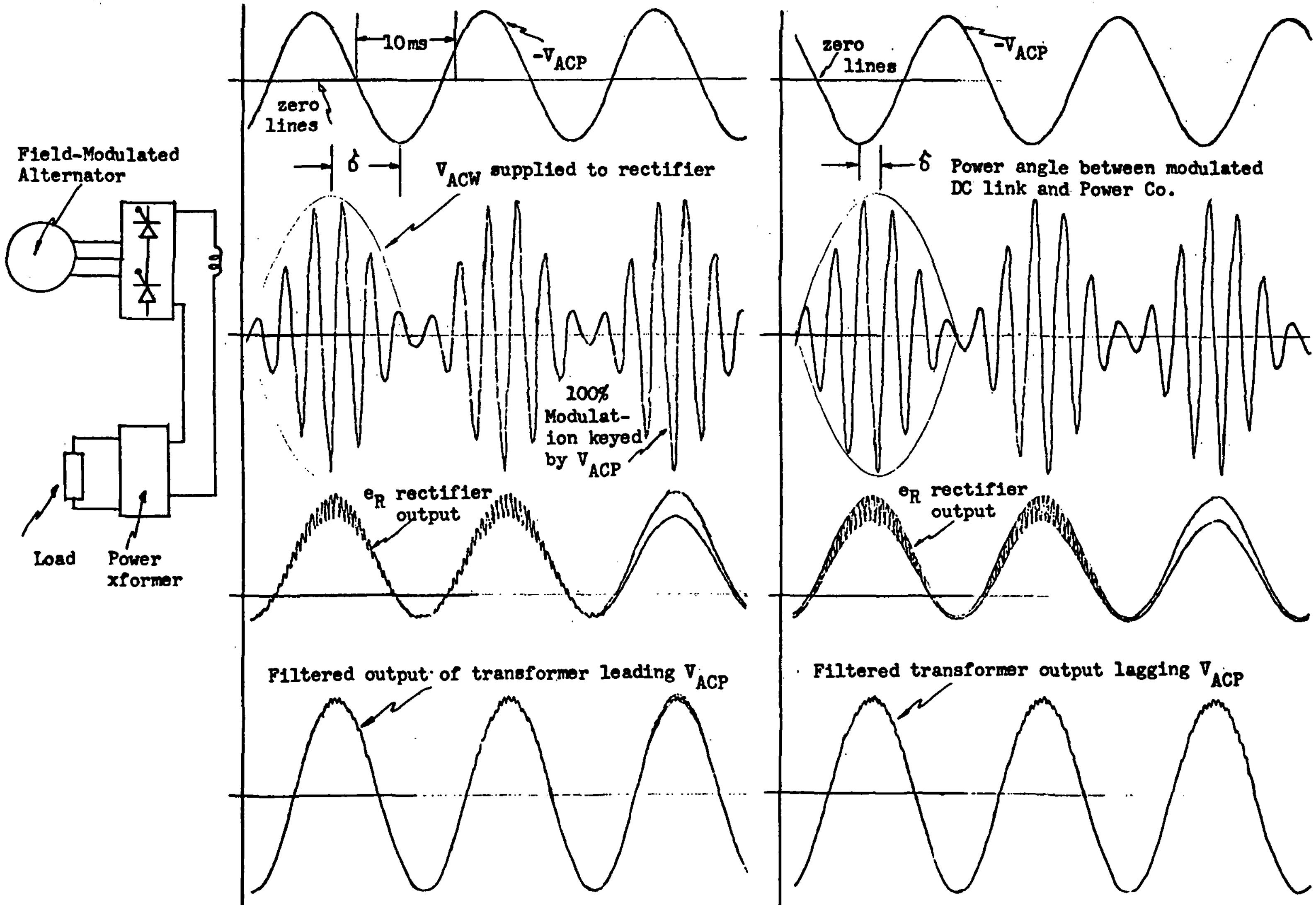

FIGURE 9. Six-Pulse Bridge Rectifier Operating From a Field-Modulated AC Alternator.

AN ELECTRICAL GENERATOR WITH A VARIABLE SPEED INPUT - CONSTANT FREQUENCY OUTPUT

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ABSTRACT

A new type of rotary energy conversion device for obtaining a desired constant frequency output independent of the speed of the prime-mover has been developed and tested, using the technique of field modulation and solid-state alternator output processing. This paper describes a 10-kilowatt prototype field modulated frequency down converter system designed, built, and successfully tested at Oklahoma State University. Experimentally obtained performance characteristics are presented and discussed.

PRINCIPLE OF OPERATION

A conventional three-phase synchronous machine of basic frequency f_r will have induced voltages of frequencies $(f_r + f_m)$ and $(f_r - f_m)$ when excited with an alternating current of frequency f_m; $f_r > f_m$. When such three-phase voltages are individually full wave rectified and their outputs tied in parallel, an output voltage containing the following components results:

(1) dc component
(2) Ripple of frequency $6 \ f_r$
(3) Full-wave rectified sine wave at the frequency f_m;

$$V|\sin \omega_m t| \text{ where } \omega_m = 2\pi f_m$$

The dc component is, in general, proportional to the reciprocal of the modulation frequency ratio m, where $m = f_r/f_m$. For values of m greater than 10, this component becomes negligibly small. The resulting full-wave rectified sine wave can be converted to a sine wave voltage at the modulating frequency f_m by using a suitable switching circuit employing controlled rectifiers.

DESCRIPTION

Figure 1 shows a simplified schematic of the frequency down converter system. It is built around a high-speed high-reactance high-frequency three-phase alternator. Both rotor and stator are laminated to minimize the iron losses. The six stator leads are brought out and three full-wave bridges are connected as shown, one across each of the phases. The outputs of the bridges are tied in parallel across the load through a silicon controlled rectifier switching system. Tuning capacitors C are connected across each of the stator windings to decrease the excitation requirements (both watts and vars) at the rotor terminals. The main switching process is accomplished by the four controlled rectifiers, SCR1 through SCR4. The commutating circuit consisting of L_2 and C_2 and the controlled rectifiers SCR 5 and SCR 6 aid in this switching process, especially when the load is not purely resistive. In addition to filtering, capacitance C_3 enables the handling of lagging power factor loads by the system.

The field is excited by an ac power source of frequency f_m. Since this frequency fixes the output frequency, care must be exercised in the design of this part of the system. In case the system is required to be completely self starting, an inverter dc source combination must be used to excite the field. The dc power might come from an exciter alternator-rectifier unit mounted on the same shaft as the main generator.

The 10-kilowatt 220-volt single-phase 60-hertz prototype designed and built has 16 poles and runs at around 7000 rpm. This corresponds to a frequency f_r of about 930 hertz. For a modulating frequency of 60 hertz, m is between 15 and 16. The dc component associated with this value of m is essentially negligible and causes no problem in the switching action of the SCR circuitry. The rotor diameter is 6 inches and active iron length is 2.5 inches. Overall dimensions of the generator are a diameter of 9.75 inches and a length of 7.75 inches. The electronics associated with the system can be arranged compactly. A photograph of the 10-kilowatt prototype system is shown in figure 2.

PERFORMANCE RESULTS

The efficiency of the generator for three values of stator tuning capacitors is shown in figure 3 plotted against output power. Figure 4 shows the rotor input power for three values of C. Stator tuning capacitors significantly improve the performance of the system.

The desirability of rotor tuning is brought out in figure 5. Rotor tuning reduces the volt-ampere capacity required of the excitation source.

The voltage regulation of the frequency down converter is improved by the variation of the effective rotor reactance with output power (see fig. 6). Figure 7 shows the variation of the output voltage from rated output rated voltage conditions as the output power is decreased. It can be seen that with $C=5\mu F$, the output voltage stays essentially constant down to about 40 percent of rated load. Smaller values of C do not result in this desirable characteristic. It is possible to exploit this property by properly choosing C to obtain nearly constant output voltage from low-load to full-load conditions.

CONCLUDING REMARKS

The field modulated generator system (FMGS) described in this paper has several advantages and potential applications. Since the output frequency is independent of the prime-mover speed, variable speed prime movers such as the ones available in aircrafts or unregulated high-speed turbines and wind energy devices can be used to drive the generator.

In addition to being smaller in size and weight, it has inherently better regulation and independence from rotor inertia effects. The principle of operation appears to be applicable to systems of any size. The efficiency of the system is similar to those of conventional systems of equivalent rating. Whereas a conventional synchronous machine operating in parallel with bus bars can receive or deliver power (motor or generator) to the supply, FMGS can operate only as a generator because the bridge rectifiers will prevent any power flow from the bus bars to the generator. The behavior of the FMGS operating in parallel with an existing power system under normal and fault conditions is yet to be completely explored. The results obtained from the prototype are promising, and further development, testing, and design optimization are underway.

DISCUSSION

Q: Do you have any idea what the dollars per kilowatt would be on, say, a 1-megawatt unit?

A: Again, you play the game the way everyone else here has played the game; that is, if you want to build a million of them, the price will be quite low. We've made a fairly careful analysis of it, and if you built a lot of them in reasonable sizes, about a hundred dollars per kilowatt is our projection. We are also standing ready to sell you some, up to the 60- to 100-kilowatt level, at a very much inflated price over that unless you want to order four of five hundred thousand of them.

Q: What is the working rpm of that generator?

A: The generator that we showed operates at 7000 rpm. It would operate successfully at any speed from, we think, around 1200 to 10,000 rpm. A 5 or 6 to 1 speed range is not inconceivable. We built it to operate at 7000 rpm because that was the nature of the prime mover in the pulley arrangement we had to begin with. We could, of course, design it to operate from, say, 500 to 5000 rpm. You take your choice as to what the speed range is. You propeller people tell us what the speed range should be and what gearing should be, and we will easily accommodate 5 to 10 to 1 speed variations, we think, with no particular problem. This particular machine's most spectacular characteristic is obtained if you run it at its rated load condition, and then if you simply turn off the power to the prime mover you will find the 60-hertz sineusoid absolutely stable until there is no prime mover turning at all. You will find, of course, that its amplitude varies.

Q: That is a brushless generator?

A: It is not a brushless generator at present. We built it to handle brushes because we figured we could make it much lighter that way. We checked with various people about brushes, and we found that in terms of trying to get a constant frequency output for variable frequency input brushes would be the least of your problems. We think we can make it without brushes, and we are proceeding in that particular direction now.

Q: Can you synchronize this on a single powerline and match your modulate with a power angle, or with the power output ahead of that?

A: We've done that, yes. You see the thing is that the frequency can be obtained directly from the powerline, as your particular discussion indicated, and then the problem is no problem at all. The only thing that you can't do with this particular machine is pump power from the powerline into it, which we consider an overwhelming asset, and that is the reason we designed it that way.

Q: Can you contrast your generator with a Precise Power Corporation's generator?

A: No, because we don't have complete information on the Precise Power Corporation's variable speed generator. We are interested in getting that information, and we will give them free access to all of ours and hope that they would reciprocate.

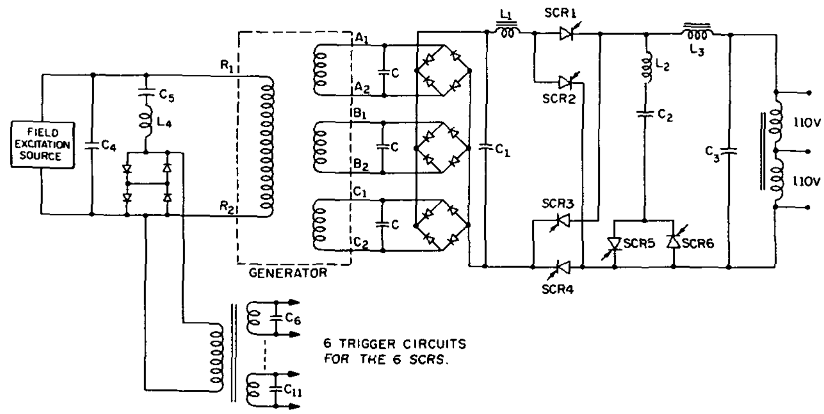

Figure 1. Simplified schematic of the field modulated generator system developed at Oklahoma State University, Stillwater.

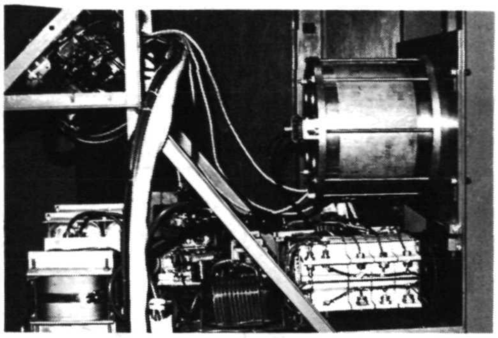

Figure 2. Photograph of the 10 kw generator prototype and the associated electronics (prime-mover not shown).

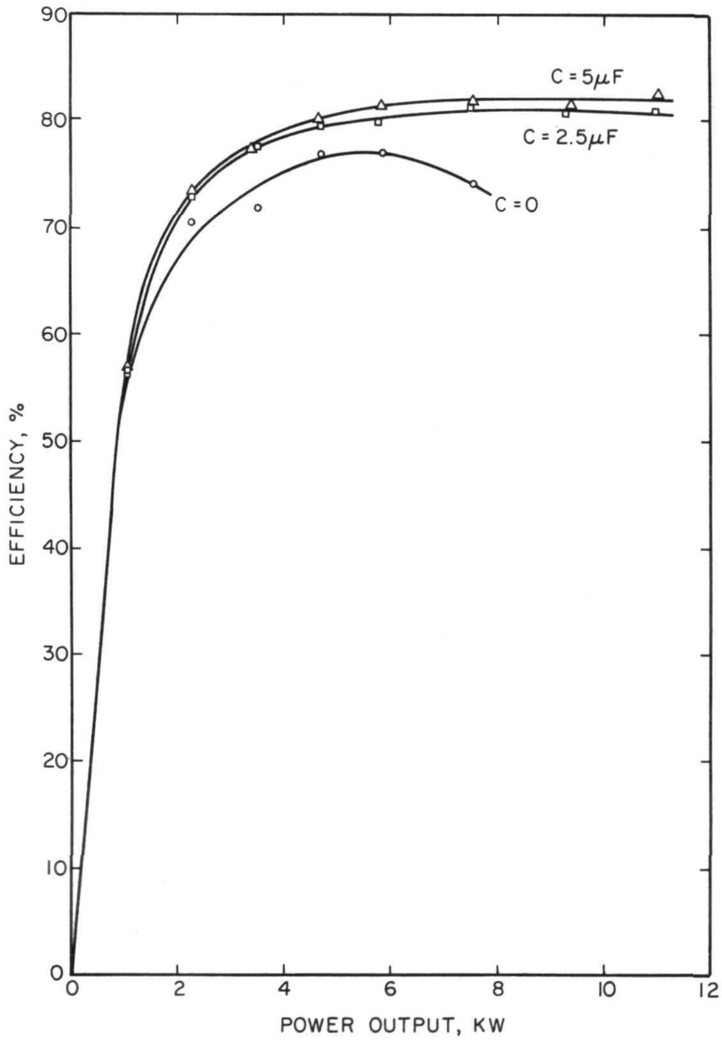

Figure 3. Efficiency versus output characteristic.

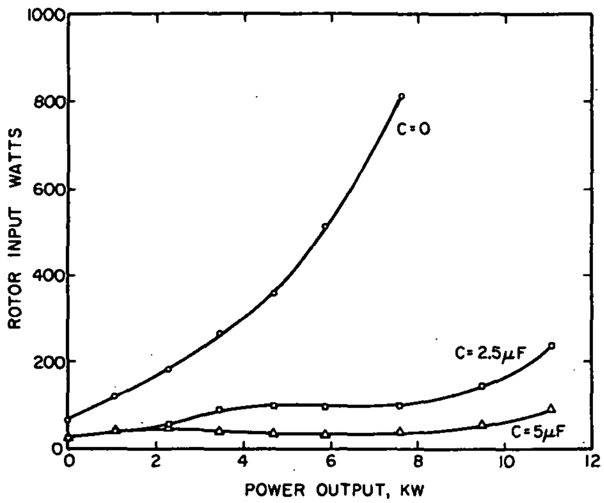

Figure 4. Variation of the rotor input power with output.

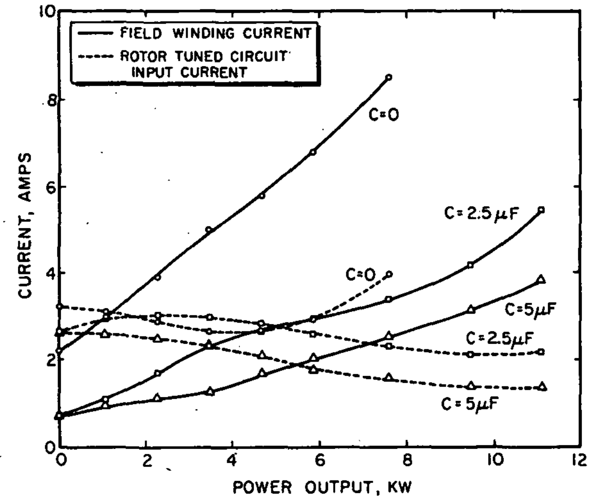

Figure 5. Variation of field winding and rotor circuit input currents with output.

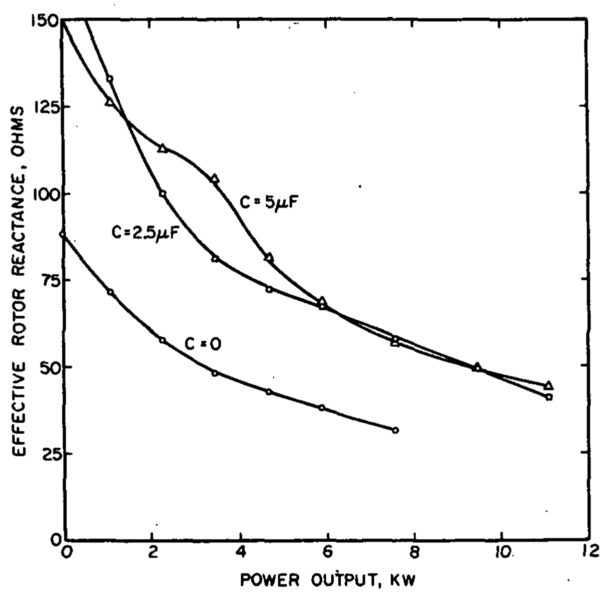

Figure 6. Plot of effective rotor winding reactance for different values of C and output.

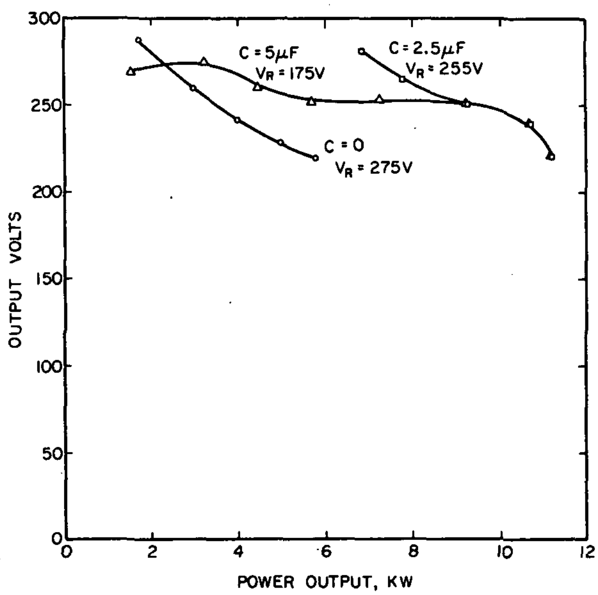

Figure 7. Voltage regulation characteristic of the 10 kw prototype.

VOIGHT VARIABLE SPEED DRIVE

Joseph Tompkin

Salem, Oregon

The variable speed drive transmission is mounted within the gondola and connected with the wind turbine blades and the hub. This unit is designed for the production of ac power. The turbine turns by means of the variable speed drive and a set of synchronous three-phase generators. This motion is controlled automatically by two wind rosettes in such a way that the wind turbine always opposes the wind direction.

Adjustable speed is frequently a problem. For the majority of machine applications, mechanical speed changers are eminently suited and often provide the simplest and most economical answer. Efficiency of power transmissions employing mechanical principles runs to over 90 percent. Through the elimination of complex hydraulic, pneumatic, and electrical elements, mechanical speed changers are simple in design, manufacture, operation, maintenance, and exchange of all structural parts.

The Voight variable speed drive is a mechanical variable positive drive gear transmission. It has an unlimited power and torque transmission, a constant ratio with high degree of accuracy, a speed variation over a wide range, and a nonslip drive. The following are some specific advantages:

(1) Any desired speed range is available from 1 to infinity.

(2) Smooth acceleration is possible from zero to maximum speed and deceleration is possible from maximum speed to zero for any character of load.

(3) Any practical number of positive drive stable speeds are available for any chosen speed variation, and they are accurate to a split rpm even with varying loads.

(4) Variable speed drive model 58100 (enclosed) covers three speed ranges from 0 to 120, 120 to 360, and 360 to 840 rpm and reverse speeds from 1220 to 2320 rpm. There are 320 nonslip fixed speeds hand adjustable under load while operating the drive.

(5) Jogging or preset speed is controlled by automatic acceleration or deceleration.

(6) Dynamic braking exists for quick automatic stopping or where

controlled deceleration of load is required.

(7) There are multiple driving units with related speeds paralleling applications controlled from a single control (for applications where two or more machines must be "link" synchronized).

(8) Operation is by remote control.

(9) There is visual speed indication of operating rate in rpm or as desired.

(10) The Voigt variable speed drive meets the demands of all three general types of power transmission: Constant torque, constant horsepower or variable horsepower, and variable torque except in the very low speed range where the horsepower is somewhat limited because the torque tends to infinity, which is impractical.

(11) Ball bearings are used to reduce friction.

(12) All operating parts are splash lubricated.

(13) Applications are possible for powers from 5 to 10,000 horsepower.

(14) Load shocks are relieved by resiliency of the chaindrive incorporated in the unit and its autotant tension.

(15) Voight variable speed drive provides a means of controlling the speed ~~of one~~ or more standard ac induction motors by simply controlling the frequency of the power applied, thus making them variable speed drives.

If wind power were to be used primarily for pumping water, instead of generating electrical power, it is most practical to produce compressed air by means of a radial type compressor built into the wind turbine hub (see enclosed data sheet and schematic diagram).

DISCUSSION

Q: Have any of these units ever been built or are these just designs?

A: The first prototypes have been built, the first one in Los Angeles. What you just saw was simply patent descriptions. We would like to get involved in building this variable speed transmission, because it will control the fluctuation of the wind velocities in our turbines. This is perhaps a key to the controls so that we can maintain or have a constant voltage on alternating current generators.

ENERGY STORAGE USING HIGH-PRESSURE ELECTROLYSIS AND METHODS FOR RECONVERSION

William L. Hughes

Oklahoma State University
Stillwater, Oklahoma

About 12 years ago, the School of Electrical Engineering at Oklahoma State University undertook what became a rather extensive and continuing study (both theoretical and experimental) on ways to store electrical energy and thereafter reuse the stored energy in various ways. Initially (about 1961), theoretical studies were undertaken of various possible storage methods, which included the following:

(1) Mechanical storage (flywheels and related devices)
(2) Pumped storage (hydroelectric)
(3) Cryogenic magnetic fields
(4) High-pressure electrolysis (producing hydrogen and oxygen)

From the outset, the O.S.U. group was concerned with developing energy systems which showed promise of being expandable to large-scale power systems. Thus, systems requiring exotic materials (such as platinum) were rejected from study as having little long-term possibilities on a commercial scale.

The result of our initial theoretical studies on energy storage seemed to indicate (to us at least) that high-pressure moderate temperature electrolysis had the greatest long-term economic promise, and our rather extensive experimental programs on storage were concentrated in that area. Over an 8 or 9 year experimental period, we have worked in the area of electrode design (both solid and porus), electrode and membrane life, and overall electrolysis system efficiency.

The primary results of the energy storage activity can be summarized as follows:

(1) A number of electrode designs were examined. The most successful was a solid nickel finned type of electrode (fig. 1). Electrolysis efficiencies in excess of 85 to 90 percent were achieved. Efficiency is defined as the ratio of the heat content of the gases produced to the equivalent electricity used to produce the gases. Current densities for these results ran at 400 to 700 amperes per square foot. Optimum pressures were around 200 atmospheres and optimum temperatures around 350° F (see figs. 2 and 3).

(2) Enough information was obtained so that a practical, efficient electrolysis system could be designed, built, and operated.

(3) Some studies were made of the projected cost of deep cavern high-pressure gas storage which indicated this technique could be feasible in some locations as long as gases were stored below normal hydrostatic pressures.

Simultaneous with the energy storage research, we undertook both theoretical and experimental studies of ways to reuse the stored hydrogen and oxygen as well as certain other energy conversion methods. The areas of effort in reconversion are as follows:

(1) Moderate temperature, high-pressure hydrogen-oxygen fuel cells using no noble metal catalysts were studied.

(2) The "aphodid" burner-turbine generator concept was studied (a method of burning hydrogen and oxygen in a long tube with an injected moderating water spray such that steam could be generated at any desired temperature and pressure).

(3) The field modulated generator system was studied (covered in an earlier paper in this meeting because of its obvious direct applicability to a wide variety of variable speed prime movers such as aeroturbines and unregulated high-speed gas turbines).

The results of the work on energy reuse were as follows:

(1) Fuel cells operating at pressures up to 200 atmospheres and 300° F were built. The effects of temperature and pressure were experimentally mapped and typical characteristics are shown in figures 4 and 5. All fuel cell work, as well as all electrolysis work, was done with nickel electrodes and no special catalysts. Rechargeable hydrogen-oxygen fuel cells employing a porous membrane (cylindrical geometry, fig. 6) made of calcia stabilized zirconia and sintered nickel electrodes with no noble metal catalysts were investigated extensively to study the effects of pressure, temperature, and membrane porosity.

(2) The aphodid burner (fig. 7) turbine generator system has never been built, but some years ago Dr. Stanley Brauser (a thermodynamicist then on our mechanical engineering staff) studied this at our request and concluded that efficiencies around 40 percent were obtainable (electrical equivalent Btu output over fuel Btu input). The difference between this and conventional plants is primarily the elimination of stack losses. Probably another few percent can be picked up by combining the field modulated generator (discussed earlier) with the aphodid burner. This would allow turbines to run at much higher speeds and probably at somewhat higher temperatures. These two factors yield higher turbine efficiency.

(3) The results on the field modulated generator have been reported; no other comments are required other than to say that it is fast approaching the stage of direct application to variable speed mechanical inputs.

(4) Finally, it should be noted that high-pressure hydrogen can be used as a basic ingredient in very efficient conversion of organic materials to various hydrocarbon fuels, including methane. We have begun to gather

technical material in this area, assisted by Dr. Wm. Crynes of our Chemical Engineering Department. Dr. Crynes is a recognized authority in coal gasification, and this area will be pursued as vigorously as resources permit.

The work described herein has, of course, been spread over several years. Much of it, initially at least, falls into the hazardous category. We have a specially built hazardous reaction facility, and, much of the work has been done there (figs. 8 and 9). That facility essentially provides an "explosion proof" chamber where reactions involving hydrogen and oxygen can be safely handled. We believe that we can formulate the rules for designing high-pressure moderate temperature electrolysis and fuel cell systems which operate safely. That, however, is a completely separate subject.

Finally, a complete wind generator energy storage system built about 5 years ago just to get an idea of the overall energy availability is shown in figure 10 on a 20-foot test platform at the airport laboratory facility. Figure 11 shows a close up, and figure 12 shows the details of the electrolysis system.

DISCUSSION

Q: How do you foresee the potential eventual use of these types of systems? Do you ever see the day when they could possibly be domestically used. There is the safety problem with hydrogen.

A: First, we're studying ways to use high-pressure hydrogen to hydrogenate organic materials to synthesize hydrozenes and methanes, and this looks very promising. So, one application that we have missed is a way of making synthetic vehicular fuels. It is not necessary to convert hydrogen to electricity to get a lot of good use out of it. Second, I'm a little nervous about using hydrogen as a domestic fuel. Looking at what we call our "Allison's boom room", the hazardous reaction facility, we have had some explosions there in a controlled environment. We think we now know how to handle hydrogen safely. At least, we haven't had any explosions for three years. Third, there is a lot of use that can be made of the hydrogen in heaters besides just converting it to electricity.

Q: I wonder if I understood the efficiency figures you had correctly. The 68 percent you gave was power into the electrolyzer compared to power out of the fuel cell?

A: When I said 60 percent overall, I meant kilowatt hours out of the fuel cell divided by kilowatt hours into the electrolyzer.

Q: Any comparable figure for the electrolyzer and gas turbo combination?

A: It's about 40 percent.

Q: You raised the question of using hydrogen in the home. I have an article that says there are two or three miles of hydrogen pipeline in Germany that has been used for 20 or 30 years.

A: I didn't know they were using it for home use, but I'm intensely interested. The Germans have, of course, been handling high-pressure hydrogen in pipelines much longer than we have and are very experienced in it. I'm hopeful it can be used in the homes.

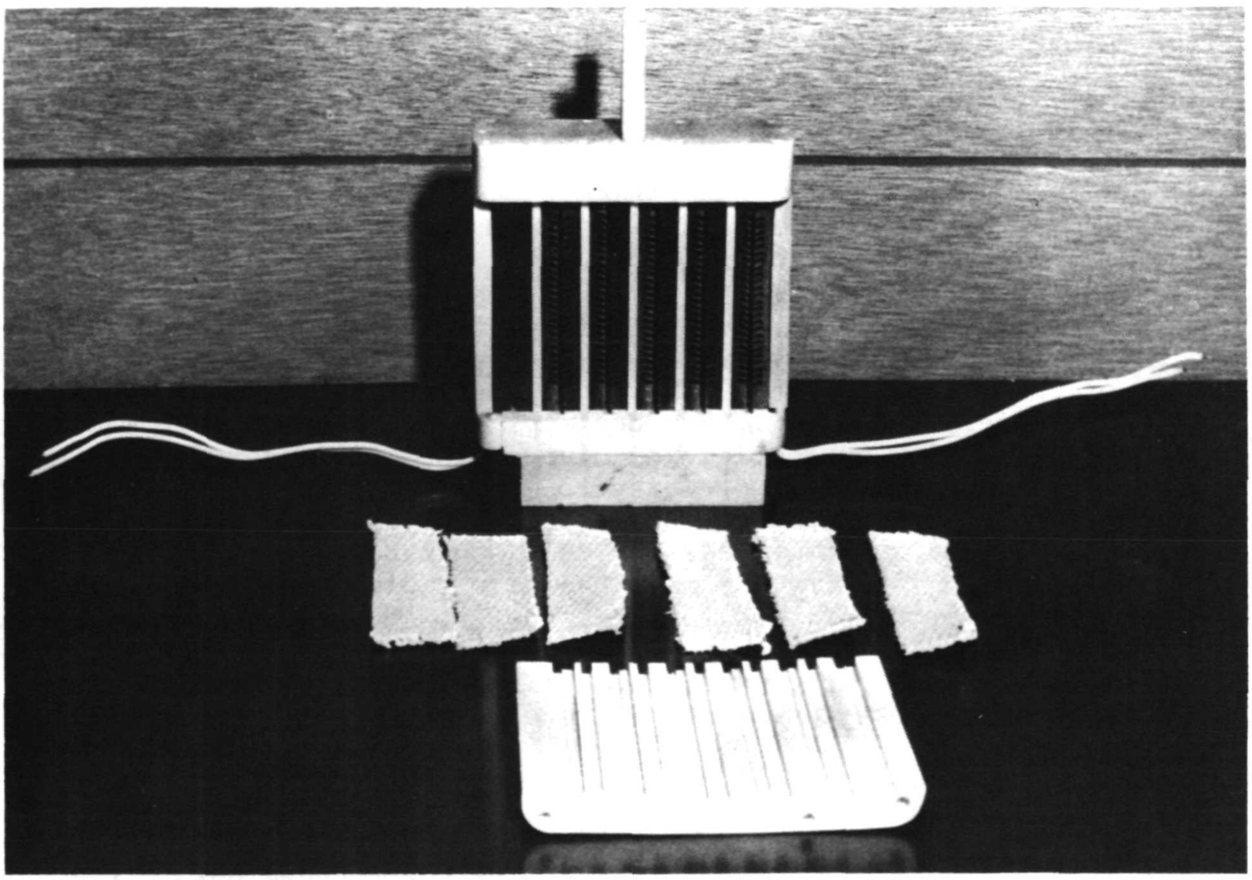

Figure 1. Photograph of six cell electrolysis module.

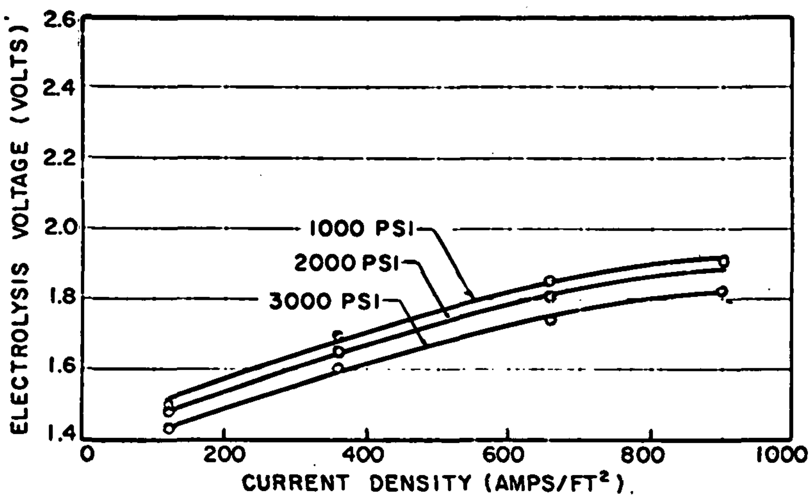

Figure 2. Effect of pressure on electrolysis cell performance at 300°F.

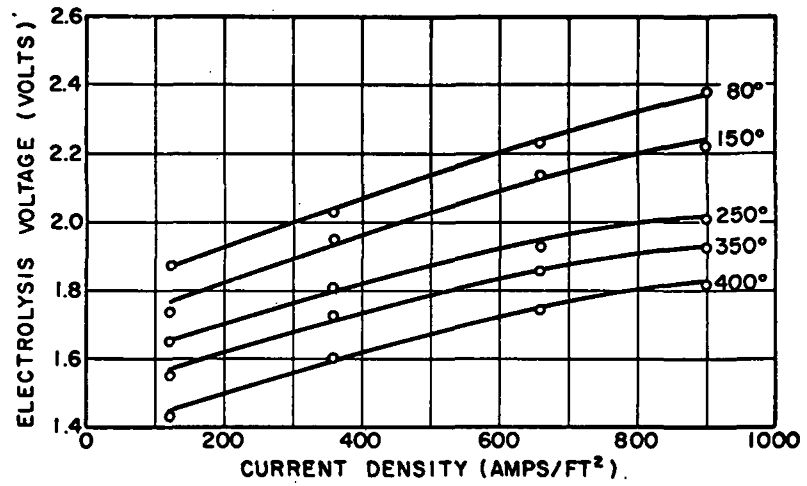

Figure 3. Effect of temperature on electrolysis cell performance at 2000 PSI.

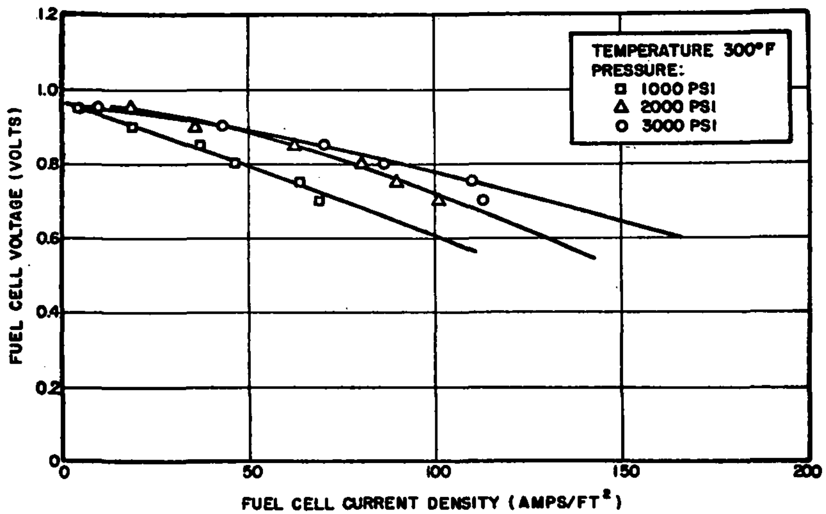

Figure 4. Effect of pressure on the fuel cell polarization curve; foam metal nickel electrodes with diamond lattice structure.

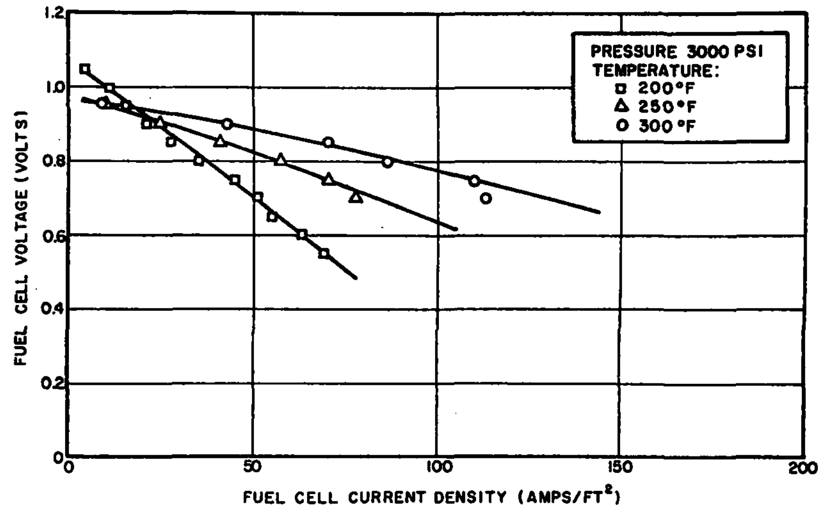

Figure 5. Effect of temperature on the fuel cell polarization curve; foam metal nickel electrodes with diamond lattice structure.

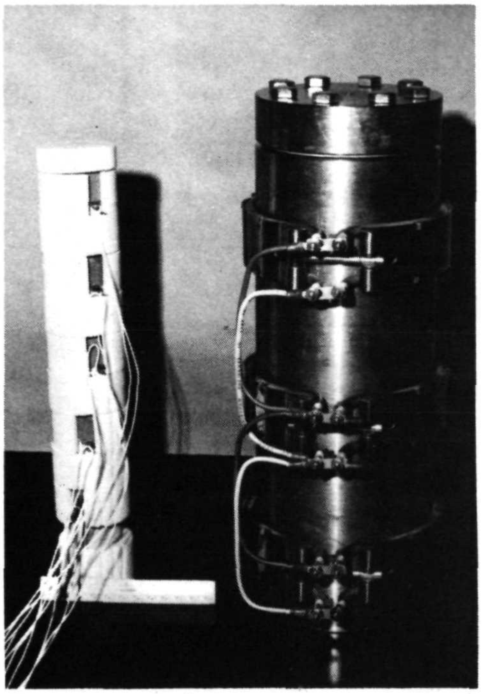

Figure 6. Photograph of a five cell battery of rechargeable fuel cells employing cylindrical porous zirconia membranes and sintered nickel electrodes.

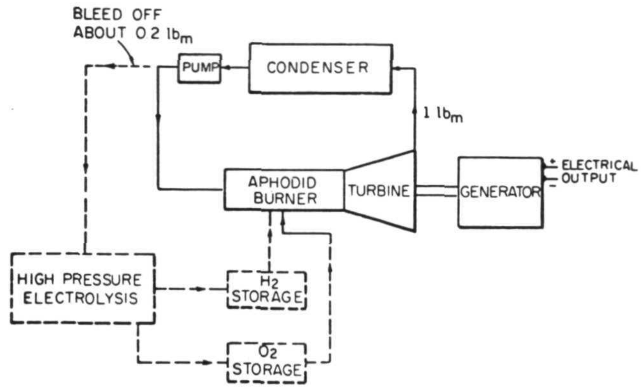

Figure 7. A simple Aphodid flow diagram.

Figure 8. OSU Hazardous Reaction Facility.

Figure 9. View of the hazardous reaction chamber of the hazardous reaction facility.

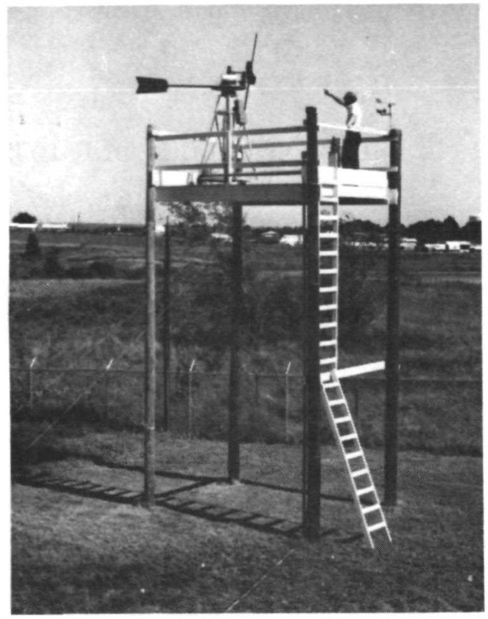

Figure 10. Photograph of the 500 watt experimental prototype wind energy storage system mounted on a twenty foot platform.

Figure 11. Close-up view of the experimental prototype wind energy storage system.

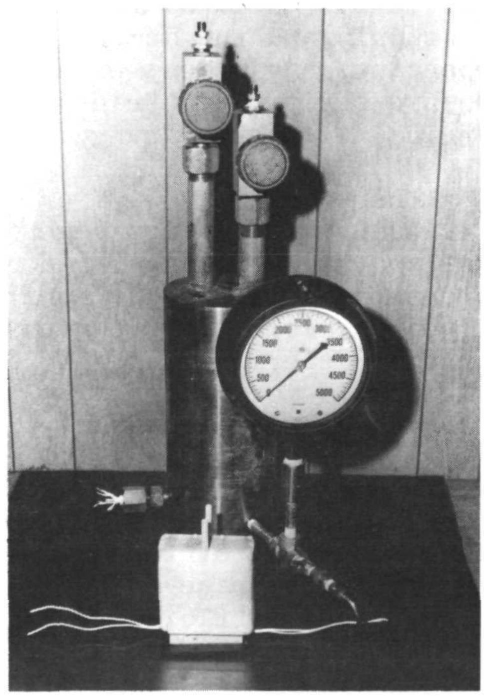

Figure 12. View of six cell electrolysis module with the high-pressure test chamber in background.

USE OF HYDROGEN AND HYDROGEN-RICH COMPONENTS AS A MEANS OF STORING AND TRANSPORTING ENERGY

Walter Hausz

General Electric Company
Santa Barbara, California

TEMPO has been interested in advanced energy utility systems, which we call Eco-Energy Systems (fig. 1) where the ecology and economics are kept in balance. Our conclusion has been that using hydrogen for transport and storage can lead to very clean, flexible systems that with improving technology and depletion of natural fuel resources can become competitive. While the primary source of energy is shown here as nuclear, the basic concept can apply for any thermal source, or for wind energy, etc. (fig. 2).

With a nuclear reactor an important reason for using hydrogen storage is to keep efficient full-load operation of the reactor while the customer demands fluctuate. With wind, Sun, and tidal energy, both the supply and the demand fluctuate so some form of storage is even more important. Hydrogen, or hydrogen plus oxygen, is an important candidate, because of its easy transport by pipeline and the flexibility it has for serving all of the energy sectors.

There are many ways of storing energy (fig. 3). The merits for a particular application depend on such things as the energy density, the ease and flexibility of reconversion to a form of energy useful to customers, and the cost per unit of delivered energy. Energy density (fig. 4) and flexibility of conversion are, of course, important ultimately for cost determinations. Hydrogen as a cryogenic liquid and as metal hydrides is more attractive than hydrogen as a gas. Of course, the hydrides of nitrogen (NH_3) and carbon (gasoline) are even more compact.

There is a rough road ahead to get the costs down. The costs of storage vessels can be reasonably determined (fig. 5, curve from the source material of the Synthetic Fuels Panel). But to really determine the cost of storage we have to examine all the energy conversions required, their efficiency, and their capital cost.

To illustrate (fig. 6), I've assumed a 1-megawatt wind energy source that operates half the time. Half of its output is used to serve customers directly as electricity; the other half is to be stored. For a system of this size, a cost of electricity at the generator of 10 mills (one cent per kilowatt-hour) may be low, but it is a convenient unit. As conversions of the storage portion are made to hydrogen, to liquid hydrogen, to stored LH_2, and back to electricity, the energy costs and capital costs of the conversions escalate the unit cost per kilowatt-hour remaining until electricity at 12.9 cents per kilowatt-hour results. Figure 6(a) shows the next level of detail of the assumptions.

Many of the high costs result from scale size and would be less for a 100- or 1000-megawatt system. With adequate research, technology will improve all of these. Such alternative means of storage as Mg_2NiH_4 and $FeTiH_2$ are being actively explored at Brookhaven National Laboratory both for mobile and utility applications. And for all but the biggest systems they may be less costly than LH_2.

Another possibility, which in the largest systems may be the best, is storing in the form of ammonia (fig. 7). While this concept shows both electricity and fossil fuel used to make the NH_3, either could be used alone.

In conclusion, system configurations that consider the storage alternatives are an important part of the research needed to achieve economic viability.

DISCUSSION

Q: One of your figures appeared to show a block with heat energy going into something and hydrogen and oxygen coming out. Are you really showing thermal dissociation as a way of making hydrogen and oxygen?

A: I made that block diagram very general so it could cover everything. But thermal dissociation of hydrogen, particularly things like the Marketti process, Mark 1 process, is one of the things that on a very large scale look best. But this, of course, requires a thermal source and this is a wind energy conference; thus, electrolysis is the means of preference.

Q: Most people dealing with hydride storage tend to talk about the volume of hydrogen that can be stored in a given volume of storage material, but since the installed cost of that system depends on how much you have to buy, would you care to comment on how many pounds of hydride or whatever is required to store it?

A: Well, let's deal in terms of per cubic foot, and I said that with liquid hydrogen you get about 4.4 pounds per cubic foot, whereas with ease you can get 6 pounds of hydrogen per cubic foot. Now the density of magnesium - and magnesium nickel is principally magnesium (only about 6 percent nickel) - is, I think, about 2 or $2\frac{1}{2}$, so you've got about 150 pounds of magnesium for your 6 pounds of hydrogen. Iron titanium is, of course, a higher density, about 5 or 6, so you've got more pounds, but it's a cheaper material. For portable use like in a car, you probably want magnesium. For utility use, I think the iron titanium with its lower cost per pound is probably superior.

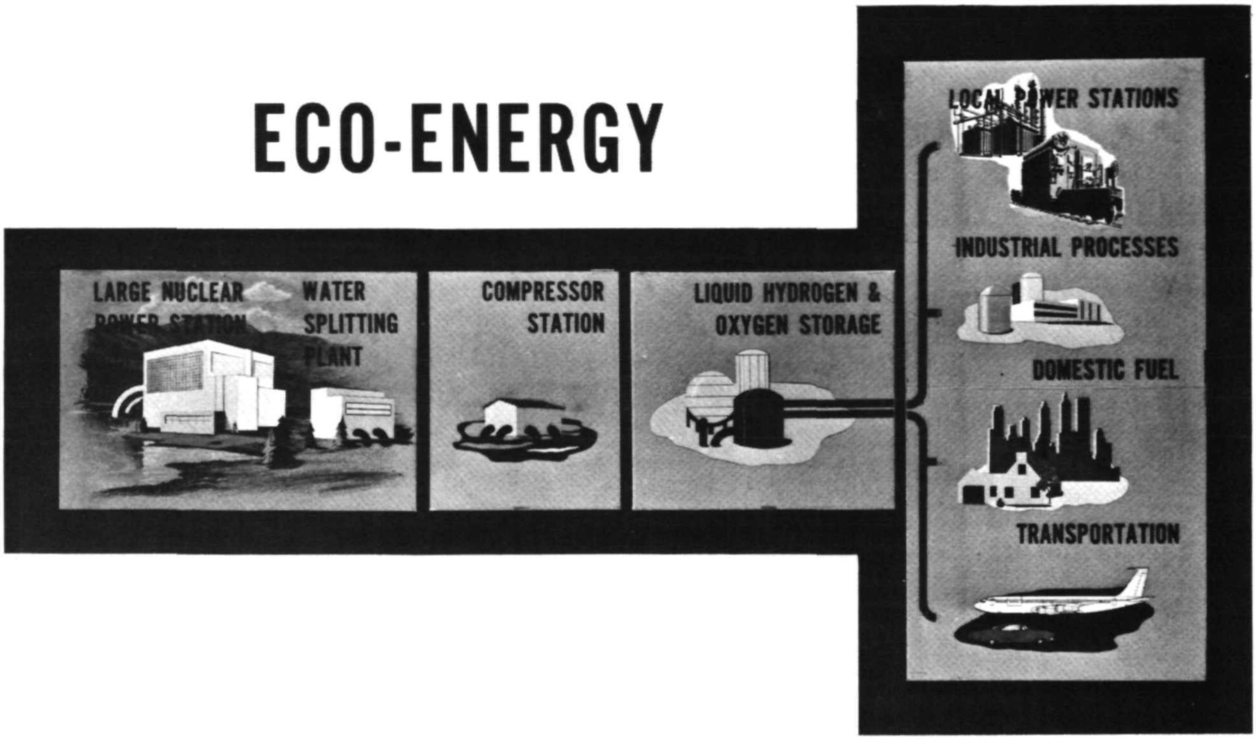

Figure 1

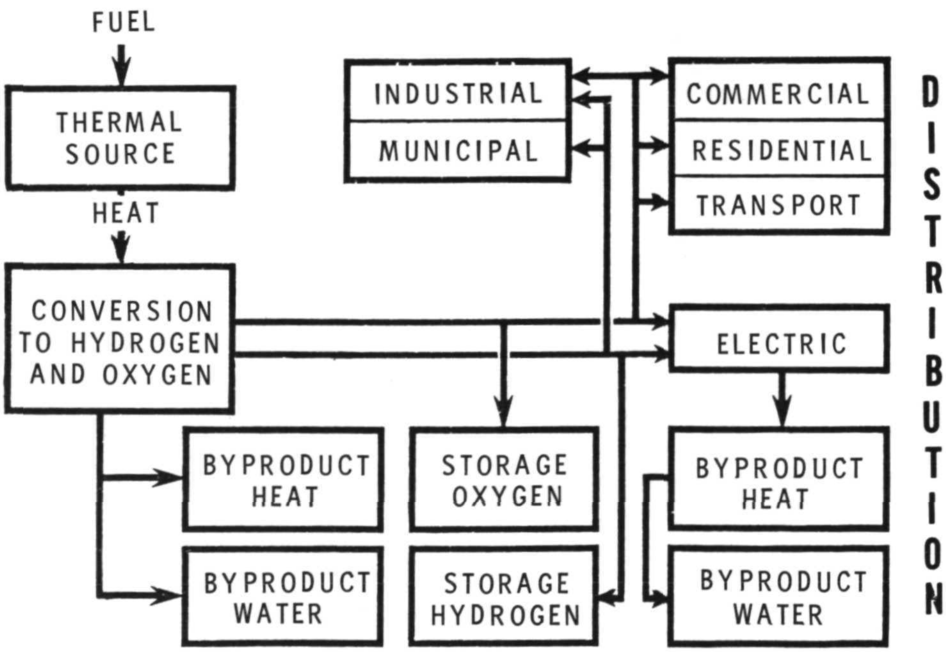

Figure 2

MEANS OF STORAGE

MECHANICAL
HOT ROCKS/METAL
HOT WATER/STEAM
MOLTEN SALTS

HYDROGEN
- GAS
- LIQUID
- HYDRIDES

AMMONIA
METHANOL
GASOLINE

BATTERIES

Figure 3

ENERGY DENSITY

			BTU/FT^3
PUMPED STORAGE	(100 ft head)		14
HOT ROCKS/METAL	60-500°F		8,000-12,000
MOLTEN SALTS	60-500°F		10,000-20,000
STEAM	15 psi	212°F	40
	130	347	340
	500	467	1,270
WATER	15	212	9,000
	130	347	16,000
	500	467	21,000
HYDROGEN			
• GAS	15	60	280
	1,000	60	18,500
• LIQUID	15	-425	200,000
• HYDRIDE	(Mg_2N_i or F_eT_i)		250,000
AMMONIA			340,000
METHANOL			430,000
GASOLINE			830,000
BATTERIES			10,000-80,000

Figure 4

FUEL STORAGE INVESTMENT (1972 BASIS)

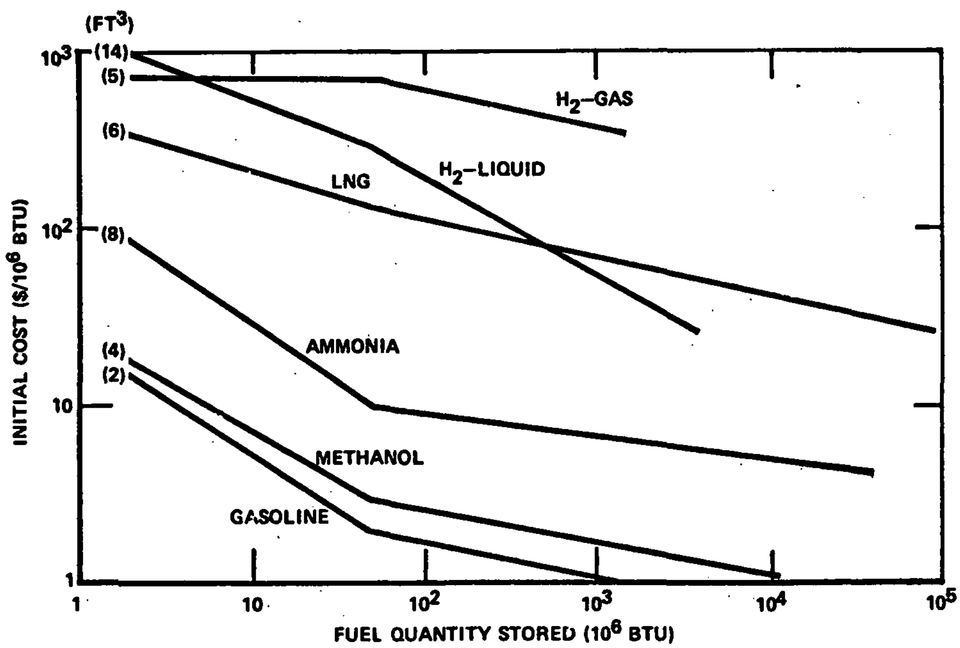

Figure 5

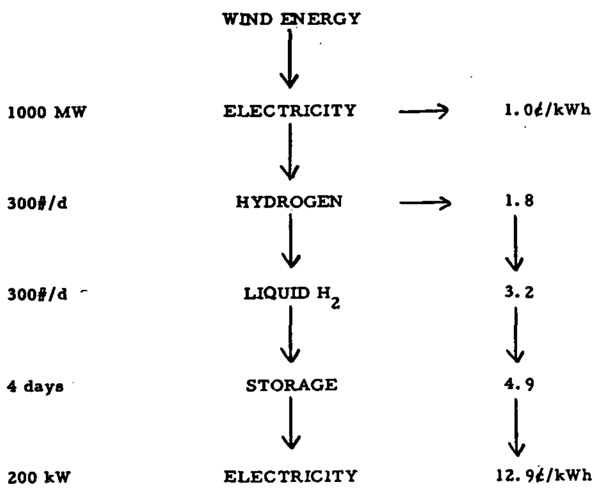

Figure 6

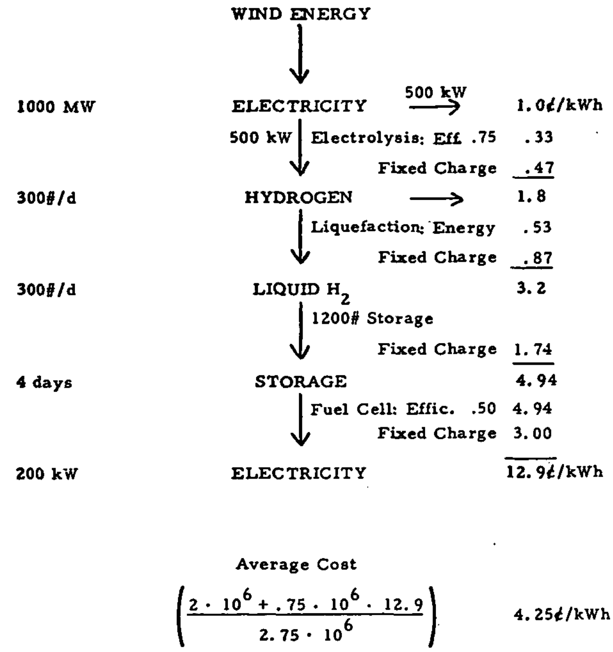

Figure 6A

FLOWSHEET OF AMMONIA SYNTHESIS

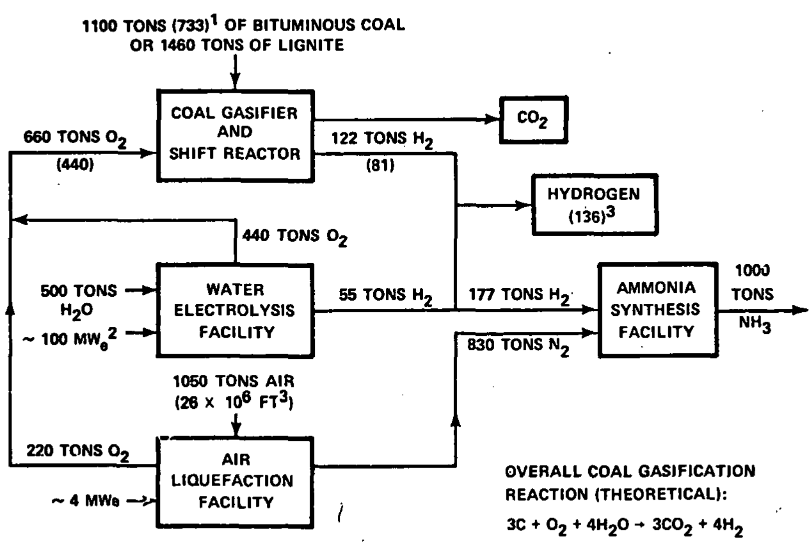

Figure 7

STATUS AND APPLICABILITY OF SOLID POLYMER ELECTROLYTE TECHNOLOGY

TO ELECTROLYTIC HYDROGEN AND OXYGEN PRODUCTION

W. A. Titterington

General Electric Company
Lynn, Massachusetts

PRESENTATION SUMMARY

The General Electric Company solid polymer electrolyte (SPE) water electrolysis technology is presented as a potential energy conversion method for wind-driven generator systems. Under development since 1967, this technology is relatively new, and further significant improvements are projected over the next 5 to 15 years. Electrolysis life and performance data are presented from laboratory-sized single cells (7.2 in^2 active area) with high cell current density selected (1000 ASF) for normal operation.

The SPE water electrolysis technology has the following inherent design capabilities as a candidate energy conversion technique in either small or large scale wind-driven generator systems:

(1) Long life capability to reduce refurbishment costs, with increased reliability
(2) High current density capability to reduce cell capital costs and size
(3) High-pressure capability for hydrogen transmission by pipe line or storage
(4) Minimum power input requirement to reduce operating costs and generator electrical capacity

Performance data with demonstrated life to approximately 9000 hours at current densities between 1000 and 1400 ASF are presented. High-pressure life data up to 3000 psi are also presented at the selected nominal design condition. Based on current technology, projections of cell life as a function of operating temperature are made which are supported by life data to 29,000 hours. For the selected design point of 1000 ASF at 180° F, a 60-cell module is sized to produce 5 pounds of hydrogen per hour with a power input of 112 kilowatts. The module would weigh 135 pounds and be approximately 16 inches in diameter by 8 inches thick. Present capital cost for a total water electrolysis system is estimated to be $3000 per pound per hour of hydrogen capacity.

Based on continued development, projected energy and capital cost improvements are presented up to the year 2000. Energy requirements

of 18 to 20 kilowatt-hours per pound of hydrogen are projected for the 1985 to 1990 period, dropping to as low as 15 kilowatt-hours per pound hydrogen by the year 2000. A capital cost of $785 per pound hydrogen per hour capacity is considered obtainable for the 1985 period, with reduction to $250 to $350 per pound hydrogen per hour by the year 2000.

DISCUSSION

Q: I am very curious of these electrolysis systems. What does the quality of the water have to be, and what effect does the quality of the water have on the expected life of the membrane?

A: As I mentioned before, we do use an iron exchange membrane principle. This is used in other applications to remove contaminants, for example, remove iron from water. So any sort of iron that would tie up the sites within the membrane would affect the performance. The performance would decrease, or the voltage go up. Its life would remain the same as long as that contaminant level doesn't increase with life.

Q: Is iron the only contaminant? What about salts?

A: We have demonstrated chlorine generators, just putting plain salt water into the system.

Q: Do you have to use distilled water?

A: Yes, you have to use water maybe of the order of 500,000 iron centimeters.

Q: This is high quality water. If we're considering a wind generator in an isolated site, it's like a water treatment factory. It's just a consideration. I'm not unfamiliar with the system.

A: Yes. That should be considered in any trade-off study, too.

Q: You mentioned you have some modern metals. What is it you have?

A: Our anode catalyst is a proprietary type catalyst. It does have platinum in it. On the cathode side it's a straight platinum catalyst. The loadings are down around 2 to 4 milligrams per square centimeter, very low loadings, so that we are now, rather than trying to reduce the catalyst loading to get the cost down, attacking the problem from the high current density point of view to keep the size of the cell down. We have somewhat reached the limit on the present catalyst systems.

SUPERFLYWHEEL ENERGY STORAGE SYSTEM

David W. Rabenhorst

Johns Hopkins University
Silver Springs, Maryland

Until recently, the use of flywheel storage systems has been limited to a very few applications. The principal disadvantages of these devices have been the limited energy storage capability (about one-tenth of that of a lead-acid battery), the poor energy storage efficiency (short run-down time), and the danger of catastrophic failure.

Modern technology has provided a tenfold improvement in flywheel energy storage capability since 1900. There have also been significant improvements in rotor drag from bearings, seals, and aerodynamic resistance, resulting in greatly improved energy storage efficiency.

Unfortunately, however, the hazard of catastrophic failure of the conventional steel flywheel has increased, because of the great increase in the energy of the failed pieces in the high-performance steel flywheel. Thus, even these higher performance flywheels have been limited to applications where either adequate failure protection can be provided or (usually) where the performance can be derated sufficiently to provide an adequate margin of safety.

This margin typically increases as the flywheel size increases. For example, the theoretical maximum performance of an optimized steel flywheel using the best available material is about 26 watt-hours per pound. Practical limitations reduce this to about 12 watt-hours per pound for a small, 30-pound flywheel (ref. 1). In a current program involving a 1400-pound steel flywheel, the rated performance is 6 watt-hours per pound (ref. 2), while a third steel flywheel weighing 480,000 pounds is rated at 0.75 watt-hours per pound (ref. 3).

For the past 3 years the Applied Physics Laboratory has been studying a new superflywheel concept. It appears to offer greatly improved safety, and its performance can be better than that of the best optimized steel flywheel. Its configuration allows sufficient distribution of failed particles in size, direction, and total time; thus, effective failure containment appears to be a practical objective.

The use of superflywheel energy storage will considerably enhance the performance of future onsite energy systems, such as solar and wind energy systems. Its chief advantages will be lower total cost and freedom of maintenance of the storage system. It will have several times the operating life of lead-acid batteries, and it will also readily accept high-power peaks associated with heating and air conditioning equipment and cooking. This same capability to accommodate high power peak loads makes the flywheel especially attractive for wind power machines, where peak power can easily range up to several times average minimum power.

The amount of kinetic energy that can be stored in a rotating flywheel is equal to the specific strength of the material used times some constant related to the geometry of the flywheel. The basic element of the superflywheel is the thin rod shown in figure 1. A number of these rods are assembled in a pregrooved hub lamina (fig. 2) so that they fan out in radial orientation (fig. 3). Thus, the free ends of all of the rods are in essentially pure tension when the assembly is rotated. Adjacent layers of hub laminae are assembled 90° in rotation to each other so as to form the circular brush configuration (fig. 4).

The failure of any rod represents but a tiny amount of the total energy in the rotor, and even if all of the rods failed simultaneously, the failed pieces would be distributed evenly around the periphery; thus, the stress concentrations are minimized in the containment structure from the failed pieces.

In contrast, the stress concentrations in the containment structure caused by the failure of a conventional solid steel flywheel could be several thousand times as great, since it would (typically) break into three large pieces, instead of thousands of tiny pieces.

Another advantage of the superflywheel configuration is that it allows optimal use of filamentary composite materials. These materials not only exhibit many times more strength to density (hence energy storage capability) than steel, but they absorb very large amounts of energy upon failure, as illustrated in figures 5 to 10. A number of 30-inch long rods about 1 pound each (fig. 5) were spun to destruction in a special test setup (fig. 6). In each test a steel ring was used to contain the fragments at failure. From the destruct sequence shown in figures 7 and 8, it can be seen that the rod is completely destroyed before the steel ring has begun to move from the impact of the failed pieces. The rod virtually exploded into the dust-sized particles shown in figure 9. Also, by comparing the shape of the steel ring after the test (fig. 10) with its other known characteristics, it was established that only about $1\frac{1}{2}$ percent of the kinetic energy in the spinning rod reached the steel ring as impact energy. It would thus appear that the superflywheel brush configuration offers the first prospect of realistic failure containment for a high performance flywheel.

There now appear to be about ten different materials that seem to offer more economical energy storage (W-hr/$) than the lead-acid battery. Some of these materials are glass, fiber glass, Dupont Fiber B and PRD-49, music wire, and some new proprietary materials. Thus, a successful superflywheel development would provide an energy storage system with the economy of the lead-acid battery, but without any of its limitations (maintenance, depth of discharge, low power peak capability cycles to failure, emissions, low efficiency, dc to ac conversion, etc.).

Also, a wind power system using the superflywheel for energy storage can be considerably more efficient than systems using any other known energy storage concept. This stems mainly from the fact that the wind machine energy can be transmitted directly to the flywheel through gears and shafting at very high efficiency. The flywheel, in turn, can be connected directly to the ac generator without the need for gearing. A nominal flywheel speed range of 2:1 can be accommodated by several generator types capable of producing constant voltage and frequency output under these conditions.

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3. Superflywheel Meeting, Inductive Energy Storage Task Group, Naval Research Laboratory, Mar. 13, 1972.

DISCUSSION

Q: Have you found PRD-49 is better than carbon for your purposes?
A: The one thing I failed to point out is that the most critical thing is energy storage per dollar, watt hours per dollar. Never mind amperes per cubic foot or square foot or watt hours per pound or anything else, except of course safety, which is on top of the list. PRD-49, at the present time, is about one-tenth the cost of graphite fibers and also has about the same performance. Therefore, it's ten times as good, if all other things are equal, and with PRD-49 they essentially are. It just so happens there is one material which is almost a hundred times better than PRD-49. And that happens to be wood. The strength of wood is about one-tenth the strength of steel; the density of wood is about one-tenth the density of steel. So the strength and density are the same. The energy density is the same as steel; in fact, it's a little bit better - 20¢ per pound.

Q: I understand that you use this material because of the tension. The problem seems to be two-fold as I understand it. The problem is the angle of the wire. This angle is not safe. Is that the reason why you choose the brush type?
A: Are you talking about the Gyroscopic forces?

Q: If you wound the wire, then when the angle comes up a problem arises. The energy density is high for a wound wheel.
A: That sounds like it's true, but it's not. You get more theoretical energy per space. No one in the published literature has ever achieved more than about 30 percent of the theoretical energy in a wound configuration. The reason is very simple. The only place on that wound wheel where the stress lines up with the filament is the

outer edge. Everywhere else there is a radial component, which is unfortunately a differential radial component with radius and therefore will always break in concentric rings. The only way you can stop this is to add radial filaments. It does turn out that there are combinations of orthogonal filament arrangements we have patents on which can be used to make a solid wheel. It is applicable for some materials like fiberglass, Scotch ply, and so on. In my opinion, the reasons for doing this are economics versus safety. If you're building a million pound wheel, you would never build it this way. This configuration I'm talking about in a million pound wheel would have no component in it except the hub that I couldn't carry over my shoulder in one arm.

Q: It is interesting that about 17 years ago I happened to be with the General Electric Company in the space power work. When we looked at flywheels then and with the high strength steels that we had, without the benefit of these composite fibers and fiber technologies, I just looked at the prediction we made then; it was 26.4 watt-hours per pound.

A: It's about 26 watt-hours per pound maximum now. The Germans are building a 480,000 pound flywheel, and it's rated at three-quarters of a watt-hour per pound.

Q: When we speak of the energy inherent in the rotation of a mass like the flywheel, we very customarily calculate that energy on the basis of how much is stored on the basis of full rotational speed minus the zero energy at standstill. Immediately then, there are two questions. The first of these is we must recognize that this energy is in a mechanical and not electrical form. In the second place, just as we can't expect storage batteries to provide us with the full output, in other words, drain them to zero level of content, we at the same time can't effectively expect all that energy from the flywheel. So I would like to ask you to address a few comments to the dual points.

One is how and with what effectiveness, with what degradation if you will, do we extract this energy on a repetitive in and out basis. And secondly, how can some sort of a fairly steady-state extraction of that energy take place, say from the standpoint of non-fluctuation of the voltage, rpm frequency, or whatever you intend to do with it. Could you give us a few comments on these?

A: How much energy is left in the wheel is of no consequence since in this instance that part of the energy never gets taken out. Even if it were, if I operated only over a speed range of 4 to 1, I can take 96 or 99 percent of the energy out of the wheel. On the question of mechanical energy versus electrical energy, we do not start with electrical energy. We start with mechanical energy; all I need is a contiguous generator of a variable field pole type, for example, which can accept the 2 to 3 to 1 input speed range and hold the output frequency precise and the output voltage within the required tolerances of approximately the percent. Now, if I go directly from the wind machine to the flywheel, the transmission energy is 100 percent.

It is not efficiency that I lose, it is a function of how long it takes the flywheel to spin down. In a rotor the size that would be adequate for a home installation, Professor Beams at the University of Virginia had a magnetically suspended rotor (several hundred pounds) adequate for a home installation with which he measured the deceleration rate of about 1 percent per week in his vacuum container. Now, somewhere between what he is doing and what is real, live practicality, we believe there is a realizable goal. We see a number of programs being initiated for the combination magnetic and mechanical bearings which can achieve a large measure of that efficiency. Now, to answer your final question, I've gone through many calculations and I can't get much below 80-percent efficiency from energy in to energy on the line as opposed to the 30's, 40's, and 50's that you'll get with every other system. It's that way. There isn't anything else in the system, whether you use the generator at 90-percent efficiency, and the electric motor to drive it, or if you connect it directly.

Q: I think I missed one very important point here. We are dealing with very high rotational speed disks and very slow speed windmills. How do you envision this coupling? You are not going to drive one of these disks directly with a windmill without a fantastic gear. How do you get this flywheel running at the enormous speed necessary?

A: There are two ways you can get the flywheel speed up. In the smaller systems, in which the size of the flywheel would be (could be) small compared to the rpm that you want to operate the wind machine in, you would have to change the speed mechanically by some means: timing belt, or gears, or rollers, all three are applicable. In the larger machines, it's much easier just to make the flywheel diameter compatible with the speed you want.

Q: How do you get this speed differential? You are operating a windmill at, say, 30 rpm.

A: Well, if you are operating a windmill at 30 rpm you can gear it up using pulleys, gears, rollers, and the like.

Q: You need a continuously variable speed transmission in order to accomplish this.

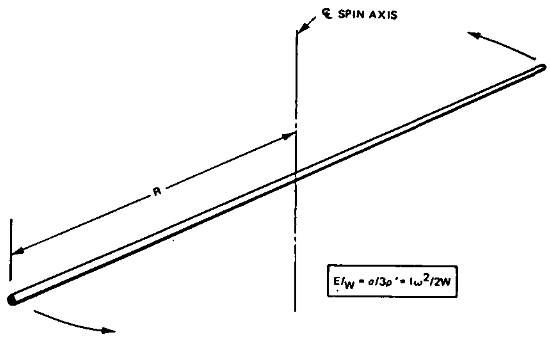
A: You either need a continuously variable speed transmission or you need something like a variable speed pole generator.

Q: How do you charge mechanically the flywheel? How do you charge at the various speeds? How do you build up the speed of the flywheel unless you have mechanical transmission to accomplish that?

A: I'm saying you can do it either mechanically or electrically. It's the reverse of driving an automobile, if you will. As a matter of fact, it's exactly like driving an automobile downbrake with regenerative brakes on. It's being done all over the world. And you can, indeed, either mechanically vary a transmission, which I had in my efficiency calculations (I had an electric variable field pole generator), or you could use a variable field pole motor.

Q: You have a windmill converting wind to electricity?

A: Definitely. Oh, yes. I'm sorry, I didn't mean to leave that out.



E = KINETIC ENERGY OF ROTATING ELEMENT (IN-LB)

W = WEIGHT OF ROTATING ELEMENT (EXCLUSIVE OF SHAFT AND HUB) (LB)

E/W = SPECIFIC ENERGY (IN-LB/LB) (MULTIPLY BY 0.314×10^{-4} TO CONVERT TO W-H/LB)

ω = ROTATIONAL SPEED (RAD/S)

σ = STRESS AT ROTATIONAL SPEED ω (PSI)

ρ' = MATERIAL WEIGHT DENSITY (LB/IN^3)

I = MOMENT OF INERTIA ABOUT SPIN AXIS (IN/LB/S^2) (FOR THIN ROD, $I = R^2W/3g$)

g = GRAVITATIONAL CONSTANT = 386 IN/S^2)

Fig. 1 ENERGY STORAGE CAPABILITY OF THE STRAIGHT FILAMENT

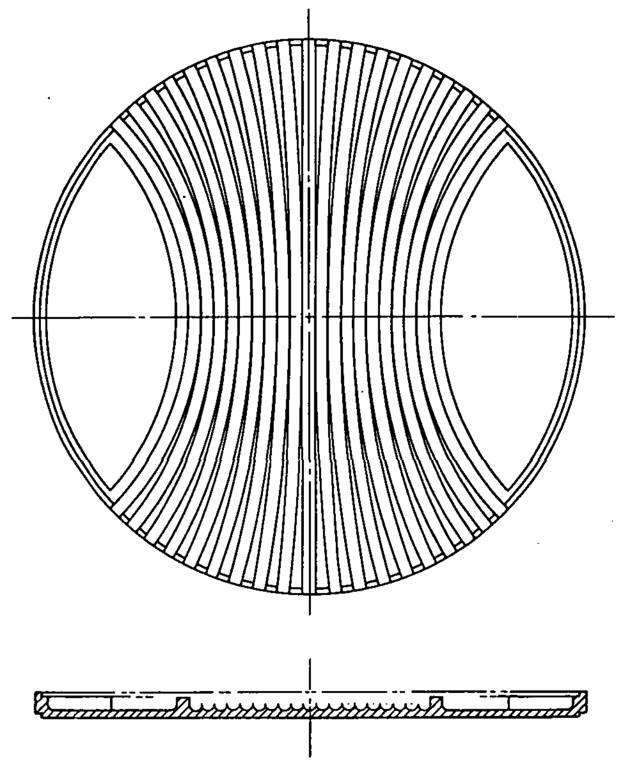


Fig. 2 TYPICAL HUB LAMINA

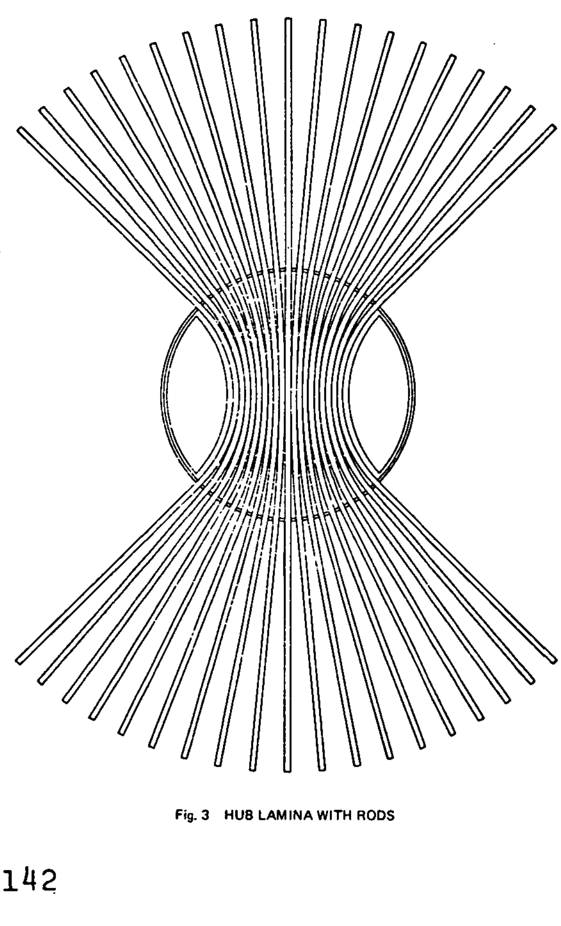


Fig. 3 HUB LAMINA WITH RODS

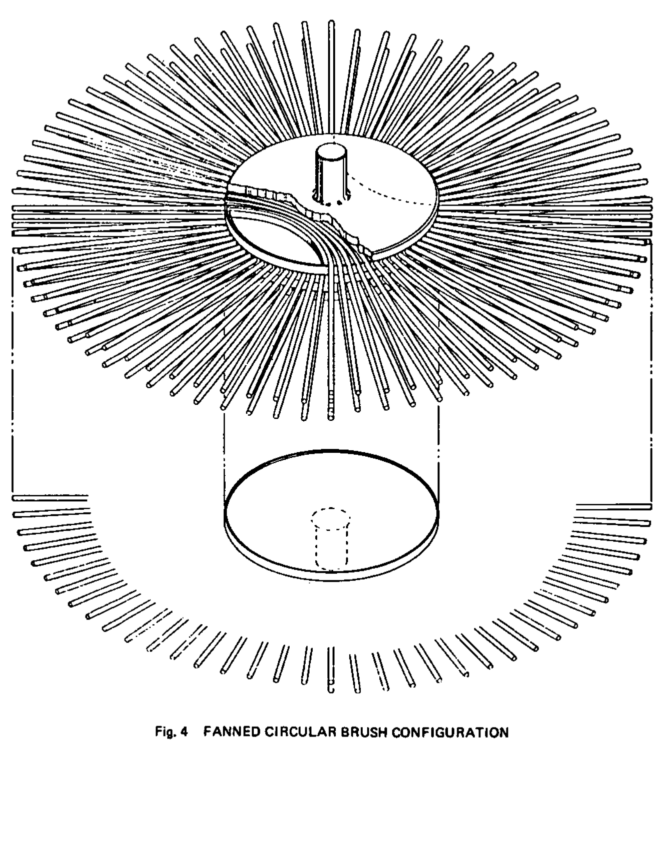


Fig. 4 FANNED CIRCULAR BRUSH CONFIGURATION

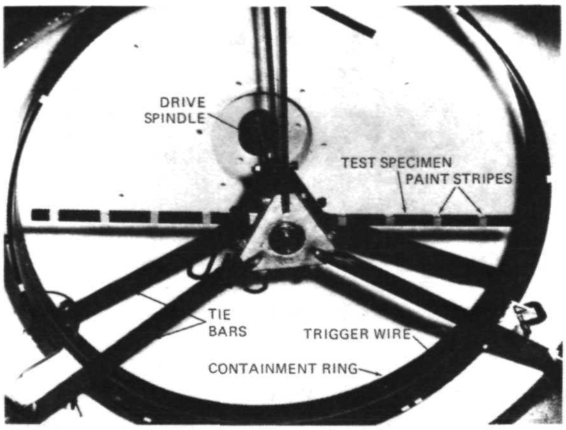
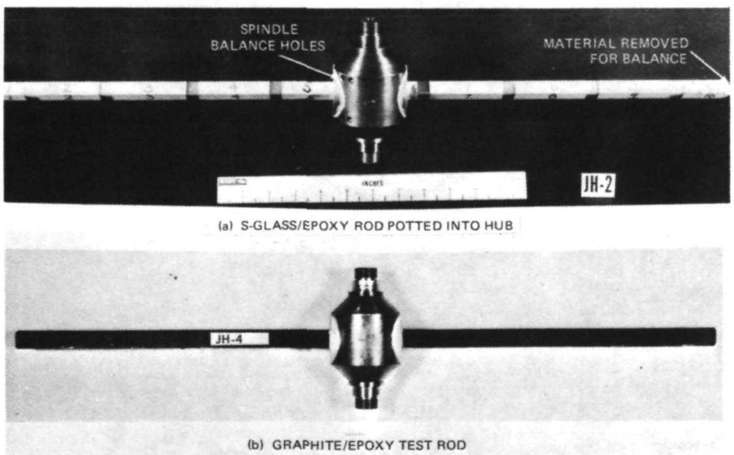


Fig. 5a INSIDE VIEW OF SPIN CHAMBER



(a) S-GLASS/EPOXY ROD POTTED INTO HUB

(b) GRAPHITE/EPOXY TEST ROD

Fig. 5b TYPICAL SPECIMENS FOR NAPTC TESTS

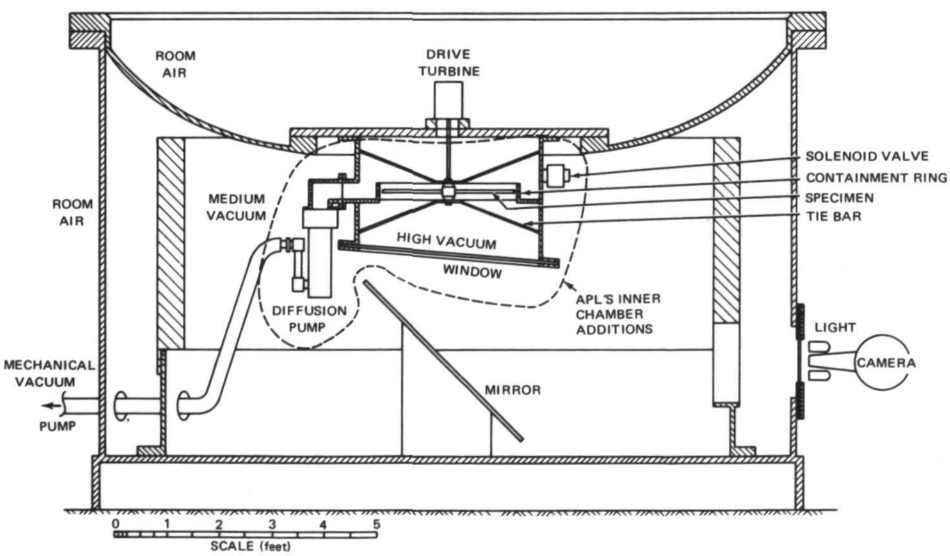


Fig. 6 GENERAL ARRANGEMENT FOR 1-POUND ROD TESTS AT NAPTC, PHILADELPHIA

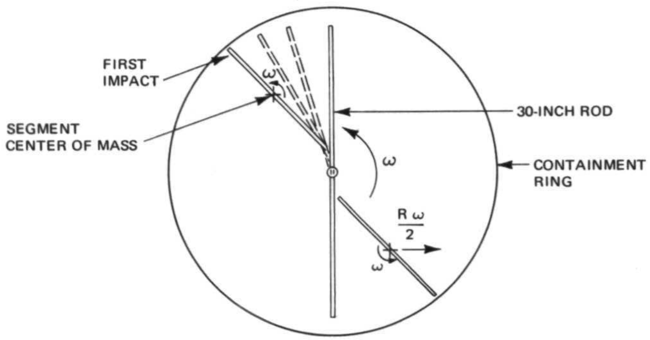
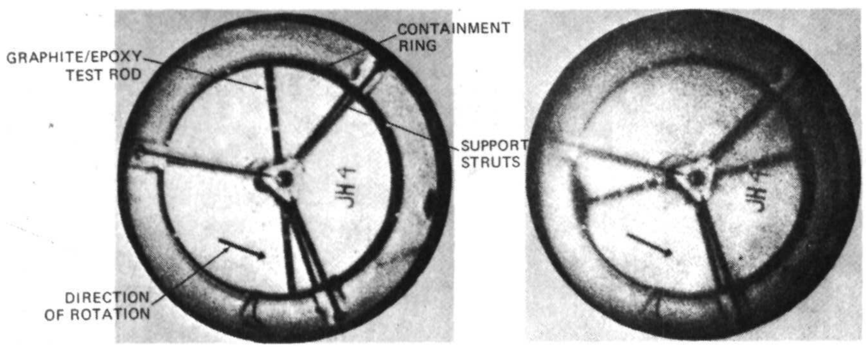


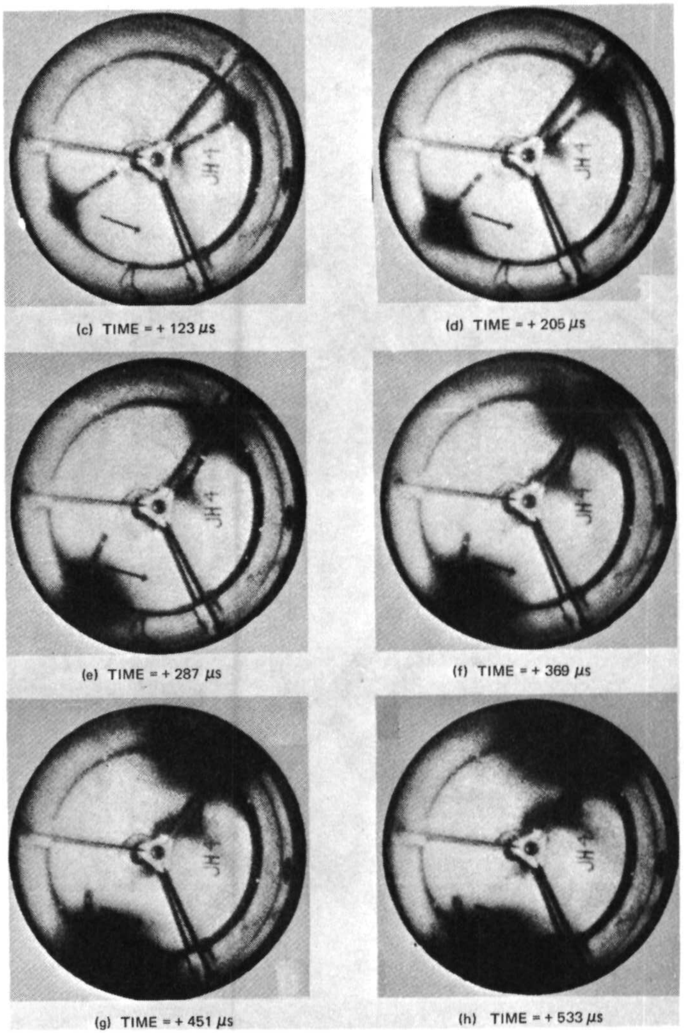
Fig. 7a KINEMATICS OF ROD FAILURE (ASSUMING TWO EQUAL SEGMENTS)



(a) PRETEST PHOTO

(b) TIME = + 41 μs

Fig. 7b PHOTOGRAPHS TAKEN BEFORE RUN JH-4 AND 7 TIMES AFTER FAILURE TRIPPED PHOTOGRAPHIC SYSTEM



(c) TIME = + 123 μs

(d) TIME = + 205 μs

(e) TIME = + 287 μs

(f) TIME = + 369 μs

(g) TIME = + 451 μs

(h) TIME = + 533 μs

Fig. 8 PHOTOGRAPHS TAKEN BEFORE RUN JH-4 AND 7 TIMES AFTER FAILURE TRIPPED PHOTOGRAPHIC SYSTEM

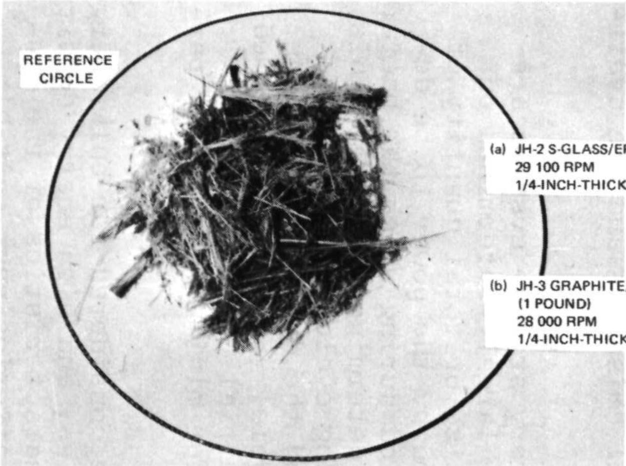


Fig. 9a S-GLASS/EPOXY FRAGMENTS FROM TEST JH-1

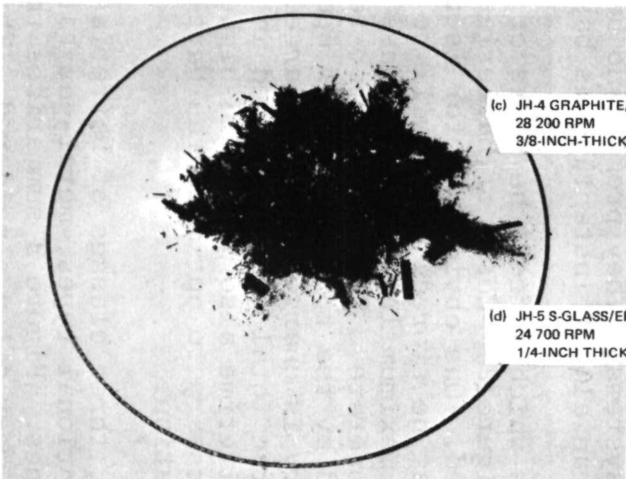


Fig. 9b GRAPHITE/EPOXY FRAGMENTS FROM TEST JH-3

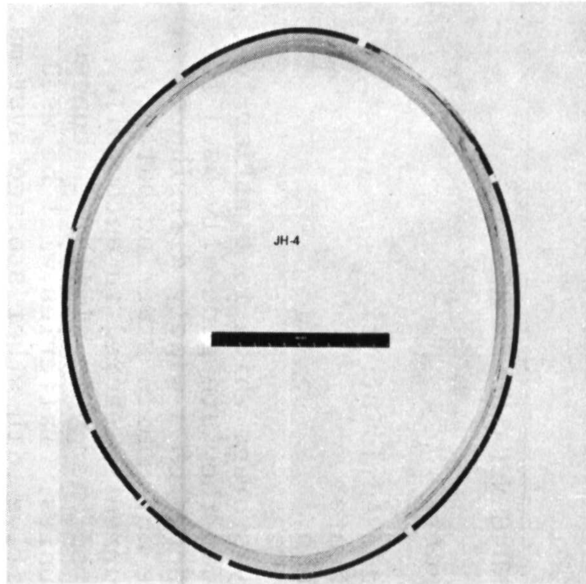


Fig. 10a DEFORMATION ON OF 3/8-INCH-THICK STEEL RING; ROD ENERGY OF 820 000 IN-LB

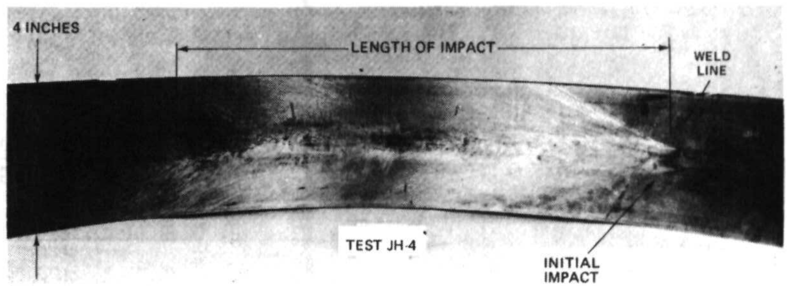


Fig. 10b ONE OF THE IMPACT ARCS ON THE CONTAINMENT RING

BATTERIES FOR STORAGE OF WIND-GENERATED ENERGY

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Batteries are the one form of energy storage which is familiar to everyone. What is often overlooked is that they are generally used for storing relatively small quantities of energy on a widely distributed basis, perhaps the best example being the automobile starting battery. An estimated 50 000 megawatt-hours are currently stored in automobile batteries alone. Storage of wind-generated energy is similar in concept, involving fewer but much larger storage units. Batteries will be used for this purpose if they are cost competitive with other storage systems. Due to time limitations, I will forego any discussion of how batteries convert chemical energy into electricity; I will concentrate instead on why batteries should be considered, what factors influence their costs, and a brief summary of the state-of-the-art of the most likely candidate systems.

Figure 1 shows the reasons batteries are considered for energy storage. Batteries are attractive because they are simple, easy to use devices which require no complex facilities and little repair or maintenance during their operating life. They can be built in convenient packages and are free of the geographic constraints found in pumped water or gas storage systems. They produce no harmful emissions and are available for use on an almost instantaneous basis.

The factors which affect the costs of battery storage systems are summarized in figure 2. Costs of batteries are largely determined on how they are used. One obvious factor is the size or total quantity of energy which must be stored. This will be fixed by the power to be delivered and the maximum length of windless period during which the battery is expected to operate. The next factor to be determined is life. This will be affected by the total number of operating cycles, the rate at which the battery is charged and discharged, and the depth of discharge, or fraction of the total energy removed in a cycle. Since designs aimed at maximizing lifetime also result in higher initial costs, it will probably be necessary to optimize the battery for minimum cost for a particular installation.

In general, three classes of batteries are considered for bulk energy storage - conventional types, metal-gas batteries, and high energy density alkali metal types. Figure 3 summarizes the characteristics of the conventional types most often considered. Three batteries seem suitable.

The lead-acid battery is the standard for comparison. For this service the energy density, which measures the size of battery required to store a given quantity of energy, is 10 watt-hours per pound. The power density, measuring its ability to deliver high current, is 20 to 30 watt-hours per pound. Batteries of this type are good for about 1500 charge-discharge cycles and cost about $80 per kilowatt-hour. It does not appear that this cost will be any lower in the future as this is a mature, cost-conscience manufacturing industry. An updated version of the nickel-iron battery is under development; it is expected to deliver 25 watt-hours per pound and 50 watts per pound. Cycle life is unknown, and a cost close to the lead-acid battery is projected. Since this battery produces substantial amounts of hydrogen on charging, reduced current efficiency and the need for frequent water additions result. The only other current competitor to lead-acid is the nickel-zinc cell. Substantial performance gains at comparable costs are expected, but the cycle life is only 200 to 400 cycles. In summary, at present no conventional battery appears able to compete successfully with the lead-acid battery for bulk storage.

Metal-gas batteries, shown in figure 4, have attracted attention because they promise at least a 4 to 5 improvement in energy density over the lead-acid battery. Zinc-air and iron-air cells offer the possibility of one free reactant which should reduce cost. Nickel-hydrogen is of interest because it makes use of two stable electrodes and should deliver long cycle life. Since air contains carbon dioxide which can reduce the life of air batteries, work on oxygen electrodes coupled with zinc or cadmium has been carried out. Each of these combinations requires air or oxygen electrodes which use precious metal catalysts. These offset the economic advantage of using air. Lifetimes measured from hundreds up to one or two thousand cycles are the best reported, so improvement is needed in that area. An attractive newcomer is an unusual zinc-chlorine battery built by Udylite Corporation to power an electric car. Chlorine is stored as a stable solid compound, chlorine hydrate, at temperatures below 10° C which eliminates the need to handle and store gaseous chlorine. Raw materials costs are low (16¢/lb for zinc and 3½¢/lb for chlorine), and inexpensive carbon can be used for the chlorine electrode. Life is unknown, but this system may have the best near term chance to replace lead-acid.

Exotic alkali metal batteries like those in figure 5 have received much attention in recent years. Energy densities of 100 watt-hours per pound and power densities of 100 watts per pound appear reasonable, and raw materials are plentiful and cheap. The most advanced is the sodium-sulfur battery which runs at 300° C and uses sodium beta-alumina, a ceramic-like sodium ion conductor as the solid electrolyte. Life has so far been limited to 2000 cycles or less. Even with cheap materials, costs of $10 to $30 per kilowatt-hour are expected. A substantially lower cost may be possible if a concept under development by Dow Chemical, which uses fine hollow glass capillaries as the electrolyte, can be brought to fruition. Argonne National Laboratory has pioneered another high temperature battery which uses lithium and sulfur. This system has suffered from severe corrosion problems and apparently will require expensive materials of construction. A lithium-chlorine battery development by Sohio has been unsuccessful. Only one large complete battery of this class has been built, a 30 kilowatt -- 30 kilowatt-hour sodium-sulfur battery to power a van. In general, these advanced systems are expected to require at least 10 years and $30 to $40 million worth of development to reach the point where they are ready for large-scale use.

Batteries work. The role they will play in wind power cannot be determined until a detailed analysis of the storage requirements of wind-generated energy systems is made.

DISCUSSION

Q: You mentioned $80 per kilowatt-hour for the lead-acid battery cost. I wonder if you could tell what's involved in that cost estimate? Also, I wonder if you have any idea what the efficiency of the lead-acid battery is?

A: Well, in answer to your first question, the cost I spoke of is the cost of the battery alone. That's about what it costs to buy commercial, industrial grade, lead-acid batteries, and it's probably as low as that cost figure is going to get. In answer to your second question, the energy in to energy out is a little more difficult, because you have to look at more than the battery. It depends on whether your wind system is driving an ac machine. If so, you're going to have to convert it to dc and use that to charge the battery; then you will have to take the dc out and convert it back to ac. If you can use dc power and produce dc power with your windmill, then your efficiency is going to be better. In that case it's probably going to be of the order of, oh, I'd guess about 60 to 70 percent. It depends on how fast you are doing the charging, and what your inefficiencies are. Without a specific design and a specific rate, it's a difficult question to answer. It will not be 100 percent.

Q: Which batteries are amenable to scaling to very large sizes?

A: That's a good point; I meant to bring it out and I forgot to.

Q: There is an auxiliary question here: where is the crossover point in shifting from very large batteries to the hydrogen-oxygen fuel cell group?

A: Let me first answer the first question. The one characteristic of a battery that you have to remember is that it does not scale well; a 2 kilowatt-hour battery tends to weigh about twice as much and cost almost twice as much as 1 kilowatt-hour battery. There is a scaling factor in practical cell sizes, but it's not like a piece of machinery, for instance, in which you can double the power by increasing the size of the wheel a very small amount.

That is the scaling factor for batteries is nearly linear in terms of the amount of energy stored. This is why you find batteries used and why they will continue to be used in places where at the present cost level relatively small quantities of energy are stored.

Now let me answer your second question. Batteries do not scale in the sense of rotating machinery where the physical size only changes a small amount for a much larger increase in output. In the past I worked on the SNAP-2 project where mercury turboalternators and a SNAP-2 alternator produced a few hundred watts.

If you go up to SNAP-8 and you're talking 30 kilowatts, the system gets a little bigger, but not 15 times as large. Batteries tend to scale more linearly.

Concerning the crossover point, I think that's an economic consideration. Most installed costs I've seen projected for fuel cells tend to be high; for instance, for a 3-megawatt system based on an acid electrolyte fuel cell, the best figure I've seen is $145 per kilowatt installed. Now you're talking power in one case and energy in the other. If you want to compare the fuel cell, then you have to compare the storage tank as well for some given quantity of energy.

Q: I would like to mention two aspects which often get overlooked. First, I don't think you can say the emissions are zero when the efficiency that you point out is 50 or 60 percent. There is one heck of a lot of heat that has to be accommodated, especially in a 1,000,000-pound battery. Actually, I have seen a 7,000-pound battery in a Mercedes bus, and it had a complete air conditioning system that goes along with it. Second, when we think of costs, we must think of costs for the application we are considering. I would be very surprised if we're not talking about 15- to 30-year life systems. If we're talking about a 30-year system, you had better multiply your cost factor of 6, according to your own numbers.

A: That's right.

Q: I would like to mention something about the batteries. We have demonstrated the performance characteristics of at least lead-acid battery powered systems. Some of the things you have in your slides run into a very difficult problem, which is creeping up on us very rapidly. This is the materials availability and cost problem. Of all the material you would want to use in your battery, I would say lead, zinc, and copper are the three most critical raw materials that face us today in terms of price escalation and availability. And of those three, copper and lead have an awful lot of recycle potential and zinc has virtually no recycle. Zinc used in our economy is mostly for corrosion protection. As such, it is sacrificed, and therefore not recoverable. While it would appear that zinc air or zinc chlorine might be a promising candidate for wide-scale use in applications, there could be a real material problem. I think that's another factor that we have to look at very carefully. And for that reason I view with a considerable amount of optimism, if we're going to use batteries, the sodium approach, which is at least one metal that is very energy intensive. I think we have to look at the availability of materials much more with batteries. We ought to also address the question of material costs. It's one place where it is proportional to the energy and power usage: twice as much power, twice as much mass. We also have to worry about the competitive uses of these fairly scarce materials.

A: If I may make a short answer to your question, I try to stay away from the subject of electric vehicles although it's near and dear to my heart. I'm going to give the keynote address at the Electrochemical Society's fall meeting on batteries for electric vehicles. I think it's a tremendous application, but when you begin talking about power in the megawatt hour scale, I'm not sure our experience in electric vehicles is really appropriate here. It's a whole new ballgame. None of us, I really feel, knows a great deal about it. Your comments on materials availability are well-taken. The cost estimates on nickel-zinc batteries, for instance, have been done by battery manufacturers and are based on recycling zinc plates in the manner in which they recycle lead-acid batteries now. But look at the vehicle situation, for instance. It would be impossible in this country to convert all the vehicles we have on the road at the present time to lead acid because we simply haven't got enough lead. That's not an answer for hundreds of millions of vehicles, and I suspect it's also not an answer for power in the scale we're talking about here. It's a good point.

ADVANTAGES OF BATTERY ENERGY STORAGE

- SIMPLE
- EASILY MODULARIZED
- NO SPECIAL SITING REQUIREMENTS
- NO EMISSIONS
- INSTANT STARTUP

Figure 1

COSTS ARE INFLUENCED BY

- TOTAL ENERGY STORED
- OPERATING LIFE
  - NO. CHARGE-DISCHARGE CYCLES
  - RATES OF CHARGE AND DISCHARGE
  - DEPTH OF DISCHARGE

Figure 2

CONVENTIONAL BATTERY PERFORMANCE

SYSTEM	PERFORMANCE		CYCLE LIFE	PROJECTED COST	PROBLEMS
	WH/LB	W/LB			
LEAD-ACID	10	20-30	1500	$80/KWH	
NICKEL-IRON	25	50	?	$100/KWH	GASSING, MAINTENANCE, EFFICIENCY
NICKEL-ZINC	30	150	200-400	SAME AS LEAD-ACID?	LIFE

Figure 3

METAL-GAS BATTERY PERFORMANCE

SYSTEM	PERFORMANCE		PROBLEMS
	WH/LB	W/LB	
IRON-AIR	40-50	10-20	CATHODE CORROSION, LIFE
ZINC-AIR	40-50	10-20	LIFE, COST
NICKEL-HYDROGEN	30-40	?	VOLUME, LIFE
ZINC-OXYGEN	50-60	10-30	LIFE, COST
CADMIUM-OXYGEN	30-40	?	LIFE, COST
ZINC-CHLORINE	50-75	40-60	LIFE

Figure 4

ALKALI METAL-HIGH TEMPERATURE BATTERY PERFORMANCE

SYSTEM	PERFORMANCE		CYCLE LIFE	PROBLEMS
	WH/LB	W/LB		
SODIUM-SULFUR (BETA ALUMINA)	80-100	80-100	200-2000	LIFE, COSTS
SODIUM-SULFUR (GLASS)	80-100	80-400	100+	LIFE, MATERIALS STABILITY
LITHIUM-SULFUR	100	> 100	2000	MATERIALS CORROSION, COSTS
LITHIUM CHLORINE (CARB-TEK®)	50	≫ 100	100	LIFE

Figure 5

ENERGY STORAGE BY COMPRESSED AIR

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I would like to discuss with you some of the general attributes of the compression of air as a means of storing what I call off-peak, central station, baseload power for peak use. But exactly the same concept can be used to store wind power.

There are essentially three components to the system: a compressor, a motor, and a turbine. To store the energy, a motor drives the compressor, which, of course, compresses the air. To extract the energy, the air is run through the turbine, which drives that same motor, which is now an alternator. This is the same situation as the pump-turbine and the motor-alternator in a pumped hydro system.

In this system the compressed air is stored underground in caverns or aquifers. The use of caverns requires a water piston and a surface lake to recover flow-work, the PV term, which normally isn't recovered when pumping into an inflexible tank, for example. It also requires the use of surface area. I like very much better the use of an aquifer to store the compressed air because the water in the interstitial spaces would act as the piston and thus no surface area would need to be used.

If you used pumped hydro to store wind energy, you'd get about 0.67 efficiency. If you put in 3 kilowatt-hours, you get out 2 kilowatt-hours. The use of pumped hydro also entails an almost $200 per kilowatt capital investment, substantial land use, and the inability to put it where you want it. Suitable sites are usually far from load centers; therefore, transmission and the capital costs of transmission are involved.

Now, a normal gas turbine system uses up about three-fourths of the total output of the turbine in the compressor; therefore, a 1-kilowatt gas turbine system normally is a 4-kilowatt turbine, a 3-kilowatt compressor, and a 1-kilowatt alternator. (By the way, those systems cost about $110 or $115 per kilowatt. They are enormous spendthrifts of energy, of fossil fuels specifically. Their heat rates are near 17 000 Btu per pound and up. They have the advantage, though, of quick installation, which is why they are used widely by the utilities.) Obviously, it is to our advantage to increase the pressure ratio. Presently, we are considering a 40 to 1 compressed air to atmospheric air pressure ratio for our compressed air storage system.

There is an additional factor. When you operate a separate turbine and compressor for some tank storage system, be it underground cavern, surface tank, or the aquifer, you have two choices:

(1) You can extract the air from storage and run through the turbine cold, in which case the performance is exactly the same as pumped hydro, that is, 0.67 efficiency or 3 kilowatts into storage and 2 kilowatts out.

(2) Or you can burn a small amount of any fuel and heat the air before it enters the turbine.

If this is done to about 4000 Btu per kilowatt-hour, roughly 40 percent of the normal heating rate, the output of the system doubles at a fairly small cost. In other words, 3 kilowatt-hours in and 4 kilowatt-hours out. This is an apparent efficiency of 133 percent, but, of course, you're expending some energy (heat) to get it.

With respect to the combination of windpower and compressed air storage, I hesitate, without making a detailed technical and economic analysis, to say why this is an applicable concept. Certainly it is physically feasible. If there were a battery of wind machines in a given area with an installed area output of, say, 50 or 100 megawatts, I believe the underground storage of compressed air would be the most attractive concept that you could consider.

Another very important characteristic of the underground storage of air is its unique flexibility. In pumped hydro, in a battery, or in a flywheel, when you are up to full storage that's all there is - there isn't any more. And what you have depends on how much money you spent. Air, on the other hand, being a compressible fluid, is quite flexible. For instance let's say we've stored 2 or 3 days worth of power, or air, at 600 pounds per square inch. If we chose to store a week's worth, which surely you cannot do with pumped hydro (pumped hydro is only stored overnight because it is so expensive and because it is inflexible) you can simply continue compression to perhaps, 650 pounds per square inch. The air will be pushing the aquifer up closer to the dome, and you will be getting the piston action simply by the air being more compressed. Because air is a compressible fluid, more energy can be put into it by increasing the pressure, or by pushing back more of the interstitial water in the aquifer.

This storage system concept has the reheat flexibility. It has the lowest capital cost of any storage system of which I'm aware, and certain beneficial environmental advantages that includes not using surface area.

DISCUSSION

Q: Why 50 megawatts as the lower limit cutoff?
A: Well, the reason for that is fairly simple. You've got to sink some wells, for both the cavern and aquifer storage systems. A rough trade-off analysis indicates, at least for commercial utility use,

that the better part of a hundred megawatts is necessary to make the machinery and the attendant structures pay.

COMMENT: My calculations show that the type of flywheel I am considering is comparable in cost and size to your system.

Q: Is there any reason why this power storage system could not be used in off-shore locations several miles off the continental shelf?

A: No, and that opens up an entirely new opportunity not present on land. The ground under the water can, of course, be used. You can also use a membrane or bag lying at the bottom of the water or at a suitable depth. Pump the air into it, and let the water pressure push it back up to you. The use of the membrane is possible only in deep water.

Q: What if aquifers are needed for other purposes, like furnishing water?

A: I don't think I'm a sufficiently good geologist to answer that. But I'll try. I think the aquifer itself would resolve that issue. There are, I believe, few fresh water wells that go down to 2000 feet. So aquifers that are 175 feet down might be used as wells or for water storage, and those 2000 feet down for power storage.

EXPERIENCE WITH JACOBS WIND-DRIVEN ELECTRIC GENERATING PLANT, 1931-1957

Marcellus L. Jacobs

Jacobs Wind Electric Company, Inc.
Fort Meyers, Florida

This report outlines the engineering, construction, performance, electric output, and different uses of the Jacobs wind electric 2500- to 3000-watt plant, thousands of which were installed in many parts of the world between 1931 and 1957.

Early engineering started on this wind-operated electric generating plant in 1925. After several years of testing different types of windmills, the three-blade aeroplane type of propeller was found to be far superior in power output. By means of a flyball-governor-operated, variable pitch speed control, the maximum speed of the propeller was accurately and easily controlled, to prevent excessive speeds in high winds and storms. The three-blade propeller was found to be necessary (as compared to the two-blade type) to prevent excessive vibration whenever the shift of the wind direction required the plant to change its facing direction on the tower.

The periods of vibration which occurred on the two-blade propeller, every time the tail vane shifted, to follow the changes in wind direction, were found to be caused by the fact that the two-blade propeller, when in a vertical position, offers no centrifugal force resistance to the horizontal movement of the tail vane in following changes in wind direction. However, when the two-blade propeller is in the horizontal position, its maximum centrifugal force is applied to resist horizontal movement of the tail vane; thus the tail vane is forced to follow wind direction changes by a series of jerks, causing considerable serious vibration to the plant.

The three-blade propeller was developed by us in 1927 to correct this condition. When in operation, the three-blade propeller creates a steady centrifugal force resistance, against which the tail vane reacts with a constant pressure and produces a smooth shifting horizontal movement of the plant facing direction. The centrifugal force generated by the very light aeroplane spruce-wood blades, when operating at 225 rpm is 550 pounds each, making a force of over 1600 pounds of gyroscopic resistance force to the horizontal vane movement for the three blades. But this resistance is in the form of an even pressure or resistance to horizontal movement, whereas the 1100 pounds of gyroscopic resistance force of the two-blade propeller to the vane movement is applied and then eliminated twice during each revolution.

A propeller diameter of 15 feet was found to produce ample power for electric generator operation to develop 400 to 500 kilowatt-hours per month, based on the available winds in most areas of the states in the western half of the United States. This required 10 to 20 mph winds for 2 or 3 days per week. A specially designed six-pole battery charging type shunt generator was developed to operate at a speed range from 125 to 225 rpm for direct connection to the governor hub of the propeller. It was designed so that its load factor would exactly parallel the power output curve of the wind-driven propeller when operating in the 7 to 20 mph range that it was felt to produce the most hours of wind per month. Wind plants that require higher than 20 mph winds to deliver their rated output will find too many areas where there are too many days with winds below that speed each month, and thus their effective average monthly output in many areas is below expectations. The generator weighs 440 pounds with a 9-inch-diameter armature with a 9-inch core length. The 60 pounds of wire on the field poles gave maximum efficiency with a drain of less than 100 watts for field coil operation. The generator output is 2500 watts at 32 volts, and, for the 110-volt generator, it is rated at 3000 watts.

Our experience with plants installed in many parts of Alaska, Canada, Finland, northwestern United States, and a number of special installations such as the plant we have installed for the joint operated United States and United Kingdom weather station at Eureka, in the Arctic Circle, and with the Byrd Expedition at Little America has shown that aluminum painted (copper edged) spruce-wood propellers have considerably less trouble with frost and ice formation than when they are varnished or when other type coatings are used.

Generators located on high-steel towers are subject to considerable static discharge from the armature through the ball or roller bearings, and excessive charges from nearby lightning will often arc through a bearing and weld spots on the balls and race, causing it to break up soon. We found the revolving propellers collected discharges into the direct connected armature and the lightning pick-up effect of the propellers was frequent and of considerable intensity. To correct this, we installed dual sets of heavy grounding brushes on the armature shaft which completely eliminated any trouble from this cause. With the additional use of a large capacity oil-filled condenser connected across the generator brushes and frame, we practically eliminated any damage to the generators from lightning, so much so that, with high grade ample insulation used throughout the generator and the grounding brushes and condensers, we gave an unconditional 5-year guarantee with every generator against burn-out from any cause and have built many thousands during the past 20 years using this construction without any replacements ever being required because of lightning damage or burn-out from any cause.

The price received at the factory for our 2500-watt, 32-volt plant was $490, less the cost of a suitable tower and batteries, which could often be secured in the country or area to which the plant was shipped. We supplied a 21 000-watt-hour glass cell lead-acid type of storage battery with a 10-year guarantee, for which we received $365. A fifty-foot self-supporting steel tower was supplied for $175, making a total cost for the plant of $1025. This is about $400 per kilowatt as the manufacturing cost of the plant. Shipping and installation costs are additional. Installation cost requires only the labor of two men for two days and a small amount of cement to put into the anchor holes when the tower is built. No special equipment or training is necessary. We have shipped hundreds of plants to most countries with not a single request for additional information to enable them to erect the plant. Regular installation and operating instructions are prepared and sent with each plant.

Operating and maintenance costs of this plant are largely limited to the replacement of the storage battery which, on a 10-year basis, is about $36 per year; from records kept of more than 1000 plants over a 10-year period, the maintenance cost of repairs was less than $5 per year. Some of the owners of our plants bought the Edison type battery and after 20 years are still using the same battery. New batteries of this type are quite expensive, but these owners bought second-hand batteries which still gave them 20 years of service.

Special generators designed for the cathodic protection of underground steel pipelines were developed by us in 1936. These generators were wound for an external circuit resistance of 1/10 ohm or higher. The generators produced 10 volts at 100 amperes and were straight shunt wound. When connected to the pipelines in any normal wind, they maintained a pipe-to-soil potential of 3/10 of a volt pipe negative. Due to the action of the current, the pipe maintained a fair degree of protection through calm wind periods. Hundreds of our plants are protecting many miles of pipelines in North and South America and in Arabia. Some of these plants have been in service since 1937.

DISCUSSION

Q: Can you tell me the present state of this design? You say you are no longer manufacturing wind generators, but are the designs available?

A: Well, I closed the plant and sold the machinery. I still have the company, but the engineering I do is a different type of engineering now.

Q: Are these designs available if another company is interested in producing it?

A: Frankly, it's been 18 to 20 years since I last produced wind generators, and I haven't made much effort to keep them. I'm busy with environmental work, developing a system for cleaning up coastal canals and waters (I have patented and developed a system for that), so I have dropped out of the wind electric business. Now, there are a lot of old plants still running here and there around the country, but no new ones. I no longer have the plans, blueprints, or information on them. I didn't keep them.

Q: Would you have any guess as to what these units would cost today in per kilowatt?

A: They would be about twice what they were when we quit building them.

Q: That's a complete system?
A: That's the plant, tower, and suitable storage battery.

Q: We had earlier a very interesting discussion on the question of electric plants. It would be of interest if you could comment on the operation of such gear.
A: Early in the thirties, about 1931 or 1932, I made a series of tests, and we put a special grounding brush on the generators. We had found that the airplane spruce propellers with the copper leading ends and the static pickup, out in wind and sand and from certain atmospheric conditions, created a static buildup in the armature, which would jump across to the main frame through the ball bearings and would wreck and damage the bearings.

And then I discovered in 1932, that by putting a set of heavy grounding brushes on the big armature shaft, which is 2 inches in diameter, that eliminated that completely. After that no bearings ever went bad and there was no more static buildup.

REVIEW OF THE WINDPOWER ACTIVITIES AT THE BRACE RESEARCH INSTITUTE

T. A. Lawand

Brace Research Institute
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Quebec, Canada

The Brace Research Institute was set up in 1961 to alleviate the problems of water scarcity in rural areas, with particular reference to improving the productivity in these regions. One of the criteria established from the outset was that as much emphasis as possible be placed on the development of natural energy, local material, and human resources so as to integrate this technology into the indigenous infrastructure. As power is always needed to satisfy man's requirements for new or additional supplies of water, it was decided that windpower should be harnessed as a possible energy source.

Historically, windpower has provided much of man's power needs for pumping, mechanical power, and navigation. The Institute has maintained a basic program of information accumulation, contacting as many of the existing windpower manufacturers as possible. It has invested heavily in library facilities and possesses an excellent series of cross referenced reprints in several languages accumulated over the past 12 years. Since 1963 the Institute has offered courses in wind power technology and utilization. The initial courses were formulated under the direction of the late Professor E. W. Golding of the Electrical Research Association, United Kingdom, under whom this author had the pleasure of studying some 10 years ago.

Initial activities in windpower were undertaken at the Brace Experiment Station in Barbados located in the heart of the Trade Winds. Chronologically, the various phases of windpower work were as follows:

1962-66 Installation and testing of a 1-kilowatt Quirk windmill at Springhead, Barbados - DC current produced (DT.4).

1963-64 Testing of a 9-kilowatt Andreau windmill. In this novel propeller design, air was forced out of the periphery of hollow blades, operating an electric generator in a central tower (T.12).

1964 Development of a simple, do-it-yourself Savonius rotor windmill (L.5).

1965-67 Development of the 10-horsepower Brace Prototype Windturbine. This unit is still in use in an irrigation project in Barbados (MT.7, R.38, CP.19, and CP.20).

Since mid 1967, the principal activities of the Institute have passed to the current headquarters in Montreal, Canada.

The following activities have continued in Barbados, Haiti, Montreal, and elsewhere:

1968-69 The 10-horsepower prototype windturbine was evaluated in Barbados in its role of irrigating land intermittently. This function was performed quite successfully from a technical, agronomic, and soils point of view (MT.8).

1970 Savonius rotors were introduced in Columbia.

1970 A 1.5-meter-diameter Lubing Maschinenfabrik windmill was tested in Haiti. This mill, still in operation, is used to pump saline water to a solar distillation plant.

1971-72 Improvements were undertaken to the design of the Brace 10-kilowatt prototype windturbine.

1971-72 A permanent magnet alternator generator, driven under variable input power to simulate wind regime was tested. Loads were induction motors which performed quite successfully (T.68).

1972 A Lubing Maschinenfabrik 400-watt wind electric generator (blade diameter = 2.2 m) was tested at Montreal. This unit, currently being examined for performance under winter conditions, powers an experimental solar/wind powered house (T.75).

1973 Designs were undertaken of reinforced concrete towers as well as reinforced concrete block towers for windmills (EP.2).

1973 A study has been initiated on developing a mathematical model which can describe the performance of any known wind electric generator whose characteristics are known, given a measured wind regime.

1973 The Brace Windturbine designs were optimized technically and structurally. Final designs were submitted to manufacturers for commercial production.

It can be seen that the programs of the Institute are continuing in an active vein. Future studies are being formulated to set up free wheeling windmills whose power output will be utilized through improved electrical and electronic systems.

In addition, aerodynamicists will examine problems relating to the improved forms of wind energy conversion to mechanical shaft power.

There is a significant potential for windpower utilization in the north of Canada, where the remoteness of the loads favor small, autonomous installations. A reexamination of equipment destined for use in warmer climes is planned so that windmills can perform adequately under these difficult climatic conditions.

The future of windpower both at home, and in the developing countries, seems brighter and more promising than in recent times.

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R.31	Putting the Wind to Work, by the Brace Research Institute, Engineering, Vol. 206, No. 5353, pp. 760-761, Nov. 22, 1968.
R.38	Notes on the Development of the Brace Airscrew Windmill as a Prime Mover, by R. E. Chilcott, The Aeronautical Journal of the Royal Aeronautical Society, Vol. 73, No. 700, pp. 333-334, Apr. 1969.
R.39	The Potential for Medium Power Wind Turbines in Canada and the Caribbean, by R. E. Chilcott and G. T. Ward, Paper No. D.50.853 AGM, presented to the Engineering Institute of Canada Annual General Meeting, Vancouver, British Columbia, Sept. 10, 1969.
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T.12	Performance Test of an 8-Meter Diameter Andreau Windmill, by A. Bodek, 24 pp., Feb. 1964.
T.36	The Economics of Wind Powered Desalination Systems, by T. A. Lawand, 56 pp., Jun. 1967, revised Sept. 1967.
T.37	Notes on the Development of the Brace Airscrew Windmill as a Prime Mover, by R. E. Chilcott, 7 pp., Sept. 1967 (superseded by R.38).
T.38	Notes sur l'Utilisation de l'Eolienne Rapide Brace comme Source Motrice, par. R. E. Chilcott, traduit par M. Lantagne, 11 pp.,

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T.56 Current State of Windpower Research in the Soviet Union, by N. Levy, edited by G. T. Ward, 10 pp., Sept. 1968.

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L. 5 How to Construct a Cheap Wind Machine for Pumping Water, by A. Bodek, 12 pp., Feb. 1965. Revised Feb. 1973.

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I.36 Notes on the Selection of a Suitable Water Pumping System for the Greenland Windmill, by T. A. Lawand, 8 pp., May 1967.

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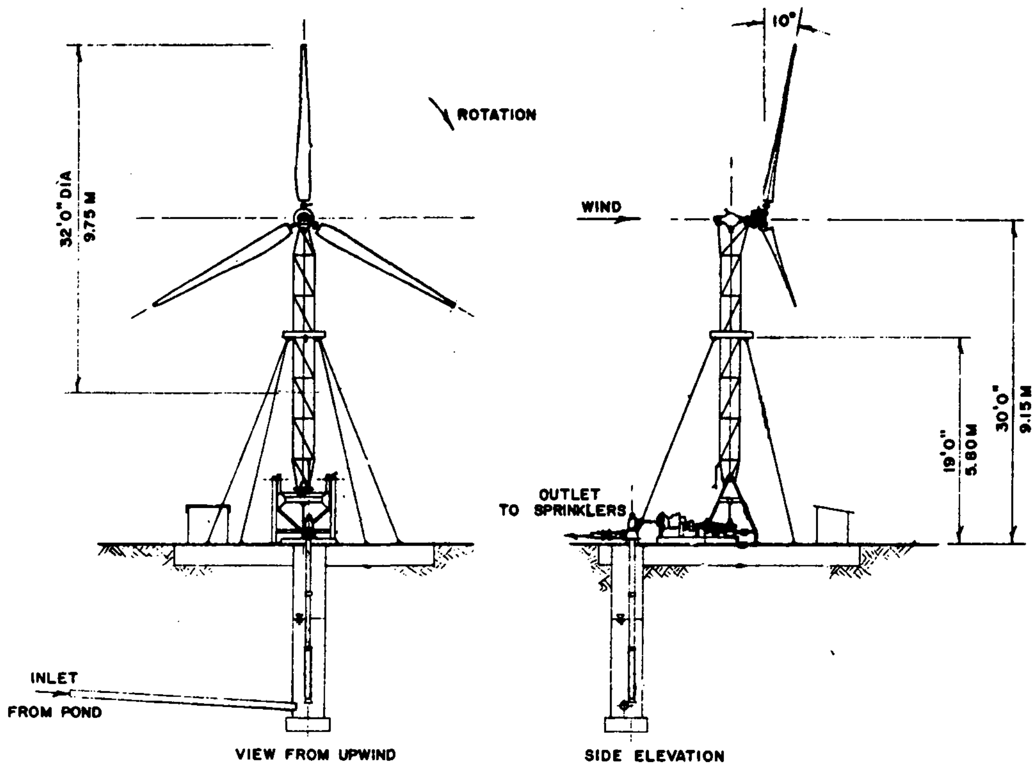

PROTOTYPE BRACE AIRSCREW WINDMILL PUMPING SYSTEM.

Figure 1

WIND POWER SYSTEMS FOR INDIVIDUAL APPLICATIONS

Henry M. Clews

Solar Wind Company
East Holden, Maine

Mr. Chairman, ladies and gentlemen, I suppose the reason I am here this morning is to tell you something of my experience in the last year or so with a modern small wind electric generating system.

Specifically, I have lived for the past year (with my wife and two children) in a house which is completely electrified by wind power. We get all of our power for lights, household appliances, shop tools, etcetera -- even a television set -- from wind power. Our wind power system, which is completely self-contained, consists of a two-kilowatt wind driven generator, a set of 19 storage batteries (giving us enough reserve power for 4 days without wind), a small dc to ac inverter, and a gasoline generator which we use as an emergency backup system in case of prolonged calm periods.

Now we installed this system ourselves, but we did not design it or build it. The entire system is based on commercially available production components which, in fact, can be obtained right now by anyone here. And, I guess my basic message to you today is that there is equipment in production right now which has been tested and proven and which can be put to immediate use in many small-scale applications. And further, and this may come as a surprise, there are many applications where wind-generated power is actually cheaper than conventional generating systems.

Let me start by giving you a little background on our installation to illustrate this point. When we moved to Maine two years ago and started building our house back in the woods (we're actually located 5 miles from the nearest paved road), we were faced with the problem of supplying electricity to our home in the wilds of Maine. The local power company looked at our situation and came up with a quote of 3000 dollars to bring us in a line. And they wanted a minimum of fifteen dollars per month for the next 5 years regardless of how much power we used.

Well, this was enough to make us stop and think a bit. But what really are the alternatives in a situation like this? The only alternative usually considered, if power lines are not available, is a small diesel or gasoline generating set, but the economy of such a system is very poor (not to mention the noise and pollution problems). A rough estimate of the cost of power generated by such a domestic generating set, diesel or gasoline, taking into account capital costs, fuel, and maintenance expenses, is 30 cents per kilowatt-hour or about 10 times the power company rate!

Now, here is where the wind-generated power comes in. Wind generated power may not compete at present with mass-produced power from the power company, but it does compete very favorably with any other type of individual power plant. Our complete installation, which I will describe in a minute, cost us $2800. There is, of course, no fuel expense, and the only maintenance associated with this system consists of changing the oil in the gearbox (1 quart) once every 5 years. Assuming, conservatively, a 10-year life for the batteries and a 20-year life for the other components and adding in maintenance and interest costs on the investment, the total costs to us of the electricity generated by our windmill comes out to about 15 cents per kilowatt-hour - or about one half the cost of the gasoline or diesel plant. This is based on an average power output of 1500 kilowatt-hours per year (120kW-hr per month) in a location with 8 to 10 mph average winds.

So, you see, in our case (and in similar cases throughout the country where power lines are not easily available), wind generated power can actually represent the cheapest available means of generating power. It is for this reason that I predict we will witness the reappearance of modern wind-electric power systems, at least on a small scale, in the coming years.

Now for a brief description of our set up in Maine. I won't go into too much detail because the whole system is described quite completely in a small booklet which we have printed recently entitled "Electric Power from the Wind." This publication, which we offer through the Solar Wind Company for one dollar postpaid, describes the operation of modern small self-contained wind electric power systems and has several tables and diagrams which allow you to calculate the power output of various size systems under various wind-speed conditions.

Our basic system consists of a 2-kilowatt Quirk's wind generator manufactured in Australia. This "windplant" as they call it, uses a 12-foot diameter propeller with a full-feathering hub controlled by centrifugal weights. The generator is a 2000-watt, three-phase, 115 volt dc, which we feed through the voltage regulator panel (included with the Quirks unit) to the batteries. This panel contains large ampere and volt meters as well as a transisterized voltage control which works by lowering the voltage to the alternator-field (thus reducing the charge rate) when the output voltage exceeds a certain value -- which you can set to correspond to the voltage of the batteries in their fully charge state. Above the panel you will see the anemometer readout, which reads the windspeed in mph at the windmill site. For storage during calm periods we use 19 lead-acid storage batteries, rated at 130 ampere-hours and 6 volts each. These give us a total of 15 kilowatt-hours of storage at 115 volts. These batteries are especially built for this type of application; they have built-in charge indicators in each cell. These batteries come from Australia and seem to be cheaper than American batteries of the same capacity. We sell a 19-battery set of these in New England for $695 or about $35 apiece.

In our installation we use much of our power directly at 115 volt dc. All our lights, many appliances including the vacuum cleaner, electric drill, skill saw, sewing machine, etc. will run well on dc. Our water pump also has been converted to run on dc. The only appliances which require ac are the television and the stereo and for these we use a small surplus rotary inverter which we purchased for under $100. Of course, for larger loads, there are several types of electronic solid-state inverters available and we are now selling units up to 8000 watts. As an example of costs on these, a 2000-watt unit sells for about $1600.

And now let me move on to some more recent developments. In addition to our arrangement with the Australian company, the Solar Wind Company has recently contracted for an agency in the U.S. for the wind driven generating equipment manufactured by Elektro G.m.b.H of Winterthur, Switzerland. It is our feeling that at present this company manufactures one of the best units available for the price anywhere in the world. (The Aerowatt unit made in France may be superior in certain respects, but they are more expensive than comparable Elektro models.)

Elektro makes several different size units. They make two small vertical axis mills rated at 50 and 250 watts in wind speeds of 40 mph. Then they make conventional units in sizes from 750 to 6000 watts output. The 6-kilowatt model delivers its full output at a wind speed of 25 mph. Typical monthly outputs from this 6-kilowatt generator are: 350 kilowatt-hours in a 10 mph average wind, 470 kilowatt-hours in a 12 mph wind, and perhaps 600 kilowatt-hours in an area where the average wind speed is 14 mph.

We have recently installed one of these large Elektro units beside our Quirks unit for testing and evaluation. So far it has performed very well, and preliminary tests show that it will produce about three times the monthly average output of the 2-kilowatt Quirks unit. The output of the Elektro unit is controlled by a servomotor at the base of the tower which operates by tensioning cable running up the center of the tower, and thus regulating generator output by rotating the tail and causing the unit to turn out of the wind. The windmill can thus be operated at any power setting from 100 to 0 percent by this control. The control can be actuated manually and remotely by push buttons or automatically by various factors. These include over-voltaging of the batteries, too high current in the generator, and excessive wind speed. A small wind paddle attached to the tower closes a contact in winds over 60 mph putting the windmill out of operation for a period of 12 hours, after which it will again start up automatically if the winds have abated. With the automatic control all the Elektro units are capable of completely automatic and unattended operation in winds as high as 150 mph.

The Elektro Model WVG-5, 6-kilowatt windplant is the largest unit currently in production. It has a three-bladed propeller of 16½ foot diameter and, like the Quirks unit, uses a centrifugally operated feathering system to limit propeller and generator rpm to safe maximum levels. The price of this unit, delivered on the East Coast with automatic controls, is about $3000.

Now I'd like to make a few comments about what I see to be the immediate future of small scale wind-driven power systems. Besides the sort of direct residential electrical power systems which I have just described, I think the most promising area for small wind generators may well be in the area of domestic heating. Some preliminary figures show that wind-driven generators in the 15- to 25-kilowatt output range, coupled to a direct heat storage system using heated water (no batteries) would very adequately heat a typical six or eight room New England home. The cost of this system might easily be made competitive with present oil or electric heating systems. Right now such a system could be set up using existing production components for about $7500 total capital cost with virtually no expenses thereafter for maintenance or fuel for a period of at least 20 years. And there is no doubt that the price will come down if any quantity of such installations is contemplated.

This brings me to my final point here today. I think if we are to get on with the job of developing satisfactory alternatives to our present fuels, we will have to approach the problem on many levels. Obviously, one wind powered home in Maine has little significance on the national energy crisis. But I feel that one operating wind power system, small though it may be, can demonstrate to many people that the wind is a viable and even practical source of energy for the future. For many people this is a more convincing demonstration than some of the ambitious proposals and schemes which seem destined to remain in the conceptual stages for years to come.

If we want to foster the idea of wind power as a viable alternative to present methods, we must support efforts to harness the wind at all levels. As I see it, the small and modest projects that we are involved in right now could be vitally important to the future acceptance of wind power on a larger scale, and so it is perhaps in this way that our work is significant on a national level.

DISCUSSION

Q: You said "we." Who does "we" refer to?

A: Well, at the moment the Solar Wind Company consists of myself, my wife, and secretary. We have another fellow joining up this summer who will be working with us, and my brother also collaborates. He is an architect. It is a very small company, we have only been in existence about 4 months. Our main work is to import these Australian and Swiss units.

Q: How much would the cost be affected by a loss of skilled manpower to erect and maintain these units?

A: My wife and I installed both of these units with the help of a pickup truck, guy wires, and a jin pole, and so on. So they can be put up in the field with very little skilled labor. They come with a set of directions and are really not hard to install at all.

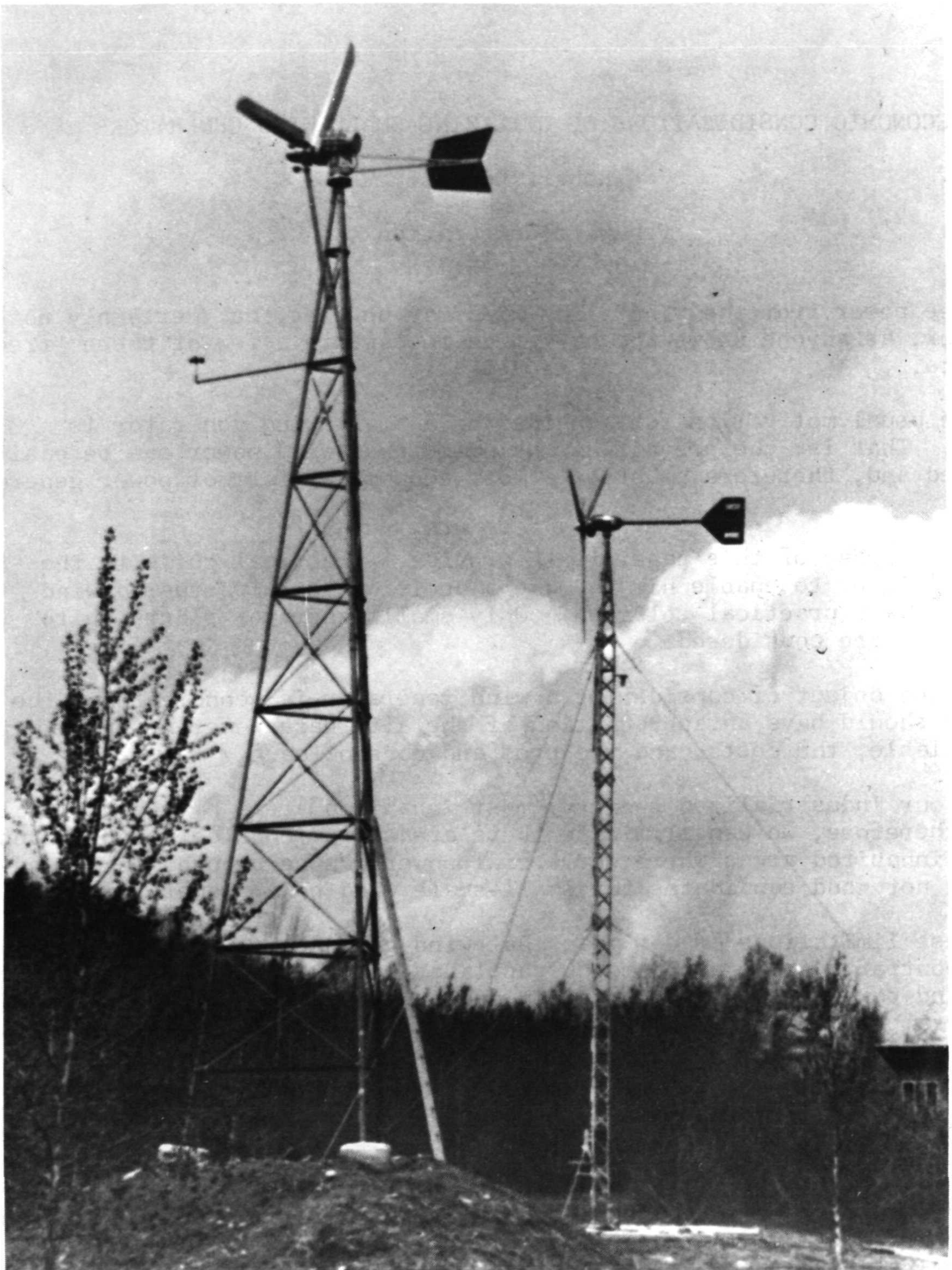

Figure 1. - Foreground: 2 kW Quirk wind generator
Background: 6 kW Elektro wind generator

ECONOMIC CONSIDERATIONS OF UTILIZING SMALL WIND GENERATORS

Robert Dodge

Pennwatt Corporation
Houston, Texas

Free power from the wind? The wind may be free, but certainly not the power, as anyone knows who has tried to capture a few of these "free" kilowatts.

The usual motivation for considering a small wind generator is economy. That is, the prevailing notion is that wind power can be easily exploited and, therefore, must be a most economical form of power generation.

The purpose of this paper is to provide a practical guide to the system designer to enable him to make a decision as to whether a wind generator is a practical solution. Only small generator plants up to 5 kilowatts are considered.

If the object of considering a wind generator is economy, then the designer should have an appreciation of the alternate power systems that are available, the costs, and the pros and cons of each.

In our industrialized society, most inhabited areas have commercial power, therefore, we can eliminate these areas from consideration. Even those uninhabited areas where commercial power can be brought in reasonably are not good candidates for small-scale wind power generation.

These limitations do not mean that wind generators are not practical. On the contrary, there are numerous applications in remote, isolated sites where wind-power generation certainly does provide a practical solution. A good example is the powering of marine aids to navigation signals. In most instances, these lights and sound signals are situated at remote, inaccessible locations. Other obvious applications are remote communication relay stations, weather data gathering stations, including weather buoys, cathodic protection, and water pumping.

These are five possible solutions available today to generate power in inaccessible remote locations: solar cells, primary batteries, thermoelectric generators, wind generators, and engine generators. Figure 1 shows the relative economics of these alternatives plotted as dollars per kilowatt-hour versus the average electrical load.

Of these five options, the primary battery is probably the least understood but the most widely used. The primary air cell has been around for some 40 years, ever since it was used to power our first radios in rural America. The air cell consists of a container with a zinc anode and an air breathing porous carbon cathode. The cell electrolyte is usually sodium or potassium hydroxide. These cells are characterized by a very low self-discharge and can be employed in series and parallel to provide up to several years of power. The cost of the cells yields energy at about $12 per kilowatt-hour. The weight is approximately 11 pounds per kilowatt-hour.

The primary air cell can be used to solve almost any remote power problem and, therefore, can be used as a basis for evaluation of any other system. For example, a 1-watt load would consume 8.76 kilowatt-hours per year. The cost of primary cells would be $12 x 8.76 = $105 per year. The weight transported to the remote site would be 96 pounds. These figures, although high per kilowatt-hour, are so reasonable that no serious consideration of a more complicated system should be entertained. The only possible exception would be where the cost of transporting the batteries to the remote site is so high as to change the economics drastically. In some cases where environmental considerations prohibit on-site disposal of spent batteries, the additional cost of disposal would also affect the economics.

The following assumptions form the basis for determining the costs per kilowatt-hour shown in figure 1.

Solar cells:	Amortization	Cells, 5 years Batteries, 5 years Housings, 5 years
Primary battery:	Amortization	Batteries, 1 year Housings, 5 years
Thermoelectric:	Amortization	Generator, 3 years Batteries, 5 years
	Fuel	25¢ per gallon
Wind generator:	Amortization	Generator, 3 years Batteries, 5 years Housings, 5 years
Diesel generator:	Amortization	Engines and Generators, 2 years Housings, 5 years
	Fuel	25¢ per gallon

An annual interest charge of 8 percent is assessed to all systems. All the systems considered are continuous power systems. Each is capable of handling intermittent loads equal to several times the average. All use battery storage to provide continuous power except the diesel generator. The solar cell economics were generated assuming a 30° latitude and 10 days storage in the secondary battery. The assumptions for the thermoelectric system were propane fuel from tanks, with the tanks transported to the site. The battery storage is ten hours. The wind generator system assumes a 10 mph annual wind velocity. The battery storage is 10 days. All secondary batteries are industrial type, low-discharge, lead calcium. The diesel generator consists of two complete plants, housing, and automatic controls for unattended operation and switchover.

The amortization periods are conservative and no doubt proponents would argue that their machines would or could operate much longer. However, no attempt has been made to add the cost of transporting equipment, fuel, and men to the remote site. Obviously these costs could greatly influence the cost per kilowatt-hour of any system. Since they vary considerably with the location, each installation requires separate evaluation.

The chart (fig. 2) shows clearly that for loads up to 10 watts, the primary air cell has the advantage. In cases where transported weight is a problem, the solar cell or small wind generator should be considered.

From 10 to 100 watts, either the thermoelectric or the wind generator are good selections. The wind generator has the advantage when transported weight is considered.

The 100 to 1000 watt range certainly favors the wind generator. In this range, the load is too light for effective use of a diesel generator, although at about 500 watts the diesel engine begins to look favorable. In this range the weight of propane for the thermoelectric becomes unreasonable. A 1000-watt average load requires 12600 gallons or 53000 pounds of fuel per year.

From 1000 watts and up, the diesel generator has a definite advantage. True, the systems are complex and, hence, prudence dictates redundancy. However, the low cost per generated kilowatt-hour makes their consideration mandatory.

All the systems except the engine suffer from being modular. That is, they consist of a parallel arrangement of units or cells so that increasing their size by increasing the number of the same size cells affords little saving per kilowatt-hour. It is the battery that is required with the wind generator that causes the cost to level out at about $1.50 per kilowatt-hour.

If the storage battery can be eliminated from the wind generator system for applications such as cathodic protection, water pumping, or possibly the electrolysis of water, the cost per kilowatt-hour is much less. This is particularly true for larger machines. For example, a 10-meter machine could easily generate 12000 kilowatt-hours per year. The cost of the machine and tower would be about $12000. Therefore, using the same 3-year amortization and interest, the cost is only 43¢ per kilowatt-hour, a figure very comparable with small diesel plants.

In summary, small wind generator plants offer an attractive alternative to primary battery systems and constantly running engines to generate power in remote areas. They are particularly advantageous where the costs of transporting fuel or batteries are high. The limitation is an annual average wind velocity of at least 9 to 10 mph. The presently available units are most useful in the average load range of 10 to 1000 watts.

DISCUSSION

COMMENT: I object to your making these look so favorable in areas where the cost of diesel fuel may run from 50 cents to a dollar a gallon. I don't think there is this large a difference in costs. I think Clews' calculations did not agree with yours.

A: I used 25 cents. Actually, the cost of fuel is quite small compared with the cost of the amortization of the machine.

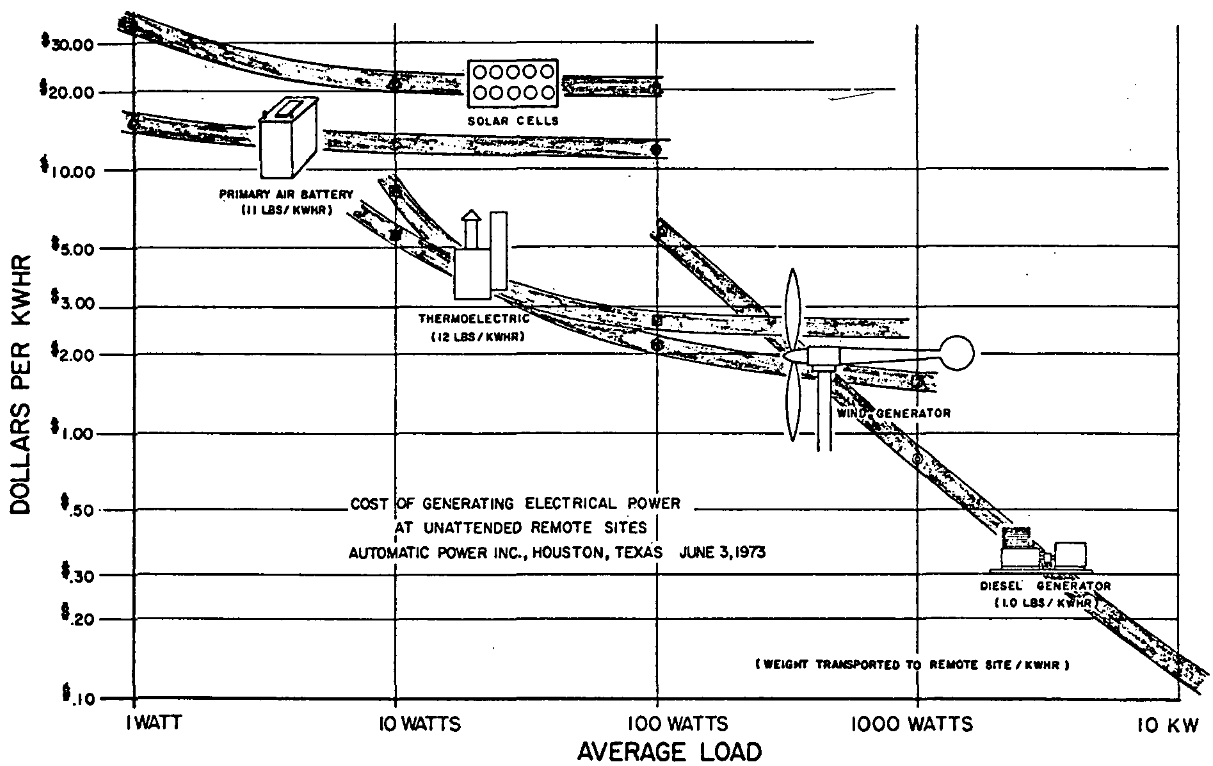

Figure 1

WIND UTILIZATION IN REMOTE REGIONS -

AN ECONOMIC STUDY

James H. VanSant

Hydro-Quebec Institute for Research
Varennes, Quebec, Canada

There are presently many diesel generating stations being used in Quebec to supply electrical power to small remote communities. The fuel costs for these stations are very high (5 to 16¢/kW-hr) and will probably become even higher. If a cheaper source of power could be used, substantial savings would result. Wind energy is a good candidate for a new source of power in many remote regions because it occurs in sufficient quantities to drive wind machines. Consequently, an economic comparison of wind generated power to diesel power for a small northern village was made to determine if installation of wind machines would be feasible.

First, we should realize the nature of the remote communities. By definition, they are isolated and undeveloped. Power must be produced locally for short-distance transmission. The communities are generally small with peak demand loads of 30 to 5500 kilowatt-amperes. Power commitments require at least one full capacity standby system. The availability of "natural energy", such as wind, sun, hydro, etc., will vary greatly from one region to another; although sufficient wind energy is available in most regions.

Any power generating system that is selected must be reliable, have long life, easy startup, long unattended operation and be compatible with local means of supply and/or storage. A most important requirement is that the system must be economically competitive.

A wind-driven generator was considered as a supplement to a diesel group, for the purpose of economizing fuel when wind power is available. A specific location on Hudson's Bay, Povognituk, was selected. Technical and economic data available for a wind machine of 10-kilowatt nominal capacity (developed by the Brace Research Institute of McGill Univ.) and available wind data for that region were used for the study. Referring to table I, after subtracting the yearly wind machine costs from savings in fuel costs, a net savings of $1400 per year is realized. These values are approximate, but are thought to be highly conservative.

A very important factor in determining the worthiness of a wind driven system is its duration of utilization. Frequently, there is not sufficient wind when power is needed. Consequently, an energy storage system that would provide power on demand is advisable. Also, a wind machine and storage system that could be "tuned" to the wind velocity for maximum efficiency would be very advantageous. Pneumatic storage with air-motor driven generators seem to be a good candidate for this type of system. However, some research and development are needed before putting a system into service.

DISCUSSION

COMMENT: I was interested to see that for the first time the economic value of windpower was compared with the actual fuel saving. When we did our arithmetic on our program, we were only looking for wind power costs. These were equivalent to the fuel costs.

The second point is you had a figure of 58000-kilowatt yearly output from a 10-kilowatt machine. This is 5800 kilowatt-hours per kilowatt, which is about the highest value I have seen for any particular site.

A: Yes. As I said, it's a fairly windy place, but we used real wind data to try to get that estimate. It should be considered fairly accurate.

TABLE I. - EXAMPLE OF WIND MACHINE ECONOMICS (ESTIMATES ONLY)

Location, Povungnituk (pop. 2000).

Diesel Data		Capital Costs	
Installed	250 kW	Wind machine	$ 5,000
Maximum demand	90 kW	Generator	1,000
Annual output	290 000 kW-hr	Transport and foundations	2,000
Fuel cost	6¢/kW-hr	Regulation	5,000
			$13,000

Wind Machine Data		Yearly Costs	
Installed	10 kW	Amortization (20 yr)	$ 1,400
Annual output	58 000 kW-hr	Lubrication and Maintenance	400
		Labor	300
			$ 2,100

Yearly savings in diesel fuel	$ 3,500
Yearly cost of wind machine	2,100
Net savings per year	$ 1,400

TECHNICAL FEASIBILITY STUDY FOR THE DEVELOPMENT OF A LARGE CAPACITY WIND POWERED ELECTRICAL GENERATING SYSTEM

Ralph E. Powe

Montana State University
Rozeman, Montana

This report describes a study to be undertaken at Montana State University with the support of the National Science Foundation. The major objective of this research effort is to investigate the engineering feasibility of developing a basic mechanical system necessary for extracting large amounts of power (on the order of 10 to 20 MW) from the wind using the concept of vertical airfoils moving along a closed horizontal track system. The research plan shows that this effort can be divided into four distinct phases, each with its own specific objectives. The accomplishment of these specific objectives will be major indicators of progress toward completion of the overall project objective. During this preliminary study, attention will be focused on those components necessary for the conversion of wind energy to mechanical energy, although the general characteristics and critical aspects of other components will also be considered. The four phases of this program may be briefly described in the following manner:

(1) the establishment of component specifications and interface requirements for major system components;
(2) the formulation of alternative sets of conceptual designs for major system components;
(3) the engineering analysis of various components and systems; and
(4) the re-examination of basic concept and identification of any desirable follow-up work.

DISCUSSION

Q: What power level are you talking about? What efficiencies are you talking about?
A: We really haven't looked at it in detail enough yet to come up with good numbers at all for this. We're shooting for a system though on the order of 10 megawatt system or so, and we estimate that we will be talking about a 5-mile-long track, 5- to 10-mile-long track, or so.

Q: At what efficiency?
A: Your guess is probably as good as mine on that. That was figured at about 30 or 40 percent or so, and that's a wild guess, really.

Q: I think you have given us a good run-down on potential problems and liabilities of this system, but I didn't see why you were considering this over the conventional rotor system.
A: We feel that the advantage in this scheme is that you can get a very large output from a single unit, whereas to get 10 to 20 megawatt output from the rotor type system requires a very large number of units from sizes that are available or conceivable now.

Q: Each one of your rolling stock pieces might be considered a separate unit?
A: Yes, it could be, that's right. But on this, to add capacity you simply increase the length of the track. When you add capacity, you don't increase the structural problems, some supporting base for the entire system, like you would with the rotor.

Q: I would like to ask you if you are familiar with the Madaras experiments, which were conducted by the Public Service Commission, Burlington, New Jersey in 1933 on this same type of scheme?
A: No, I'm not.

COMMENT: I think it will save you a lot of time if you become familiar with the Madaras experiments.

Q: I think that some of the questions and comments that you have just made save me repeating them. But I still have one nagging problem with what you have here in the slides. And that is I see a very substantial program of technological analysis which is devoted to, let's say, shedding light on a series of connected questions. But in each one of your approaches I sense what I consider the primary key question is always placed at the end as something of an appendage, and quite frankly that is economics. Why go through all this detailed, complex analysis if you can have established at once at least an estimated economics which show the scheme to be favorable. Would you comment on that, please?
A: Well, we felt that we should show it could technically be done first, and then, like most of the other units, cost is something you can sort of affect if it proves to be technically feasible and you went into production on this type of unit. So this was the logic in putting the cost at the end.

Q: In other words, you're going to undertake a very expensive technological feasibility evaluation program and then if it looks good, then you are going to look at economics. Why not look at economics first, because manpower is a pretty scarce resource?
A: First of all, it's not a very involved and expensive study to start with, and I didn't mean to imply that we are going to completely ignore economics during this first phase by any means. It's going to be looked at, but the economists that have been involved in the group that's been working on this are not going to be involved to a large extent during this preliminary study, although they will be used as consultants. This would come in after this one year period.

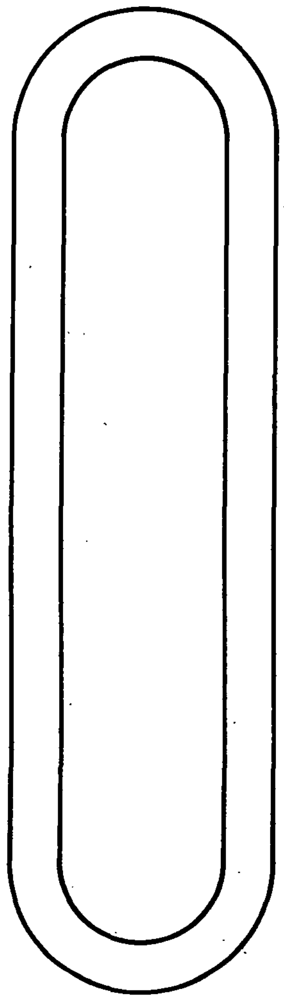

Figure 1. Anticipated Typical Track Arrangement

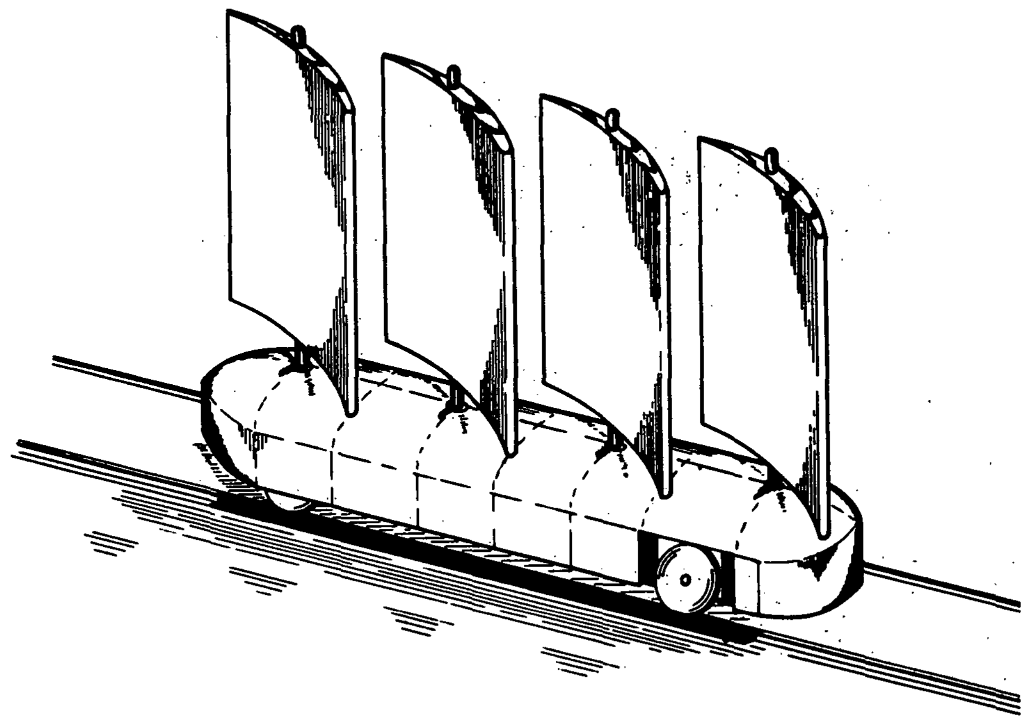

Figure 2. Anticipated Typical Airfoil Installation

THE OREGON STATE UNIVERSITY WIND STUDIES

Robert E. Wilson

Oregon State University
Corvallis, Oregon

This discussion concerns the work in progress done on engineering analysis of wind operated power for Oregon State University's Wind Power Project. The objective of the project is to assess the economic feasibility of commercial use of wind-generated power in selected areas of Oregon. Wind data collection and analysis is being accomplished by the Department of Atmospheric Sciences; the engineering work is centered in the university's Department of Mechanical and Metallurgical Engineering.

A number of machines for generating power have been examined. These include the Savonius rotor, translators, conventional wind turbines, the circulation controlled rotor and the vertical-axis winged turbine. Of these machines, the conventional wind turbine and the vertical-axis winged turbine show the greatest promise on the basis of the power developed per unit of rotor blade area.

The estimated cost of Palmer Putnam's 1500 kilowatt preproduction unit was updated from 1945 to 1971 using only the effects of inflation. Without taking into account the effects of 26 years advance in technology, the 1971 inflated cost was estimated to be $700 per installed kilowatt. The major cost component in Putnam's design was the rotor, which accounted for 43 percent of the total cost. As a result attention has been focused on the structural and fatigue analysis of rotors since the economics of rotary-winged, wind generated power depends upon low cost, long lifetime rotors.

Analysis of energy storage systems and tower design has also been undertaken. An economic means of energy storage has not been found to date. Tower design studies have produced cost estimates that are in general agreement with the cost of the updated Putnam 110-foot tower.

OREGON STATE UNIVERSITY WIND POWER PROJECT

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OREGON P.U.D. DIRECTOR'S ASSOCIATION

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PROJECT STUDY AREAS

1. Wind data collection and analysis
2. Wind tunnel investigation of terrain modification
3. Engineering analysis of wind power systems.

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SCOPE OF ENGINEERING ANALYSIS

1. Energy storage schemes
2. Update of Putnam cost estimate
3. Wind generator performance analysis
4. Tower weight and loads
5. Identification of problem areas

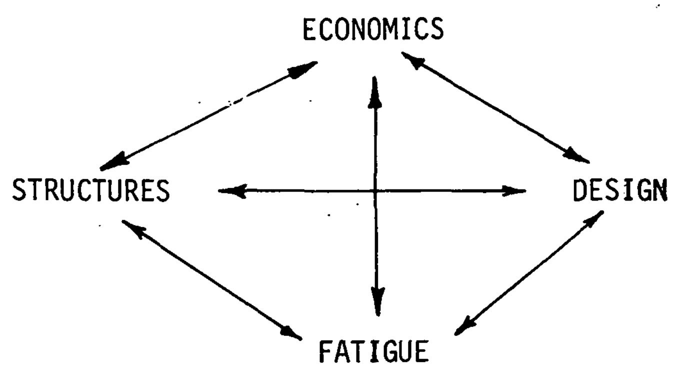
TYPICAL P.U.D. LOAD CHARACTERISTICS

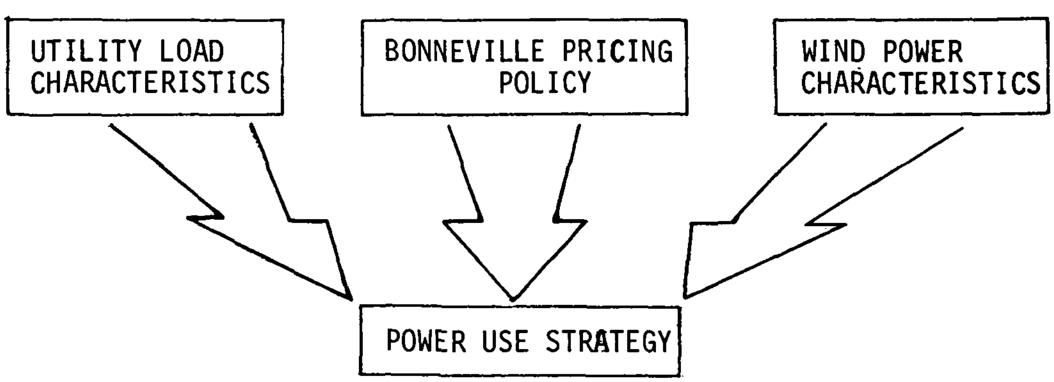
Load is split between residential and industrial

High incidence of electric heating

200 MW peak load

Peak load occurs in winter months





WIND POWER MACHINES

Standard

- Savonius
- Translators
- Propeller

Novel

- Vertical axis winged turbine
- Controlled circulation rotor

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MACHINE SURFACE AREA REQUIRED TO PRODUCE 1 MW IN A 30 MPH WIND

Machine	Area, ft^2	Tip Speed Ratio
Drag Translator	180,000	1/3
Lift Translator	600*	10
Savonius	60,000	1
Smith-Putnam	1,700	6
Vertical Axis Winged Turbine	1,700*	6

*$C_L = 1$, $L/D = 15$

COST SUMMARY OF PUTNAM DESIGN FOR 1945 AND FOR 1971

	1945 Cost Per Unit	Inflation Factor	1971 Cost Per Unit
ENGINEERING	$ 10,000		$ 20,000
MANUFACTURING			
1) Standard Equipment			
Generators	8,870	3.5	31,045
Main gears	20,344	3.72	75,680
Electric coupling	4,612	2.36	10,884
Governor	2,508	3.50	8,778
Bearings	16,282	3.5	56,987
Switch gear	5,125	2.55	13,069
Coupling, flexible	1,970	3.5	6,895
Elevator	2,665	3.5	9,327
Service hoist	1,680	3.5	5,880
Miscellaneous electrical	2,100	2.3	4,955
Tower (includes erection)	21,395	3.6	77,022
Paint	691	3.5	2,418
Subtotal	$ 88,242		$ 302,940
2) Rotor Components			
Blades	29,480	3.72	109,666
Hub assembly	42,935	3.72	159,718
Pintle assembly	48,600	3.72	180,792
Patterns, tools, jigs	800	3.72	2,976
Subtotal	$121,815		$ 453,152
INSTALLATION			
Freight	2,054	3.0	6,162
Land	0	0	0
Roads	7,460	3.43	25,587
Erection	30,000	3.43	102,900
Total Installed Cost	$260,071		$ 910,741
CONNECTION			
Transformers	3,600	1.92	6,912
High line	15,000	2.55	338,250
Unit cost	$278,671		$ 955,903
Contingency 10%	27,867		
	$306,538		$1,051,493

TOWER ANALYSIS

Design based on

1. Pinned joint truss
2. $\sigma_{allowable}$ = 17,000 psf
3. 60 mph wind loads
4. Dead weight at top = 500,000 lbs
5. Wind loads from "Smeaton table"
6. Design factor of 2

*

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TOWER WEIGHT

Tower Height	Weight
70 ft	13,000 lbs
120 ft	38,000 lbs

Sensitivity at h = 120 feet

$$\frac{\partial \text{ Weight}}{\partial \text{ Height}} = 1000 \text{ lbs/ft}$$

$$\frac{\partial \text{ Weight}}{\partial \text{ Topload}} = 0.03$$

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FURTHER STUDY

Prediction of rotor life

Energy storage system technology

Wind power regulating agencies

Aerodynamic analysis

Vibration analysis

FRENCH WIND GENERATOR SYSTEMS

John M. Noel

Aerowatt Corporation
Paris, France

HISTORY OF THE LARGE FRENCH 800 KILOVOLT-AMPERE WIND GENERATOR

B.E.S.T. (Bureau d'Etudes Scientifiques et Techniques) was a consultant engineering firm in the field of applied aerodynamics. This company worked for 18 years on contract for the French Electricity Authority (E.D.F.) in the field of wind power. B.E.S.T. was dissolved in 1966, and the newborn Aerowatt Company acquired the know-how, the patents, and the staff of B.E.S.T. that were involved in wind power. The Chief Engineer of the 800 kilovolt-ampere wind generator project is now the Technical Director of Aerowatt.

The Project

The objective was to design a wind driven generator with a rated power of 800 kilovolt-amperes, capable of being connected to the main network.. It was an experimental machine and not a prototype.

The rotor was a three-bladed propeller. Each blade was twisted. The fixed pitch of the blades was, however, adjustable. Other aerodynamical features are

Diameter of propeller, m (ft)	31 (105)
Starting wind speed, m/s (mph)	7 (15.6)
Rated wind speed, m/s (mph)	22 (49)
Survival wind speed, m/s (mph)	56 (130)
Nominal rotation speed, rpm	47

The asynchronous, 800-kilovolt-ampere generator was driven by the propeller through a gearbox. In the event of a no-load condition in the network, the machine was connected to a dissipating resistor made of iron wire located on poles (to prevent overheating).

The hub was supported by a vertical, pivotable tower having the length of a blade. The pivot rested on the top of a three-legged pedestal at a height of 33 meters. The entire system could be tilted about a horizontal axis going through the feet to two legs. So with the aid of winches, it was possible to lower the hub for maintenance and repair.

Tests

The machine was located near Nogent Le Roi, a small country village 120 kilometers west-southwest of Paris, in a wide flat plain. The site was reasonably gust-free.

The first propeller on the machine lasted 18 months without any trouble, and the generator was connected many times to the network. Sometimes the delivered power reached 1.2 megawatts. We do not know the total energy delivered by the machine during the period.

To improve the characteristic, the rigid propeller was replaced with a flexible one. Tests in a wind tunnel had shown a flutter effect on such blades. Nevertheless, the new propeller was installed. Experience demonstrated the wind tunnel tests to be correct: one blade was broken; the hub was then destroyed by the unbalanced torque. It was the end of the E.D.F. experiment on large-scale wind machines. It ran for 18 months from 1958 to 1960.

Results

The results of this experience were the following:

The breakdown of the second propeller due to a flutter effect led B.E.S.T. to make a thorough study of this point and to find ways to avoid such a phenomenon on new propellers. We have since designed long, slender propellers without having any trouble.

We believe we now have the knowledge necessary to build a large-scale wind driven generator.

TODAY'S USES OF WIND POWER

Wind energy is free but it has two drawbacks for a normal use: its short term, random character and its power varies as the cube of the wind speed.

In the recent past interest in the wind energy has declined because of the developments of networks and heat engines. At the same time the need for small, remote power sources has grown. The development of solid-state electronics has enabled stations of any type to be unattended as long as the life of the equipment. For instance, 20 years ago a microwave relay station needed kilowatts of power; nowadays only a few dozen watts are needed. Then, a major lighthouse was fitted with a 6-kilowatt lamp; now, with a 1-kilowatt halogenous lamp.

The Wind Motor

We can split a wind generator into two parts: the wind motor (i.e., the propeller, the hub, and the rudder-fin) and the generator.

The problem with the wind motor is that it must meet two opposite requirements: It must deliver full rated power at low wind speeds to overcome the need for energy storage; and it must be automatically transparent to the high wind speeds.

We have designed autoregulated machines which meet the second requirement. Six major lighthouses have been fed by such machines for 15 years. We have seldom stopped the machines with the centrifugal brake, but these machines do not meet the first requirement. They are only useful in high wind areas (Around Brittany the average wind speed is about 10 m/s, i.e., 25 mph.). So we think the solution to the problem can be found only in the variable pitch propeller.

The characteristics of all present Aerowatt wind generators are the following:

Average starting wind speed, knots	3 to 6
Average wind speed necessary for power delivery, knots	6
Nominal wind speed at full power, knots	14
Rotation governor efficiency (wind speed, over 14 knots; load-no-load speed ratio)	5
Survival wind speed, knots (m/s)	120 (60)

The Generator

All the Aerowatt generators are permanent magnet ones. Hence, no excitation power is required. The generator output is ac current, which is easier to handle than dc. In addition no maintenance is required. For medium range machines the delivered current is of the industrial type: three phases ac, 50 c/s.

Survival in Extreme Conditions

In sandy areas the problem is the blocking of ball bearings or slip rings with sand. This problem is overcome with sealed ball bearings and tight bodies. Propellers are protected against erosion with a Neoprene coating.

In icy areas the most dangerous enemy for the wind generator is sleet. Two ways of beating this enemy are

(1) oversized machines, able to withstand, at nominal rotation speed, the unbalanced torque given by a 1-inch-thick layer of ice on only one blade, and

(2) Teflon coated hub, blades, and rotor to reduce the adhesion of ice.

Several years experience with these machines in the Alps and in Norway has shown that these methods of reducing the chances of damage caused by sleet are successful.

Storing the Energy

For small machines or small installations, the random wind power production is smoothed by storing electricity in a battery bank. Aerowatt has combined the off-load working ability of its machines with the ac delivered current in a solid-state control device, which stops the rectifier when the gassing voltage of the battery is reached. So, in temperate climates, there is no need to add water to the battery within a year.

For medium machines it is possible to install a diesel generator in parallel with the wind-driven one. Energy is stored in a negative way, that is, by saving diesel oil when the wind blows.

Ultimate Power Source

Primary Cells. - The industrial uses of energy require a no-break power supply, so Aerowatt delivers with the small machines a bank of primary cells that are able to deliver a steady current of 5 amperes, with a capacity of 1000 ampere-hours. These primary cells have a shelf life of 3 years.

Diesel Engine. - The wind-driven generator control boxes are fitted with special circuits enabling it to start a diesel engine when the main battery bank is discharged and to stop it when full charge is reached.

Conclusion

Aerowatt has developed a comprehensive system (see table I and figs. 1 to 3) based on wind power able to meet industrial requirements for power in remote areas for unattended stations.

NOTE ON THE UTILIZATION OF WIND POWER FOR PROVIDING INDUSTRY ELECTRIC POWER IN THE FUTURE

Wind power has always been used to meet the human needs, either to provide driving power to windmills, or once transformed into mechanical power to propel ships. Nowadays one is interested in transforming this potential power into electric power, the easiest form of power to use. Studies and tests have been carried out during the last decades to apply this transformation industrially, that is, to provide electric power to a distribution network.

Machines with a 1200-kilowatt nominal power rating have been built. And the Aerowatt Company has the technical data of the B.E.S.T. 800-kilovolt-ampere wind generator. However, none of the machines that we know of ever made use of standardized applications. We believe that these large machines failed because they were too complicated, and therefore, too expensive. The price of the supplied kilowatt-hour was too high as compared with that provided by other sources, for example, fossil fuel plants or water power. This was due to the basic characteristics of wind power, namely, it is impossible to store, and it is impossible to forecast when the wind will blow.

Let us compare wind power with water power. We notice that, at least originally, they are both random. It is difficult to forecast whether it will rain next week, and in the same way it is impossible to forecast whether the wind will blow. Water power can be stored in the form of potential power, on the one hand thanks to mountainous areas and to water mean flow speed, and on the other hand by the creation of dams (artificial storage). As far as wind is concerned storage is not so easy.

However, the "Comite Technique pour l'Etude du Vent" has made observations over a few years, and these observations have shown that the average annual wind velocity on a given site does not vary much, about 20 percent.

Existing Possibilities

We have stated here that previous efforts to master wind power failed because of the high price of power supplied to the network. Actually, if we look closer at the machine we know best, the BEST-ROMANI 800 kilovolt-ampere machine, we note that it was equipped with a three-blade 30-meter-diameter propeller and that it supplied 800 kilovolt-amperes for a wind velocity of 22 meters per second. Moreover, the aerodynamical regulation did not allow the machine to operate off the network, and a brake had to be provided so that the machine would not race if the connections with the network were interrupted. The twisted-wing propeller was difficult to build. Finally, the machine, a purely experimental one, was too expensive for the relatively low power supply.

We believe that the problem has been solved since the Aerowatt Company designed and built a variable pitch propeller which operates far better than the other existing variable pitch propellers. Thanks to this propeller, wind-driven generators have been built that can provide their rated power as soon as the wind speed has reached 7-meters-per-second (14 kts). For example if we consider the chart of wind velocity characteristics on a site off the French coast, Sept Iles, we notice that this wind velocity (7 m/s) is reached or exceeded 72 percent of the time, whereas the 22-meter-per-second wind velocity is reached or exceeded only 1.5 percent of the time. As soon as the nominal wind velocity is reached or exceeded, the machine rotational speed is constant to $\pm$ 1 percent, whatever the wind variations are, of course, within the machine-power limits. The variable pitch allows the machine to keep its normal characteristics even for high wind speeds (up to 60 m/s). In short the Aerowatt variable pitch propeller allows us to build machines that, over a year, operate at their nominal power for a greater number of hours than the machine built heretofore. The result is due to the simplicity of the design. Under given conditions electric power could be supplied at a price that is more competitive with steam-plant produced power.

Machine Structure

The Aerowatt high power wind-driven genérator has the same structure as the low and average power wind-driven generators built up to now with, however, some operation improvements in consideration of the machine size.

<u>The Propeller</u>. - As for the other Aerowatt wind-driven generators it is a two-wing propeller regulated by pitch variation and maintained at the stalling limit. The propeller wings are made of extruded aluminum alloy, and have a constant section. They are guyed with compensated stretch guys.

If necessary, they can easily be coated to protect them from ice deposit or sand erosion. The wing setting is calculated so that the propeller reaches its maximum efficiency within the more common wind velocity range, usually 3.5 to 7 meters per second.

The design propeller nominal rotation speed is limited to a 90 meter per second relative wind speed (vector sum of the wind speed and rotation wind speed) at wing tip. Thus the aerodynamical flows always remain within the low subsonic range.

The hub has two kinds of springs: the starter springs and the regulation springs. The starter springs set the rotor blades, when at rest, to a value high enough, in relation to the wind, to get a starting torque larger than that for $V > 3$ meters per second. The regulation springs compensate for the centrifugal force on the blades by controlling the setting so that the rotation speed remains constant, independent of the wind, once it has reached its rated value.

The Mount. - The mount holds a spindle, the step-up gearbox, and the pivot. The shaft of the spindle is connected on one end to the propeller hub and on the other to the step-up gear train by means of a coupling. The step-up gearbox brings the propeller rotation speed to such a value that the coupled electric generator supplies an industrial-frequency electric current. The pivot allows the machine to swivel windwards under the action of the vane moment. The pivot also holds the sliprings, which transfer the electric power supplied by the generator towards the distribution network.

The lower part of the pivot is fitted on the driven generator support. The upper part is connected to the mount by a spindle assembly. The pivot is protected by a flange of the same length. The flange is connected to the mount and carries a ladder which provides access to the mount.

Of course the center of gravity of the machine moving parts is adjusted so as to lie on the pivot axis.

The Vane. - As for all Aerowatt wind-driven generators, the propeller rotation plane is located up wind of the pivot. So located, the propeller operates in a stream which is not disturbed by the pivot wake. The main purpose of the vane is to keep the propeller rotation plane perpendicular to the wind. The vane essentially consists of a surface fitted at the end of a long shaped support linked to the mount rear part. This surface, the tail fin, tends to stay in the wind stream. If it deviates from this position or if the wind direction changes, the thrust on the tail fin no longer goes through the pivot, and a return moment places the propeller rotation plane perpendicular to the wind direction.

The high power wind-driven generators are equipped with a new device designed by Aerowatt. This device limits the yaw rotational speed to a preset value and, in consequence, limits the stresses due to gyroscopic effects on the propeller. This is very important for the propeller mechanical strength.

Limits for use. - We shall consider the following type of operation: supply power to a small distribution network, not connected to a national network, using a heat engine plant with "n" generators of "p" kilovolt-ampere unit power driven by diesel engines as the power source. If the network under consideration is in a very windy area, or is so far from the usual sources of petrol products that the latter once delivered are very expensive, then the price of power supplied by the high-power wind-driven generators would then be lower than that of the fuel necessary for diesel engines to supply the same power.

Operation conditions. - The wind-driven generator has a quasi-constant power. Yet, taking into account the characteristics of the Aerowatt wind-driven generators, the power that is supplied to the network when the wind speed ranges between the starting speed and the nominal speed is negligible.

On the other hand, the wind-driven generator has a low operating cost, in that the primary source of power is free, and the maintenance expenditures are very little. So, once money has been invested in a wind-driven generator, it is desirable to use all electric power it supplies.

Under the limits of use already specified, the costs of the diesel-driven generator includes the price of the fuel used and the price of the maintenance, as diesel engines require periodic maintenance which is a function of the operating hours. It is thus desirable to use the diesel engines as little as possible.

The normal operation of the electric network, however, adds new restrictions. The power required by this network must be supplied at any time, independent of the wind conditions. The frequency of the supplied electric current must remain within narrow limits. And the required power varies over a short period of time according to human needs. Clearly, it is impracticable to have alternately periods when power is supplied exclusively by diesel-driven generators and periods when power is supplied exclusively by wind-driven generators, because there are transition periods when the wind speed comes to the starting threshold and then to the rated productivity threshold, either increasing or decreasing, and periods when the network requirements increase. It is our belief that the best solution consists in having a diesel-driven generator in continuous operation. This generator would have two main functions: It would define the frequency of the electric current supplied to the network, and it would absorb the rapid variations either of the power required by the network or of the power supplied by the wind-driven generators when the wind speed ranges between the starting threshold and the rated power threshold. Under these conditions the wind-driven generators will be coupled to the network most of the time. We are sure that this will be easier if the electric generators coupled with the wind-driven generators are asynchronous, as they are strong electric machines that are perfectly suited to wind-driven generators.

The idle power necessary for network operation can be supplied either by the power generator or generators still working and at least partly by the batteries of the condensers.

Adapting the Wind Driven Generator to the Site

Figure 4, curve A, shows the theoretical maximum specific power that can be taken from the wind according to BETZ theory; that is,

$$W = \frac{16}{27} \times \frac{1}{2} \rho V^3$$

Yet to take off the whole wind power would mean that the wind speed downwind of the propeller would be zero, which of course, is impossible. Curves B_1, B_2, and B_3 of figure 4 show the variation of the specific power output actually supplied by the propeller with wind speed for three different values of rated wind speed, 7, 9, and 11 meters per second.

Figure 5 shows the probabilities θ for having a given specific power (kW/m^2) (Power duration curve) taking the three characteristics of figure 1 as parameters and taking into account the data of the V(t) function in two places:

(1) Sept Iles lighthouse, northern coast of Brittany, France, where $\phi = 48^{\circ}$ 53' N, G = 3° 10' E, and the mean wind speed is about 8.5 meters per second

(2) Johannesburg, South Africa, where $\phi = 26^{\circ}$ 18' S, G = 27° 10' E, and where the mean wind speed is about 4.8 meters per second.

Aerowatt systematically chose to adapt its low- and average-power wind-driven generators according to curve B_1; that is, the machines start between 3 and 3.5 meters per second and supply their maximum power around 7 meters per second. This allows a greater use range of wind-driven generators to areas where it was not possible to use them hitherto; and at the same time in the other areas it facilitates the storage of electric power as the number of productive hours is increased.

However, in the areas defined in the section <u>Limits for use</u> where high-power wind-driven generators are to be used and according to the regularity wanted, it can be economical to modify the wind-driven generator decreases with the propeller diameter. If at a given site the percentage of time during which the wind speed exceeds 9 meters per second for example is close to that during which the wind speed usually exceeds 7 meters per second, it is desirable to choose a nominal speed of 9 meters per second for the propeller diameter will be reduced by $(9/7)^{2/3} = 1.46$. Moreover the reduction of the mechanical multiplier gearbox, and of course its price, is linked to the dimension of the propeller, for a smaller propeller can rotate more rapidly and the multiplier will thus have a lower torque to transfer and a smaller velocity ratio to provide.

Figure 5 gives an example of the diameter evolution of a wind-driven generator supplying an average power of 50 kilowatts at nominal speed if it were installed in Sept Iles.

Power of Wind-Driven Generators to be Built

Table II gives the approximate dimension of wind-driven generator propellers according to their power, for a 7-meter-per-second nominal speed.

Building a wind-driven generator with a propeller diameter of 45 meters does not require expensive technologic methods. With a propeller of the same size and a nominal speed of 11 instead of 7 meters per second, the wind-driven generator could supply a power of about 400 kilowatts; and with a nominal speed of 22 meters per second, like the machine built in 1958, the power supplied would be 3000 kilowatts.

Table III gives a different view of this question. It shows how the choice of different adaptation speeds affects the main parameters of a wind-driven generator, this in the site of Sept Iles, the power supplied over a year being maintained constant.

DISCUSSION

Q: What is the cost of these units? Do you have any estimates of either the smaller ones or the larger ones of those units?

A: Yes. I can give you some ballpark price for f.o.b. machine in the U.S.A. The costs start from $1800 for the little one, the 24-watt machine, up to $10 000 for the 4 kilowatt machine including the machine itself, the rectifier, the controls, and so forth.

Q: Will you describe the 800-kilowatt machine; its size, the number of blades, and other characteristics? I might add that I have had a great deal of difficulty finding literature on the efforts in France, so anything you could tell us would really be helpful.

A: This big machine was a three bladed one. It was running on the principle of autoregulation. That is to say it was fixed pitch, but the speed of rotation limitation was done by the difference of the slope of the generator itself and the curve of the propeller. The propeller was located downwind of the pivot.

The structure was able to swing around the wind rotor axis so that the machine could be built on the ground and not on the top to save some money.

The span was 31 meters, roughly 110 feet. The rotation speed was 47 rpm, the cut-in wind speed, as I already said, was 14 knots, and the rated wind speed was 45 knots. That is the reason why we think this machine was only experimental. Such windspeeds are only available about 5 percent of the time.

It ran very properly for 18 months. The problem was when we installed the flexible blades, we had trouble with flutter and no more blades.

Q: What year was this?

A: It ran from 1958 to 1961.

Q: Why did you switch from rigid to flexible?
A: To try to improve the wind speed and to reduce the rated wind speed.

Q: Do you remember what the cut-in speed was with the flexible blade?
A: It was the same cut-in speed, 14 knots.

TABLE I. - SOME FIGURES ON AEROWATT BIG WIND GENERATORS

Model No.	Span, ft	Rotational speed, rpm	Total blade weight, lb
4100FP7	31	150	130
15KFP7	59	75	1 000
50KFP7	107	45	6 000
100KFP7	153	30	16 000

TABLE II. - RELATION OF PROPELLER DIAMETER TO OUTPUT POWER

Rated power kVA	Propeller diameter, m
4.1	9.2
15	18
50	32
100	45

TABLE III. - EFFECT OF ADAPTATION SPEED ON MAIN PARAMETERS OF A WIND-DRIVEN GENERATOR

Adaptation speed, V, m/s	Generator rated power, P, kW	Propeller diameter, θ meters	Torque on propeller shaft, C, m·kg
7	60.6	32.5	1552
9	68.5	25.7	999.5
11	82	28.8	790

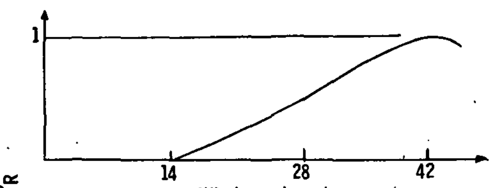

Figure 1. - 800 KVA B.E.S.T. machine.

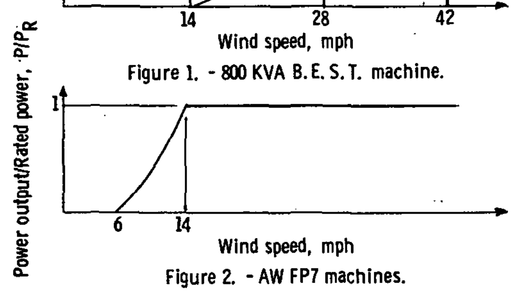

Figure 2. - AW FP7 machines.

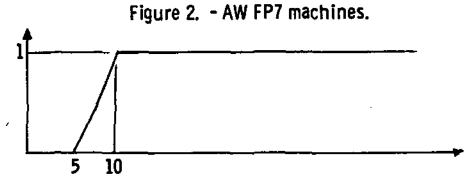

Figure 3. - AW FP5 machines.

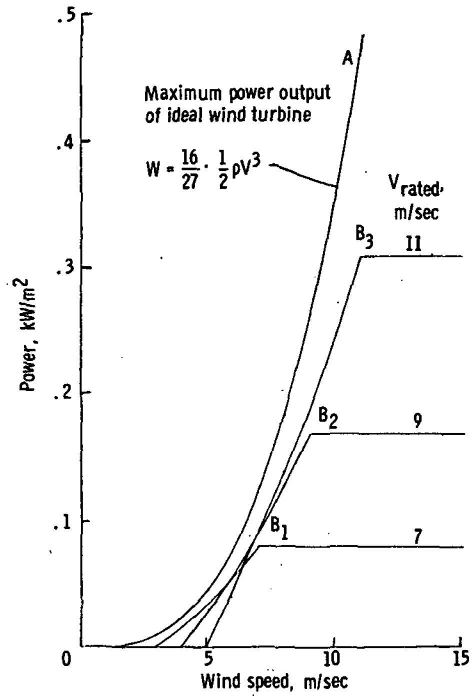

Figure 4. - Power output characteristics of wind generators having various rated wind speeds.

	Johannesburg			Sept Iles		
Rated wind speed, V_R, m/s	7	9	11	7	9	11
Average spec. power, $\bar{P}$, kW/m^2	0.036	0.052	0.060	0.66	0.124	0.19
Rated spec. power, P_m, kW/m^2	0.08	0.17	0.31	0.08	0.17	0.31
Ratio $P_m/\bar{P}$	2.22	3.27	5.5	1.21	1.37	1.64
Equivalent percent time, τ, at rated power operation	45.5	30.3	20	82.5	73	61
Rotor area diam., φ, m	1.0	0.84	0.77	1.0	0.73	0.59

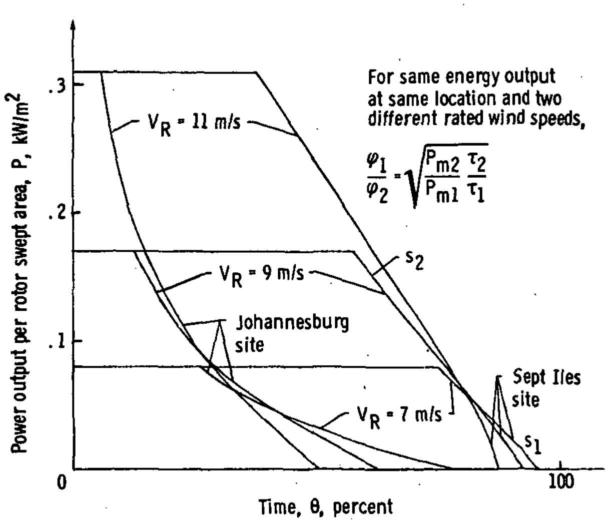

Figure 5. - Power output duration (cumulative frequency) curves for wind generators operating at Johannesburg, South Africa (mean wind speed, 4.8 m/s), and at Sept Iles lighthouse on North Coast of France (mean wind speed, 8.5 m/s) and for rated wind speeds V_R of 7, 9, and 11 m/s.

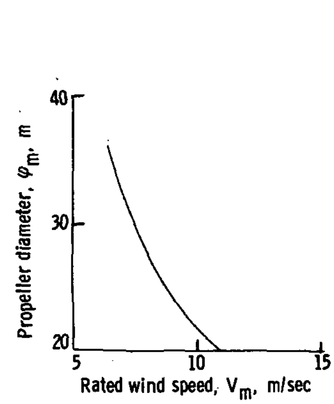

Figure 6. - Propeller diameter as a function of rated wind speed for a wind generator having 50 kilowatt rated output and sited at Sept-Iles Island.

A PROPOSED NATIONAL WIND POWER R&D PROGRAM

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My interest in wind power began back in 1970 when a group at the University of Massachusetts was studying a proposed increase in the electrical generation system for the Connecticut River Valley. In other parts of New England others were concerned about the problem of how to meet the increasing energy demand without causing serious ecological damage to the New England environment. These studies led to a University of Massachusetts proposal to investigate a national network of pollution-free energy resources - the wind being one of them.

As a member on the NSF/NASA Solar Energy Panel, my involvement with wind power increased. It was clear that a comparison of the energy potential of the different methods was needed. So, I decided to evaluate the potential of wind power using one totally wind-driven system. The objective was to calculate the cost of energy delivered to the customer on demand in New England and to compare this with the cost of energy from systems that were being planned at the time. Meanwhile, the cost of electricity was increasing from 28.2 mils per kilowatt-hour in 1968 to 32 mils per kilowatt-hour.

The system I chose to analyze was the "off-shore wind-power system," which consisted of wind-driven electrical dc generators mounted on floating towers in the waters off the coast of New England where the winds are high. The output from the generators supplied underwater electrolyzer stations in which water was converted to hydrogen and oxygen. The hydrogen would be piped to shore where it would be converted to electricity in fuel cell stations.

With this system, it was estimated that 159×10^9 kilowatt-hours per year could be produced at an average annual revenue somewhat higher than the 28.2 mils per kilowatt-hour of 1968. Even though the estimated price was higher, the absence of the pollution that would result from fusion-combustion processes was a benefit that was worth the added cost. This fact - the reduced pollution resulting from wind power - and some deeper thinking led me to the conclusion that solar energy (includes wind energy) is the only way out of the nation's energy (and pollution) dilemma in the not too distant future. The sooner the nation starts using solar and wind energy, the better off everyone will be. There are several reasons for this:

(1) We have been converting matter into heat at an ever increasing

rate and we may be close to the time when the temperature of the earth is going to start increasing.

(2) The coal, gas, and oil that are left stored in the Earth are among the most valuable fossil resources that nature provided for man. It is a crime against mankind to burn any of it.

(3) I don't believe that the U.S. chosen alternative to fossil fuel, namely, nuclear power, is proper. The nation is headed for very grave trouble with that alternative, a major part of it being economic. The costs of energy have risen dramatically in three years and will continue to rise. These then are the reasons I believe the nation needs a national wind-power program.

The major conclusions of my wind energy study are

(1) The wind is an enormous source of power, but we must go where it is, namely, high up, over 500 feet above the ground, to get it.

(2) It is incorrect to view and to cost out wind-powered systems solely as fuel savers. A self-contained storage system is needed, and power should be offered for sale on demand. The costs should be made on that basis.

The national wind-energy program I envision should consist of three general programs:

(1) A technology program whose objectives would be to improve the performance of components, reduce their costs, increase their life, and develop new concepts.

(2) A resource assessment program aimed at determining the energy potential of the nation's wind, the most suitable sites for wind power systems, and the effects of the wind systems on the local weather.

(3) A production plan program with the objective of using the nation's tremendous productive capacity to produce at reasonable costs the large number of wind power plants that are going to be needed.

In addition, an assessment should be made of the social, political, and legal problems associated with wind power.

The implementation of the wind energy program is also an important part of the overall program. One possibility, for example, is to suspend large numbers of small wind-generator units on cables like suspension bridges, or on other types of very tall towers.

In conclusion, my studies suggest that wind-powered energy systems have the greatest chance of being used to supply an important portion of the U.S. energy need in the near future at costs that are competitive with other available systems.

DISCUSSION

COMMENT: I don't think the professor has left us any questions really to ask. I am absolutely with him, really. If we look at the world as a whole and at the future of mankind, we must look more than 50 years ahead. (And mankind usually doesn't look more than 5 ahead.) I see a future in which our reserves are so low and our pollution levels are so high that the sort of life that is left is not the sort of thing that I want for my children, grandchildren, or greatgrandchildren. If we don't want that to happen, obviously we've got to do something now. Whether windpower is really the answer I don't know. The professor is a slightly more imaginative man than I, and I see perhaps more barriers than he does. But I am entirely with him, that wind power is one of the energy methods that we should develop now and as hard as we can.

Q: What is the relative height above ground level that you are contemplating these suspended windmills, and what logistics problems you might envision in a reasonably congested land area like the Northeastern corner of the United States? I could easily foresee a machine like this being used in Canada and I can see it in some of our uninhabited islands, but I really wonder, with people's addiction to small airplanes, glider clubs, et cetera, what legal problems you might see, in your immediate vicinity?

A: Well, let me take that last thing first. If we do have problems with small aircraft and gliders, then perhaps it's time that we make that choice. We shouldn't ignore these choices any more, and just because the FAA has allowed the small plane pilot certain privileges over the years is no reason why that has to continue. Now, that is the way I feel.

As for the sizes of mills or machines I studied, the system I put together for the off-shore wind-power system was based on two sizes of machines, because they were available to me: a 200-foot-diameter machine and a 60-foot-diameter machine. I copied the New York University report and was very happy to have their results. As I said, though, I have since come to the conclusion that in much of the United States smaller windmills will do. As a matter of fact, I promised a Senator from Wisconsin a study that is now a couple months late (but I'll get to him). In that study I've been looking at wind power supply in Wisconsin. Perhaps I can answer your question in that context.

On the north-south running highways, which run about 20 miles apart in Northern Wisconsin from Green Bay north on through upper Michigan, significant wind energy could be extracted using wind generators suspended over the highways. It is just as straightforward to talk about north-south wind barrages located over the woodlands between the highways. In this kind of wind barrage the axis height of the lowest machine would be 100 feet. We could suspend large numbers of wind generators in a suspension system whose towers would rise to some 600 feet. They would be, perhaps, cage-mast type towers with a bottom so configured that they could straddle the highways. The span would be half a mile. The upper wires would drop from 600 to 300 feet. Now, on those wires we would suspend groups of vertical axes. Each axis, capable of turning to face the wind, would in turn carry the structural framework on which many machines, about 32 feet in diameter, would be installed - 20 kilowatt units. (Mr. Noel probably feels that he has made a convert. And I think he has!)

Q: Obviously you studied the Russian work that was done many, many years ago on that same thing. What is your opinion of that?
A: I think the Russians have done some very excellent work in wind power, but they aren't doing much of anything now. At least the last two to whom I spoke simply ignored it or wouldn't discuss it with us. They said it was entirely too old-fashioned for the Russians.

Q: They had looked at the grid system approach, hadn't they?
A: Yes, they had. In fact we could use structural grids. A very interesting study to make would be to go back to Grandpa's Knob and that design of a 175-foot-diameter machine (which I thought was magnificent), and substitute for it an array of 100 32-foot-diameter wind generators, each of 20-kilowatt capacity for a total of 2 megawatts installed capacity. This array would look somewhat like a big billboard, or radar mattress. They could be spaced far enough apart so that each machine could develop its wake fully, so we wouldn't suffer an efficiency loss there. How would this different 2-megawatt wind generator compete? I think it would do a lot better than the 175-foot-diameter machine did.

COMMENT: May I make a brief remark about the Russian effort? Very recently I did some intensive digging, talking to people in Washington and elsewhere about this alleged big wind power effort in Russia. Most of the Russians just smiled and thought I was rather primitive. They pointed out that they had built a few, but that they had so much hydroelectric power that they could run wires anywhere in the country. They don't need windmills.

COMMENT: I will just make an observation on the basis of the WKY towers. There is about a 40-percent higher wind velocity at 600 feet and about an additional 60 percent up to about 1000 feet.

COMMENT: Putnam, I think, came out with those figures quite nicely. He showed that you are really in the realm of diminishing returns by the time you go much above 150 feet. But I feel that you have to say, "Okay, so I'm in the realm of diminishing returns, but that's where the wind is. If I want to stay below it, I'm not going to get much wind." It's like those systems studies of fishing in the Gulf of Maine that said so conclusively that the most economic place to fish is in the street in front of the fish pier! The only problem is that the fish don't know that.

COMMENT: There is one point we must remember, unless you've thought of a new way of keeping your machines up there: The higher the tower, the more steel or some other metal you have to use. It takes some 13 200 kilowatt-hours to produce a ton of steel and 50 000 kilowatt-hours to produce a ton of aluminum. We shouldn't waste energy in the structure before it's even built, there's no energy balance in that.

Q: How sensitive are your power costs in the final step of converting hydrogen to electricity if it's done by fuel cells. What lifetime energy have you amortized in the case of fuel cells?

A: It's quite sensitive in the case of the hydrogen fuel-cell link, though the most expensive portion of that system is the blades of the wind generators themselves. The second most expensive portion was the complete system from the electrolyzer through the fuel cell. Now, the fuel cell life I used was 15 years, and you go ahead and whistle! I know that some of you people keep saying that Pratt & Whitney really don't know what they're talking about. But I happen to have been in their lab off and on for many years, and I'm quite confident that the 15-year life is going to be achieved. In fact, this is just one aspect of the wind power system using a hydrogen link that I feel has a real future - all right, go ahead, shake your head! I'm sorry!

COMMENT: I think I have to answer that. I worked in the last 15 years in the field and I can't share their optimism that a 15-year fuel cell is around the corner. I've seen no test data from anyone that exceeds 2 years.

A: Someone thought enough of it about 4 months ago to assign them a $90 million R & D program.

COMMENT: I understand that some of our people are going to work on it. That's fine.

COMMENT: I would like to join him. Oklahoma State has had 10 or 12 years experience. You must know something we do not see in the published literature. I don't think a long-life fuel cell will come around in the next 5 to 8 years.

A: I know of one New England utility who is purchasing from Pratt & Whitney right now a considerable number of kilowatts of hydrogen-air fuel cells at a total cost of $185 a kilowatt, which includes reformer. Now, I don't know the life specs, but I'm sure that it's at least 15 years. Now that's as much as I know; you've got me in over my eyebrows!

The most significant work in fuel cells perhaps has not been - and this is really going to hurt - the NASA work of the last few years, but the U.S. Navy work which created the fuel-cell power system for the deep ocean search vehicle. Those results are not available to all of us.

COMMENT: Bill, I think you have released a flood of philosophy here, which I think is not unwelcome. I am frequently called on to address groups on the subject of the energy crisis and the like, and I have been using a subtitle to my talk. Usually it's something having to do with the resource crisis. I think it's appropriate this afternoon to mention it and perhaps coin a new phrase.

What I am referring to is that in any resource pinch such as that in which we find ourselves now, our criteria have got to change very rapidly. The escalation of the energy crisis really took off essentially like a rocket in about 1969. Many of us take a good deal of comfort in looking at the average cost of energy curves. Though the average costs are up from 1969, they are still artifically depressed by the fact that some of the energy contracts in force today were negotiated several years ago. If you look very carefully at the current contracts, you will see that a cost of about 90 cents per Btu is fairly common. Those are the numbers we should look at, not the averages.

Now, when Bill speaks of suspension via hydrogen balloon or cables or towers, or what have you, I don't think it's exactly pertinent to point out that aluminum takes so many kilowatt hours per ton and steel so many. These are one-time costs, and they can be energetically amortized.

Now, the subtitle to which I refer and which I think is appropriate today is, "Don't worry about Mars and Venus. The question is 'Is there intelligent life on Earth?'"

I would also like to add that, if we assume that our present point in history is perhaps 5000 years removed from the first time man recorded things by infusing them on stones, perhaps this generation has another five thousand years. The fossil fuel era, through which we are presently half way through and passing very rapidly, I very inelegantly refer to as a small pimple on the rear end of history.

I think it would also be appropriate for us to ask ourselves something to the effect that (I think the word "war criminal" was coined during the latter stages of World War II) "Are we behaving as "resource criminals," because we're using it up just as fast as we please without a thought to where it ends and what our children and their children will have to do with when their time comes?"

COMMENT: If you are brainstorming, you can come up with all kinds of designs for windpower plants. I could surprise you by some of the ideas. For example, if you put a heavy rotor on a tower and put a rope on it and drive it, it will go higher up in the air. Then, if you fix the next one then you can put both rotors up in the air to the stratosphere.

This is just one of the hundreds of ideas that could be mentioned here. The solution to accumulate many rotors on a system of steel ropes or something like that has been brought up by Russia and by Holland in the middle of the twenties. Going in this direction is a market question.

Let me mention one thing, which is the best size for wind electric power. This is an important question. If you make small ones, you can produce them in quantity and get the advantage of a lower price by their small size.

If you make big ones, you get advantages of the fewer parts and there is somewhere a minimum of the cost, and we have to be very careful to do this. We can calculate the minimum.

A: Doctor, I think some of your fellow engineers have designed very distinctive wind generators. I am not sure I could contribute anything.

A COMMENT ON TOWERS FOR WINDMILLS

H. P. Budgen

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The earliest windmills appeared almost simultaneously in France and England towards the end of the twelfth century. In England windmills were built in grain growing areas, where there was insufficient water-power, and were to be seen in a line east of a line connecting Newcastle with Portsmouth.

No early designs have been found, and it would appear that the parts were set out full size on the workshop floor and made to templates. The earliest accurate drawings of windmills are perspective views shown in Ramelli's "Le Diverse et Artificiose Machine" of 1588. The descriptions given would enable a millwright to make a complete windmill. The earliest published working drawings are those of the fine Dutch mill books, starting with that of Pieter Limperch, a millwright from Stockholm. These drawings were published in Amsterdam in 1785. The earliest mills were very simple, called post mills, and consisted of a box shaped body, supported on a vertical post. The earliest known illustration of the post mill is in the "Windmill Psalter", made in England about 1270. Later the tower mill was developed, and Dutch mill books show this practice before 1700. Thus, towers were incorporated in the main structure. In the fabrication, or design, if any, of these earliest windmills, the main considerations were to accommodate machinery and to hold the windshaft, which was usually inclined 5^{o} to 15^{o} to the horizontal. Generally, there were four sails, but five were used in Leeds, England, by John Smeaton in 1774. Also a few with five and eight sails were tried. Matters of wind obstruction, or 'drag', on towers were not ever seriously considered. Later towers were made of masonry and tapered to the top cap, which was rotated manually at first and later by a small fantail. Towers built in the Caribbean about 1750 were of masonry from local quarries. These towers were profiled in side elevation, much in the form of a parabola, and not as cones, so common in later Dutch and English construction.

Of later years the concept of using windpower more efficiently has lead to compact grouping of machinery, whether for pumping or, more recently, electrical generation, and at the same time to increased speeds and reduced overall swept area of the vanes. Because of this regard to minimize size of the rotor blades and to attain high speeds, much consideration has been given to the economics of tower designs. This has been possible because of the near universal grouping of all mechanicals and electrics in one housing, so that it operates concentrically with the rotor shaft. In such a manner only the conveyance of mechanical, or as may be, electrical energies has to be considered. This can be via a designed structural frame, a structural steel tube, a concrete or a masonry tower. The requirements for any of these alternatives is dictated by the weight and size of the complete operating system. For small wind turbines manufacturers mount the complete power assemblies on a tube, the height of which is determined according to wind obstructions. Such tubular towers are usually guyed, but the system is arranged so that the whole can be lowered, using a winch, about the fixed baseplate. For the larger power units made, tubular towers are popular, but access has to be provided into or outside of the overhead power system.

For a similar power output consideration, Brace Research Institute designed and built a windmill for pumping in Barbados, which, with a three-vane rotor and a 32-foot swept area, develops a pump water horsepower of 1.16 and 31.3 at wind speeds of 10 and 30 mph respectively. This had a structural tower that could be raised or lowered as required. More recently, Brace Research Institute has designed an improved structural tower to be raised or lowered, a 3-foot diameter standard drawn telescopic tube tower, a parallel concrete circular tower, with a 6.5-foot outside diameter, and one built of reinforced standard concrete blocks with a 6.5-foot outside diameter. All these towers are suitable for the designed mechanical pumping, or electrical generation components designed by the Institute.

In the design of any tower, consideration had to be given to the effect of normal wind forces on the rotor and the tower and to the drag effect of the rotor vanes, and the tower, all create an overturning moment. Circular tubular or masonry towers present a relatively simple aerodynamic solution. This is not the case with lattice structural shapes. Because of this easier approach and because of lower manufacturing costs, the tubular tower now takes precedence everywhere for small and medium sized windmills.

The Brace Research Institute examined concrete, and standard concrete block designs for towers, especially for construction on sites by local labour in developing countries. These designs were found to be cheaper than shop prefabricated steel structures which have then to be freighted to the areas of usage.

Fabricated steel towers cost $4750 (made in Canada) to which freight must be added. A circular reinforced concrete tower made in Canada costs $6787, but $1984 if made in a developing area with lower labour costs such as the Caribbean. A reinforced concrete block tower made in Canada would cost $5000, but, if made in a developing area it would cost about $1600. A telescopic 3-foot diameter, reducing to 2-foot diameter, tube which can be extended by two small winches incorporated within the tube, costs in Canada about $3000.

Thus, on-site construction of towers for medium sized wind turbines, is cheaper when made of locally available materials--largely because of labour costs. For similar constructions in Canada the steel tubular tower is probably the cheapest.

SOME EXTEMPORANEOUS COMMENTS ON OUR EXPERIENCES WITH TOWERS FOR WIND GENERATORS

Ulrich Hutter

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The supporting tower of a wind generator is subjected to various forces, the dominant ones being the horizontal component of the rotating machine (horizontal or vertical axes) plus the horizontal force of the wind. Also, because the wind is usually fluctuating in time, the tower is subjected to vibratory forces and hence fatigue forces. Hence, a tower must be designed to withstand the fatigue forces imposed on it.

Another important design consideration is that caused by high winds and gusting. Heavy gusts cause little trouble with fast rotating rotors that have high tip to wind speed ratios because the rotor blades are stalled and the forces on the blades do not increase. The more serious danger is that of overspeeding of the rotor which could destroy the machine. Hence, the structural integrity of the tower is dependent not only on the strength of the tower, but also on the regulating systems. If the regulating systems are not foolproof, the tower will be destroyed even if it is 10 times stronger than it should be. Finally, the regulating system has a great influence on the cost of the plant because of the influence on the cost of the tower. Thus, it is essential that all possible accidents be considered and that fail-safe controls be incorporated into the plant.

Another important force is imposed on the tower by the rotor. If the rotor is located upwind of the tower, the wake of the passing rotor blades causes a change in the wind forces on the tower. Thus, the tower is subjected to pulsating forces caused by the passing blades. If the rotor is situated downwind of the tower, the vibrations on the tower are drastically reduced, but the blades are subjected to vibratory forces because they pass through the tower wake. Given a choice of failures, it would be less catastrophic for a blade to fail than for the tower to fail.

The last important question considered concerns the height of the tower. The wind velocity increases with height according to a power law where the velocity is proportional to the height raised to a power, say 1/7 (the exponent depends on the ground roughness, among other factors). The optimum tower height depends on the cost of the energy to the customer because an increase in height results in an increase in the cost of the plant, which, in turn, offsets the increased energy output. My studies of this question suggest that the costs are minimum for the shortest tower and that, since the energy extracted varies as the square of the rotor diameter, the rotor should be as large as possible.

WIND MACHINES

P. B. S. Lissaman

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Starting in 1969 the American Institute of Aeronautics and Astronautics (AIAA) has sponsored an annual technical symposium on the aero-hydrodynamics of sailboats. As AIAA Distinguished Lecturer (1972-1973) the speaker was asked to prepare a semi-technical lecture describing the history and contents of these four symposia under the title The Ancient Interface, Blackboard to Bluewater. A version of this talk was given, with the emphasis on wind-driven vehicles.

The basic elements of the air/water momentum exchange were described: the environment, the potential, the air and water subsystems, the total system, and the rule. Many of these topics have direct analogues in aerogenerator design. Aspects of optimal sail design and of waveless hulls were briefly outlined. A wind-driven vehicle, designed by Andrew Bauer and capable of moving directly downwind faster than the wind, was described.

The lecture was illustrated with slides and movie clips showing surfing catamarans (Arnold), land and water versions of the Bauer vehicle, hang gliding (Kilbourne), land sailing (Ripinsky), and wind surfing (Schweitzer).

REPORT OF THE COMMITTEE* ON

WIND CHARACTERISTICS AND SITING

Reliable data for wind power installations are not always readily obtainable from existing records. Wind stations have often been located at airports in order to meet the requirements of aviation.

Wind power needs are best served by choosing sites where the winds are higher than those representative of a broad area. Unfortunately, there are few wind records for such high wind speed sites. Having in mind the desirability of several established proof-of-concept units in the near future, it is recommended that three areas be chosen in which such units will be located.

On the basis of existing meteorological data, three recommended high wind areas are the Pacific Coast, the Great Plains, and the Atlantic Coast. A variety of nonmeteorological as well as meteorological criteria should be employed in pinpointing exact sites.

Relevant meteorological data are wind speed, wind direction, wind turbulence, and the variation of these within the lowest hundred meters. A priority listing of research and development requirements for an area is given below.

1. Basic wind information, existing data: A search should be made for all existing wind data for the area. These data should be assembled, their relevance assessed, and then analyzed if the data appear to be relevant and reliable. A summary of existing relevant wind information can then be prepared.

2. Basic wind information, new data: These are hourly averages of wind speed and direction at two heights, 10 meters and 30 meters, along with peak gust speeds at both heights with the frequency of occurrence of gusts in the high range specified.

A minimum of 12 months of data at each site is required, overlapping the long term record at a nearby station to determine if the winds for the 12-month period are reasonably representative of climatic normals.

Devices for recording directly the standard deviation of wind speed are commercially available and are recommended for the 30 meter height.

*E. Hewson, chairman; W. Barnes; D. Beattie; K. Bergey; R. Cohen; V. Nelson; R. Rotty; A. Stodhart; T. Wentink; and J. Wharton.

Standardization of units and of methods of making and analyzing measurements should be adopted.

3. Basic wind information, turbulence structure: A detailed study of turbulence structure in the lower levels should be undertaken, using existing wind data from one of the Great Plains' instrumented TV towers. Such a structure may be taken as reasonably representative, except over very rough terrain.

The extensive literature on the dynamic wind loading of structures should be examined as being highly relevant. Discussions should be held with the leading authorities in this area for the purpose of determining the extent to which recent research may be applicable to the design of equipment for generating power from the wind.

4. Weather modification: The possibility of significant weather modifications being caused by single or clustered wind turbines should be examined.

5. Public policy: The content of environmental impact statements should be set forth for the guidance of those who are to prepare and those who are to evaluate such statements. Possible legal restraints should be analyzed in detail. Sites should be selected so as to minimize both audible and visual pollution.

6. Dissemination of information: A comprehensive, annotated bibliography should be prepared, kept up to date, and widely distributed. Translations of significant results of research in other languages should be made and distributed. Some appropriate agency should be encouraged to collect and reproduce the documents that are fundamental to wind power studies. Many of these are generally unobtainable at the present time.

Explorations should be commenced with the Solar Energy Society and its Journal concerning the possibility of changing names to the Solar and Wind Energy Society and Journal. Sponsoring agencies should support such publication by authorizing substantial page charges.

7. Size of proof-of-concept units: Since ten 100-kilowatt wind turbine units appear to have substantial advantages over one 1000-kilowatt unit at this time, sites chosen for proof-of-concept units should be suitable for accommodating ten such units even if all are not installed at one time.

DISCUSSION

Q: Why do you recommend that the heights 10 and 30 meters be established as standard for measurements of hourly average wind speeds and directions, along with peak gust speeds?

A: Thirty meters was chosen as being approximately the height of the hub of a large wind turbine. For a smaller wind turbine the hub would be below 30 meters. Thus the winds at 30 meters could be taken as giving roughly those which specify anticipated wind power production and associated with gust loading on the system of rotating blades. A second set of wind measurements at 10 meters offers two primary advantages. First, since 10 meters has been adopted internationally as the height at which surface wind observations should be taken if at all possible, winds at this height at proposed wind power sites permit ready comparison with long term winds measured elsewhere. Second, wind measurements at two such heights permit meaningful vertical extrapolations of wind speed, direction, and peak gusts beyond 30 meters to provide valuable preliminary wind power design data.

Q: Why not take measurements up to 500 or 1000 feet to obtain wind information at heights which were of interest to Percy Thomas of the Federal Power Commission?

A: The group's recommendations are based on the premise that the first larger wind turbines to be built in the United States, such as the proof-of-concept units mentioned above, will have a rated capacity of 100 or perhaps 200 kilowatts. Wind measurements at 10 and 30 meters, along with the upward extrapolations that such measurements permit, are entirely adequate for the preliminary wind surveys designed to locate possible sites for wind power installations. If much larger units are contemplated, wind measurements up to 500 or 1000 feet require expensive high towers.

Q: Use a balloon.

A: A balloon will not give the required long term data. Do you mean a pilot balloon?

Q: A tethered balloon.

A1: Tethered balloons are both expensive and difficult to use, and especially so for measurements for a full year. When high winds - those of great interest for wind power - occur it would be necessary to reel in the balloon to prevent it from being blown away or driven to the ground. Attempts have been made to measure higher level winds by the use of tethered balloons but very limited success has been achieved.

A2: If we are concerned with winds at high levels above ground, measurements are not needed because synoptic data for gradient winds 2000 feet above the ground can be obtained from the pressure pattern charts.

Q: If I understand you correctly, you mentioned 10 units of 1 megawatt each. What were the size of these?

A: No. I spoke of 10 units of 100 kilowatts each for a total of 1 megawatt.

Q: Why did you choose those numbers and sizes?

A: This choice represents our group's distillation of the discussion of the previous two days. This was, in our opinion, the consensus of the workshop. We also mentioned five units of 200 kilowatts each for a total of 1 megawatt. The total capacity of a group of proof-of-concept units should be no greater than 1 megawatt in the present stage of development.

Q: What is the present status of the wind measuring network in the United States? How adequate is it?

A: For the flat areas of the Great Plains and the land to the east, the network is adequate for first rough estimates of wind power potential. Over both coastal waters and the mountainous regions the existing information is completely inadequate. For wind power estimates for such areas, we need information not on representative winds but on ones that are not representative because they are stronger than characteristic regional winds. For example, over coastal waters the wind currents and water currents are a coupled system with feedback from each component to the other, and the whole must be considered as a unit. Thus the location of maximum coastal winds may be expected to shift somewhat with the season in a manner which may become predictable as the dynamics of this coupled system is better understood through research. Similarly, research into the kinematics and dynamics of high-speed air flows in mountainous terrain will assist in locating favorable wind power sites. For certain selected areas over both coastal waters and mountainous terrain there is already sufficient wind information available to permit us to proceed with proof-of-concept experiments of the type discussed in this workshop.

REPORT OF THE COMMITTEE* ON

ROTOR CHARACTERISTICS

I would like to preface my report on the Rotor Committee's work by two pieces of information that have come to my attention since we left our meeting last night. I think these points help us understand better the challenge facing wind power. One of them is an observation, by one of the more active participants in this symposium, that every time he sees the pictures of Professor Hutter's hundred kilowatt machine which is truly an engineering achievement of some significance, he is reminded of the fact that it provides approximately half the horsepower that is under the hoods of each of the United States' 50 million automobiles. The other piece of information that I think is worth remembering comes under the general heading of "the black goo that comes out of the ground is tough to beat." Perhaps some of you saw on the TV news this morning that the AEC has announced that 150 000 gallong of radioactive waste leaked into the soil in Richland, Washington, recently. But they assure us there is no need for concern for the population, and in 150 years the soil will be usable again.

To summarize the conclusions of the Rotor Committee, the quest for improvement in performance of rotors should not look for improved aerodynamic performance of the rotor blades. The current state of the art is getting all but about 7 percent of the theoretical limit of the energy that is in a square foot of wind. The magic 0.593 number is there, and we are not going to beat it by improving blades. The concentration of effort in aerodynamic performance, per se, should direct itself either to capturing a greater fraction of the wind stream tube by use of novel concepts, or to reducing the cost of energy available by conventional means. It is in that context that the rest of the Committee's information is to be interpreted.

1. The most significant technical problems that limit improvement of rotors are in the dynamics of the blades. Blade dynamics becomes an increasingly important factor in escalating costs as one attempts to go to larger machines in order to realize the economies of scale.

2. Today's commercial state of the art deliberately sacrifices a little aerodynamic performance in the interest of producing a blade of a particular size and load capacity more cheaply. This makes perfectly good sense, because in losing a couple of points in efficiency you can change the cost by a very large factor, and therefore get more power per dollar. Rather than look for improved aerodynamic performance, we need

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*R. Oman, chairman; H. Chang; U. Hutter; T. Lawand; P. Lissaman; H. Meyer; W. Nixon; J. Noel; R. Ormiston; R. Puthoff; W. Vance; W. Wiesner; C. Wilcox; and R. Wilson.

better aerodynamic performance for a given investment.

3. One of the problems that is significant in terms of the reliability and long life of rotors is the general problem of fatigue - and I deliberately avoided calling this metal fatigue because there is good indication that fiber-reinforced composites will be used extensively in wind turbine blades. Fasteners are a particularly bad cause of local fatigue problems in the vibratory environment of a turbine. The aerospace industry has made recent progress in improving fatigue life of fastened joints by the use of interference fasteners, but their costs are still quite high.

4. The definition of the failure modes of windmills is an area that needs specific study. What are the ways in which windmills can go bad? What are the pathological conditions of the loading of a windmill rotor?

5. Although materials and manufacturing improvements can be taken from other technologies, there is still a great need for improvement in both of these areas, especially with the direct result of reducing cost. Costs of advanced composites are dropping rapidly with increased usage, and some of the unique stiffness properties of advanced fibers make them very attractive candidates for blending into a fiberglass layup to increase stiffness. High stiffness and low weight are very important in raising the vibration-limited speed of large blades.

6. One point was made after we adjourned, but was discussed in an impromptu appendix to our session because it is considered to be rather important. The use of strictly disciplined dynamic modeling - careful observance of similitude laws in small-scale experiments - is a very powerful technique that should be given considerable emphasis before commitment to any large-scale expensive installation. The emphasis here cannot be made too strongly on the need for strict similitude discipline in that work.

7. A lot of people have worried about the wakes from towers and the passing of the tower disturbance in the wind field as the blade goes by. The consensus of those who have experience in this area is that the turbulence, gust loads, tower vibrations, and so forth, present far more significant dynamic disturbances to the rotor than do the wakes of the tower.

8. There is a very strong need - and perhaps this should not be so far down on the list - for better, and totally reliable, control techniques to match rotor speed and pitch characteristics to changing wind factors. This is particularly important in terms of ensuring that any failure of the wind turbine will occur in a safe manner.

9. Under the requested general heading of environmental problems, it seems to be unequivocal at this point that wind turbines are not noisy. Professor Hutter cited an example of a large installation on top of a hotel in the Schwarzwald where the wind turbine could not be heard

anywhere around the hotel, but the diesel generator that it replaced was audible to everybody in the hotel at all times that it was running.

There is the general aesthetic problem of the visible impact - visible pollution, if you wish - of large numbers of large wind towers, but that must be left to somebody other than rotor designers to solve. The increase in surface friction factor of the wind and its potential effect on climatology has been a concern that many people have voiced. The consensus of this Committee is that it is more likely to be a favorable than an unfavorable effect in most of the places in which wind turbines would be installed, most notably the Midwest plains, where what the farmers want most is something to "soak up" the wind. If you have ever sailed around Nantucket Shoals, you would agree with that conclusion.

There were concerns for such things as vandalism and public safety, the need to fence and to protect wind turbine sites, air traffic interference and direct impact by airplanes, the wakes of wind turbines as a disturbance factor to airplanes, and the legal questions of wind rights. No one felt these problems were basic limitations, and we felt they were outside of our charter to deal with rotors.

To summarize the development tasks to be done and their relative priorities, Professor Hutter nominated the following list, and it was enthusiastically received by the balance of the Committee.

The first priority is selecting and trading off configuration candidates; that is, deciding the best way to get the most power per dollar out of the wind. I would personally add that we probably should start with the European systems that have been developed most recently and use them as baselines against which to compare candidate designs and concepts.

The second priority is the question of dynamics, particularly dynamic problems associated with removing those limitations to the increase in rotor diameter that are the main factor responsible for escalating the costs of large designs.

In a normal engineering development program, the place we start is in the definition of the requirements; the determination of what the thing we are going to make is supposed to do. In this list of priorities, we place the definition of the requirements for wind turbines third because wind turbine requirements are so heavily dependent on particular site and demand characteristics. However, requirements definition must receive some emphasis, in particular, the identification of failure mechanisms and acceptable failure modes.

Fourth on the list would be a better understanding of the control problem, both from the standpoint of the computational end of it - the autopilot, to use an aerospace analogy - and of how one actually brings the intelligence of the control logic into the control surfaces - the hydraulics, the muscles, mechanisms, whatever. Both of these areas need further emphasis.

Materials, fatigue resistance, and aerodynamic improvements of blades were not called out for special mention, because wind turbine technology can be copied directly from applicable portions of current practice in aircraft technology. The rest of the questions of wind turbine design we feel were best left to the provinces of other committees.

DISCUSSION

Q: What should the size of the first prototypes be and how much power should they deliver? Should you go for large or intermediate size windmills?

A: Well, the comment on the need for dynamic modeling is relevant to that question. If we are going to be choosing configurations, it would be my personal opinion that we would want a small one if we are talking about something which is not pretty close to the types that have already been pioneered. Scaling laws that have been carefully formulated can be used to generate larger prototypes from the performance of the smaller machines. If, on the other hand, we decide on a machine that looks very much like Professor Hutter's or the one that Mr. Noel is selling, where considerable amount of development work is done, then I think we can go pretty big right away with good design.

Q: What do you mean by pretty big?

A: I think everybody has his own idea what big is, but a 100-kilowatt machine is state of the art. Beyond that there have been problems with blade failure. The blade failure is largely attributed to vibration problems and metal fatigue. So, if we feel we have a good handle on the vibration and fatigue problems, we can go bigger than that. That's one answer.

Q: Any suggestions or recommendations as to what type of rotor has been recommended as the most economically feasible? Maybe Professor Hutter may have a comment on that.

A: If you want me to comment on this, I should say the plant in 1942 had a diameter of about 53 meters. That was the state of the art in 1942. Presently, there are some installations between 30 and 34 meters diameter. Eventual problems occurred in lesser rotor diameters so we came from this point to increase the diameters as necessary.

The next aim should be a plant of 130-meter-diameter swept area. This should be a step not to get into too serious risks. But the aim could be to make even bigger ones and find the solutions to do this.

As we mentioned yesterday, there are additional problems - especially dynamics - of erecting such a plant. A very special problem that could occur would be that the formation of the blades, due to the gravity field, could cause a permanent unbalance of the rotor system.

We should aim towards 10 000 square meters. This should be feasible in the next few years.

We should be able to develop this and put such plants into operation and put them in many climate conditions from Alaska to Florida.

I have just a short remark. The question has been how much power should be installed in such a plant. This is a question which has been a topic of some of the organizational studies.

I plan to install not too much kilowatts. If you install less kilowatts per square meter, less than 300 watts per square meter, it should be an average of 200 watts per square meter. Plants of this installation size have been operated with many years successful running.

If you install more - if you have a 5000 kilowatt plant, it looks good, but it doesn't give any more kilowatt hours.

I might add, as an aside, that when I attended this session last evening, one of the men commented that a wind turbine system is really a fatigue machine. I thought that was a nice description.

REPORT OF THE COMMITTEE* ON

ENERGY STORAGE AND ENERGY CONVERSION SYSTEMS

This summary has been prepared from the notes of Dr. George Szego of InterTechnology Corporation who served as Chairman for this session. The group agreed to limit our deliberations to that area of the wind energy system between the rotating shaft and the end load. We also decided to consider all approaches in terms of a 30-year service life requirement.

Let me first discuss energy storage systems, starting with the electrolysis of water which stores energy in the form of hydrogen. It was generally concluded that for a 30-year system, costs on the order of $200 per installed kilowatt capacity were approximately the present state-of-the-art. This is reported to be a reasonably mature technology, although problems such as hydrogen embrittlement are going to require future study. The availability of suitable water is also something of a problem, with purification being required before electrolysis. The end product is hydrogen, and there was some discussion of the feasibility of storing hydrogen in the gaseous state. We feel this is primarily an economic rather than a technology problem.

If the hydrogen is transported by pipeline, there may be problems related to leakage rates and, therefore, safety, and there is also a question of the economic feasibility of doing this because of the higher pumping power losses involved in compressing hydrogen gas compared with natural gas. Liquefaction is practical and is used today. However, it is an extremely low temperature process which would require special pipelines. A question was raised as to the loss rates from large storage tanks, and whether these are economically acceptable? A general feeling toward hydrogen is that it must be regarded as a potential hazard, and the safety aspects will have to be explored carefully. There is also a psychology problem -- that is, a "Hindenburg Syndrome" -- involved in getting the public to accept large scale use of hydrogen.

For secondary batteries, the performance characteristics can be reasonably well identified. Presently, energy densities tend to fall in the range of 10 to 100 watt-hours per pound and power densities at 30 to 100 watts per pound for lifetimes of a maximum of 5 years. The cost associated with 5-year lead-acid batteries is about $80 per kilowatt-hour. Lead-acid batteries like water electrolysis is a reasonably mature technology, and it is felt that there is only a modest opportunity for

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performance and cost improvements. The most promising research and development opportunities are in other advanced battery systems. Regarding policies, there appear to be possible critical materials shortages, particularly if lead and zinc are going to be required on a very large scale. There is also a question of whether bulk energy systems based on batteries will have heat dissipation problems and therefore result in thermal pollution. Batteries, in general, were considered to be nonhazardous, with the possible exception of large, high-temperature, alkali-metal batteries.

Compressed air storage was discussed at some length. The general cost figure arrived at was $80 per kilowatt with a land area requirement of about 6 acres per megawatt.

Efficiencies of cold air storage systems were reported as 67 percent -- that is, three kilowatts put into this system would yield two kilowatts delivered later on.

(Note: Regarding the question of efficiency, Dr. Szego asked that it be entered in the record that by adding 4500 Btu's per kilowatt-hour to the stored gas before it enters the turbine, the overall system efficiency is raised to 130 percent. Based on the information available, the committee was unable to assess the validity of this claim. Research and development is required, particularly in the area of turbine technology since the 600 psi systems will require a 40-to-1 pressure ratio turbine, which is not state-of-the-art. This approach does not appear to be applicable for very small installations. It appears that the approach would be environmentally satisfactory.)

The flywheel is reported to be capable of storing 30-watt-hours per pound, and delivering extremely high powers for short periods of time; the figure of 1000 kilowatts per pound for 2/10ths of a second being one example given. Costs are expected to be in the order of $50 to $75 per kilowatt-hour for a 30-year lifetime. Research and development are needed in the areas of economic analysis, construction of prototypes, and on technical problems related to bearings and dynamic resonances. In the policy area, the major questions seemed to be, first, safety and, second, the public's lack of familiarity with this concept.

Pumped water storage systems are fairly straightforward. Efficiencies are about 67 percent. Costs are reasonably well-defined. A figure of $180 per kilowatt-hour electric was quoted. They suffer mainly from the limited number of acceptable sites available which are determined by the climate, geology, and geomorphology of the area. Frequently, the acceptable areas are far from load centers, and they are environmentally undesirable because they occupy large areas of land. No R & D seems to be required in this area since this is an established procedure.

In the energy conversion area, it was noted that there are some approaches to wind energy utilization that require no energy storage. On-line generation of wind power, for example, was felt by a number of members of the panel to be feasible without storage by simply feeding the power into the grid as it's produced. This would require frequency-controlled alternators, as one approach. Research and development is needed for such alternators to accomplish reductions in weight, size, and costs. Direct, nonsynchronous machines were also advocated. Here ac is converted to dc and back to ac again, using batteries as the intermediate dc step. This has the advantage of decoupling the variable frequency source, the windmill, from the fixed-frequency load. This procedure has been used for large scale plants. Some development would be needed for small scale applications.

Because of the limitations of time and the broad scope of this topic, the Committee was concerned that these recommendations could gain unwarranted authenticity and credibility by virtue of their appearance in the proceedings of the conference. The Committee wishes to note that these are the opinions of a heterogeneous group, and that they should be reviewed by competent authorities to assure that the recommendations are, in fact, credible.

DISCUSSION

Q: I'm an electrical engineer and couldn't be expected to know anything about thermodynamics and I really don't. But I am having trouble comparing compressed air and pumped water storage, for example. Obviously, if our experience tells us we can get two for three with a noncompressible fluid, how do we get two for three with a compressible one? What happens to dv/t? I'm not criticizing, I'm just asking somebody to explain it.

A: I don't feel I know enough about Dr. Szego's concept to comment on it. I have not read an analysis of the pumped storage versus gaseous storage approach. Is there anyone else who does feel comfortable in discussing this point?

COMMENT: It seems to me you have an upper limit in a noncompressible one, but I could be wrong.

Q: Did you mention our discussion of energy storage with cryogenic conductors and our decision that it is of little promise?

A: Thank you for reminding me. I accidentally skipped it, as a matter of fact. Cryogenic conductors were discussed. They are too expensive, too large, and too hazardous. And they did not represent any appreciable R & D opportunity. The adjectives used to describe the approach ranged from "impractical" to "absurd."

COMMENT: There are two things I'd like to comment on. I didn't quite catch the point about the synchronous principle. There doesn't seem to be any problem about which type of machine one uses on a network. This seems to be a common principle.

The point I would really like to make has nothing to do with that. It's a pity in some ways that this energy storage problem has been discussed with and associated with wind power at this meeting. Because if anybody ties these figures for energy storage costs to wind power costs, then you have completely jammed the thing before you start. I think energy storage is a problem and it probably associates with all sorts of things. But not particularly with wind power.

A: I agree.

Q: There is another aspect of energy storage that we may not have discussed in the session last night. Thinking in terms of a large power generating unit that would supply utilities, how we would cope with the peak demands or base loads when the winds are below the optimum range? Perhaps to alleviate the economic factor of storage, I think the storage facility should be located near the wind-generating plant. I learned that little lesson 4 or 5 years ago where we had to set up our wind facilities to generate power and even produce hydrogen gas in, let's say, West Palm Springs to supply some of the needs, let's say, somewhere in Oklahoma, because they may have tornadoes. We cannot have units there. I'm speaking of a very large system, a grid system. So this storage problem and the economic costs could be minimized if we could study meteorological data to determine where we can install wind power plants and have storage facilities nearby. Hopefully, there is a transmission system in that proximity which the meteorological data could justify as an appropriate location.

COMMENT: I would like to add one comment to what Mr. Stoddard said. I think perhaps energy storage was discussed in the wrong context at this meeting. I think the question of energy storage has to be raised, and should be raised, but until you can define fairly clearly what the energy storage requirements are and whether they exist at all, it's very difficult to discuss methods for providing storage intelligently.

REPORT OF THE COMMITTEE* ON

APPLICATIONS

A three pronged attack should be made to convince the people of the United States, applicable windpower manufacturing industry, and eventually the electric utility industry that wind power should be applied within the United States:

1. A rather short-term program that would provide financial support toward the demonstration of existing or improved windpower hardware for either heating or the provision of electricity at a number of demonstration residences within the next 2 years.

2. A relatively short-term program of about 3 years duration which would result in operating wind power plants of 25 to 100 kilowatts capacity by 1976.

3. A more deliberate 5- to 6-year technology improvement program which would culminate in the selection, construction, and operation of a number of wind power systems, totally self-contained with storage subsystems, of the 500- to 25 000-kilowatt size.

The suggested locations for the operating systems are

1. At institutions of higher learning which show a genuine interest in using the product and in using the installations as instructional, research, and public service facilities.

2. At one or more National Laboratories who want windpower systems and are willing to operate them as research and public demonstration facilities and who want to use their product.

3. At one or more remote U.S. Air Force Bases and at a number of other U.S. military bases where the wind resource is good and where fuel logistics are burdensome. Cooperation with the DOD should be investigated here.

4. At a very large number of new construction private homes.

5. At one or more New Town or institutional sites in conjunction with the MIUS program administered by HUD.

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*W. Heronemus, chairman; E. Barnhart; H. Clews; W. Hausz; W. Hughes; M. Jacobs; B. Jessop; R. Madey; J. Mockovciak; R. Powe; F. Rom; M. Sherman; and J. VanSant.

The geographical location for any one of the above should be such that the windpower resource is at least modest, and preferably large. Operating plant in regions of good winds near large population centers would be of greater value than remote plant. The New York City - Long Island, the Boston, and the Cape Cod regions are suggested as starters. Buffalo and Rochester, N.Y., and Cleveland, Ohio, are other suggestions.

We wondered if somehow a significant wind-power demonstration plant could be added to any 1976 BiCentennial parks or cities that might yet be considered.

A coordinated effort should be made to obtain the cooperation of the rural electric cooperatives and other state or regional associations of publicly owned utilities in the advancement of wind-power systems.

We agreed that in the next year and perhaps during the next 2 years, the major introduction of windpower systems to the U.S. public as reliable, operating alternatives would be done by individuals or very small companies like Henry Clew's "Solarwind" and Hans Meyer's efforts. Those efforts warrant support.

The impact of large numbers of single-dwelling units, perhaps a 25-kilowatt generator on a 40-foot pole with a 0.20 plant factor and a 300-kilowatt hour lead-acid storage battery, in any one market, operating successfully and economically for their owners, might be the best impetus toward adoption of wind power by a utility.

The federal government should be asked to consider direct grants to utilities to encourage their early adoption of significant windpower plant, following the pattern used by the government to encourage construction of nuclear plants.

It was asked that NSF/NASA sponsor the publication of a monthly newsletter to be mailed to anyone interested in windpower, this to be above and beyond any quarterly R&D project reporting system. Many younger people are seriously interested in this energy alternative, and they would like to be kept informed. "Communitas" of Washington, D.C., has offered to start such a newsletter based on the attendee list of this workshop. It was suggested that the newsletter be called "The Zephyr".

It was suggested that other deliberate continuing action be taken to encourage the interest of younger people in this program. Perhaps here we have something started which is "technology patterned for humane living". The country must convince many young people that technology can not only create problems, it can also be used to get us back on the track of a more ecologically sound way of life. How many excellent brains would again be turned toward hard science and engineering if the chance of making a contribution toward windpower systems and other pollution-free energy systems were the goal of that kind of education? Perhaps here we have a good opportunity to put at least some of the old and the new back into genuine harmony with each other.

As many people as possible should be shown that windpower can contribute. As many enterprises as possible must be excited into producing windpower hardware. Then, through large-scale defection from the individual residence utility customer and through an indoctrinated or propagandized portion of utility management the program must bore in. And if that by itself doesn't bring us ever-increasing amounts of wind-generated electricity, then direct grants should be attempted. In those areas where the federal government is already in the role of electricity producer and/or marketing agent, the job of conviction and conversion may be easier. In the East, particularly, where those roles are predominantly private-enterprise roles, the job will be tougher.

The debate about visual pollution associated with large wind plants should be started at once. It should be a moderated debate, kept both lively and honest An educated public, if given full particulars, will and should settle this. We must learn to face issues like this democratically.

DISCUSSION

Q: How about the identification of agencies which would come under regulation and control of wind generated power?

A: We did not talk about that last night. This is certainly something that has to be looked at as part of any significant deliberate program. The political institutional problems associated with ever getting something off the ground are just as important and perhaps more important than the technology. Yes?

COMMENT: I went to the Utility Commission in Oregon to find out their views or opinions on wind generating plants. First of all, they have no objection, provided it does not have any adverse effect on the community in which these wind generating plants would be located.

I asked if they would object to my getting into the business of producing electric power. "That's your prerogative", they said. That's the Utility Commissioner's answer in the state of Oregon. This will probably be the comment in many of the other 49 states.

COMMENT: I have an idea we would find 50 different approaches to this, and it's very important that we find out what they are.

PANEL DISCUSSION

Moderator:

Dr. Frederick H. Morse
National Science Foundation

Members:

Mr. Everett Lutzy
Manager, Town of Hull Municipal Light Plant

Dr. Robert L. Loftness
Manager, Washington Office
Electric Power Research Institute

Mr. Lawrence M. Robertson
The Western Electric Industry

Mr. James Wharton
Tillamook P. U. D.

Mr. Charles W. Lines
Assistant to the Chief
Division of Power Surveys and Analyses
Bureau of Power
Federal Power Commission

Mr. Brian R. Jessop
Rural Electrification Administration
U. S. Department of Agriculture

Mr. Lee L. Douglas
Boeing Vertol Company

Mr. John Mockovciak, Jr.
Manager, Energy Systems
Grumman Aerospace Corporation

Moderator, Dr. Morse:

One of the elements of any program which is introducing a new energy source, or perhaps not a new, but in the picture today is relatively new, it is quite important to get the point of view of other government agencies, of utilities, of the user, and of the industry or industries that might be involved in manufacturing the system.

So we have asked several people from other government agencies, from some utilities, and from industry if they would briefly say what the present or future role of their agency, company, or utility might be in a wind energy program and what the key problem or problems from their point of view might be. Then, as a group we will ask them what they feel the Federal government role should be in a national wind energy program.

Later we have scheduled a discussion of the NSF wind energy program and the NASA involvement in that program. Although this might be a minor handicap for our present discussion, let us remember that the objective is to develop wind energy systems which are reliable and economic and to prove the concept of large-scale wind energy extraction.

Mr. Lutzy:

In our nation, it is important how a company stays competitive in serving the public. Basically, our plan is to provide electric rates that are at least equal to, if not lower than, the rates of our competition. Secondly, the reliability of our service must be as great as, if not greater than, our competitors. And the service we offer must be equal to or more advanced than our competitors.

Now, since we are a municipal light plant, we are part of a town government. Therefore, we feel that the life of the utility depends on the life and the success of the economic conditions of the community we serve. Since the public owns us, we answer to it.

We meet our annual costs from revenue. We have a substantial investment in any generation and transmission of a distribution facility. Since we generally have to get bonds issued, this requires that we go before the public and get the vote of the people to approve any project we have. We must, therefore, show that our suggested project is good for the community, particularly since in Hull we have one of the highest tax rates in the nation. So naturally we don't propose anything that is not economically sound.

We are always watching technological developments for ways to improve the efficiency of operation of our electric utility. An example is automatic load control where you can see in the system what's exceptionally out of line on an on-line, real time basis. This automatic load control can improve the efficiency of operation, and it is variable, based on the way the customer uses it. We are considering telling the customer that if we use load control it will benefit him as well as us. Since a load control of his different appliances reduces our power costs, that part of the saving goes to him.

The highest peak demand in our electric system is at a time when the wind blows the hardest and that's generally when the temperature is the lowest. Therefore, the chill factor is such that tremendous heat loss occurs at the time the wind is blowing the strongest. So, the question is - is there any way to economically convert this wind power to a meaningful use? For us in Hull, its major use would be for heating in the winter.

If the total use was 20 000 kilowatt-hours a year, practically 60 to 70 percent or more would be used for winter heating, and this would result in saving fossil fuel energy. Also, when the wind blows, you use that energy and you don't do any polluting.

Dr. Loftness:

The Electric Power Research Institute (EPRI) has inherited the ongoing R and D activities of both the Electric Research Council and the Edison Electric Institute. Dr. Starr and members of the technical committees have reviewed those research and development programs still under negotiation at the time of the transfer and most of them have been approved.

We are now in the process of looking at new activities, including new energy sources. The role of EPRI will be to provide the utilities with options for the future and to fund research and development that is not being funded elsewhere to the extent our revenues from the utilities permit.

As far as I know, in reading the documents of EPRI and its predecessor organizations, I have not seen much reference to wind energy. This does not mean that the Institute will not be interested in wind energy. In fact, a symposium or workshop such as this is extremely valuable in pointing out the technical as well as economic status of wind energy. As with other alternate energy sources, the problem wind energy will have in the future will be the question of competing energy systems.

As you all are aware, the problem the country faces is a growing shortage of petroleum. In terms of national policy, it is possible that the Federal government, if it so desires, could require that wind energy machines be installed, even if the cost is higher, in order to reduce the importation of oil. The government could also direct that we gasify or liquify coal to meet our oil and gas needs or that we adopt other options, for example, the construction of large solar stations.

Decisions on these options by the government will require a factual base of information. On its part, EPRI would also like to have as much data as possible on the technical merits, the history, and the economics of alternate energy sources as well as information on new programs and proposed ideas. I am not saying that EPRI will fund every new idea, but we will certainly include them in the broad assessment we will have to make in judging which technical activities the Institute will fund.

Mr. Robertson:

I am here in a dual role: One as retired Vice President of Engineering of the Public Service Company of Colorado which is a utility which serves much of the State of Colorado and have a load of about two million kilowatts; the other role as the representative of the Western Energy Supply and Transmission Associates (WEST Associates) which is an association of about 23 organizations and utilities (public, private, and municipal) in the western one-third of the U.S.A. and Canada with a load of about 25 000 kilowatts. These utilities are all interconnected into a large network covering this area. Since this is a large area, there is quite a diversity in atmospheric conditions and wind velocities in different locations so that there would probably never be total calm nor severe storm conditions over the entire area at any one time. Therefore, I would assume that the total generation of power by wind, could be somewhat of an average if the units were located at suitable places over the area.

It appears that the wind units would not be large in relation to the capacity of the system and with the wide diversity possible, that the units could generate and feed power into the system in an amount and at such times as wind would be available. This should not upset the system and should not require any special system load control, dispatching, or scheduling.

With this sort of operation, it would not be necessary to provide energy storage equipment which some presentations at this workshop indicate would be quite costly and might even be hazardous and high maintenance. Thus, the kwh fed into the system could be metered and the value might be the incremental fuel cost at the location. This would dispense with involved and expensive metering and controls and this could be the best procedure at first. There seems to be some foregone conclusions that storage was needed but it would appear that this would not be necessary nor economical.

The fact that the units are relatively small compared to the load of the system means that they could be connected into the low voltage distribution systems at small cost and avoid requirement of expensive transmission and substation installations. The distribution lines cover most of the rural, suburban, and urban areas and little or no investment in such facilities would be required.

The utilities are interested in the wind energy conversion and would cooperate in obtaining data and in studying the proposals that might be made for installations and to assist in the plans and developments.

The utilities are interested in conserving energy and resources and in the public welfare and providing energy at the lowest cost and maximum reliability.

The units should be dispersed to get diversity of wind conditions, appearance, environmental satisfaction, security of service and equipment from storms and vandalism. Towers over 100 feet tall might produce severe objections.

Cost figures over the units which were presented at the workshop may be in line, and it would be necessary to determine the wind data, environmental data, costs of installation, fixed charges, operation and maintenance costs, and data, and revenue to be expected to establish the feasibility. It appears, off hand, that the idea might be feasible and economic in certain locations and under certain conditions.

The utilities are regulated by the Federal Power Commission and by State Utilities Commissions and whatever is done would have to be worked out with these bodies.

Mr. Wharton:

Since our utility in Tillamook, Oregon, is publicly owned, I was elected by our consumers; thus, it follows that I have to use economics as a guideline. In Tillamook, we are interested in windpower, because of our windy coast features and the Columbia Gorge wind exchange.

I would like to suggest some ideas that I feel would be of use to the utilities in the near future concerning windpower. In the Northwest only, where our power is hydrogenerated and it costs 3 to 3½ wholesale mil rate to our consumers, I think the 1 000 kilowatt size, or clustered even to produce 1 megawatt, could be feasibly run into the grid. I believe 5 or 6 mil wholesale rates should be the financial guideline. Now, if the Northwest is going to use wind machinery, you're going to have to realize that at present-day you're going to have a 5 or 6 mil economic guideline, unfortunately. And, at a later date, possibly when they run the nuclear plants that are now in construction into the grid at Bonneville, you then will be probably be talking about 8 mils. Now, please understand that these are just my opinions.

I would like to see a workable unit constructed and in use so that the utilities could look at the costs and esthetic ecology. I would ask you to consider a low profile. I realize this is not popular either, but you are not going to get the ecology movement to hold still for a gang of windmills hanging from a balloon or up on a wire. Anything that sticks up and attracts attention, is going to be attacked by the ecology people. I think 30 meters should be your extreme height. Now, this is going to put you in a pigeon hole again. It may be that I am wrong; this could easily be. But I think esthetics and public relations with ecologists will demand this, not only in the Northwest, but probably nationwide. Since the Northwest is not wind machine oriented, we must do a public relations job. The wind machine will definitely be in a fish bowl, so it should be engineered with an ecology and an economic basis in mind. The energy squeeze is on us, and utilities will want to make commitment decisions very soon. Therefore, I would urge you to use some haste on a prototype.

I would like to suggest the diversity of location concept, so that a wind machine would be run at varying times. I believe the Northwest would not need any storage facilities, because of the inter-tieline to Southern California, which we can use as an energy reservoir.

It will be extremely hard to sell the Northwest utilities on an experimental involvement basis. They are not used to this. They are used to an industry coming to them with a working model with the cost available and an environmental impact study already made.

Mr. Lines:

I believe the matter of policy, with regard to not only Federal agencies but the utility industry as a whole, has been mentioned. The Federal Power Commission, as a regulatory agency, establishes its policy, in general, by means of hearings, rule-making procedures, and the like. Therefore, nothing I can say, as a staff member, can predetermine any policy that the Commission, through its actions, might establish.

It may be of interest to review some of the responsibilities of the Federal Power Commission. In the area of licensing generating facilities and attendant bulk-power transmission systems, it is the licensing authority for non-Federal hydroelectric projects on navigable streams or on streams that affect interstate commerce. It has no licensing authority over thermal plants or any other kind of plants. It has no siting responsibilities or authority, other than those directly associated with the hydroelectric plants previously mentioned. For me to guess how a type of generation that has already been used in the industry would be considered in the future as to Commission policy would not be warranted. I do re-emphasize that a wind-electric generator has already operated in synchronism with the interconnected network of the utility industry.

The Federal Power Commission's responsibilities, with regard to the bulk-power systems of the United States, embraces, in the area of rates, the approval of wholesale rates. These are the rates between contracting utilities engaged in interstate commerce and not rates applicable to utility retail consumers. The quantity of energy subject to Federal Power Commission rate jurisdiction is relatively small when compared with the energy subject to retail rate approvals. The states generally, through state commissions or other agencies, exercise retail rate-making authority as it affects the ultimate consumer.

In other activities, as detailed in the Federal Power Act, the Commission collects data from all segments of the industry and disseminates these data in many forms for public use. Many of these data serve to keep the Commission staff current on trends and costs that affect the consumer. The cost of delivered electric energy as affected by any means, including the actions of the Federal Power Commission, is of interest to the Commission and its staff. The electric utility industry in the United States is the most capital intensive industry. Its capital requirements are tremendous and constitute quite a problem. In advocating the extensive use of wind powered generation, this capital intensiveness must be kept in mind. Wind power offers a costless source of fuel, but from what I have heard here, its use requires a very costly capital investment, firm capacity-wise, for an already highly capital intensive structure. It is a combination of these fuel and capacity costs that will have to be sold to the industry. I would not take exception to the range of costs that the preceding gentleman has mentioned, but wind powered generation does not appear to be currently competitive. One must also consider logistically the magnitude of the industry and the size of generating units employed in relation to the size and cost of the wind powered units discussed here for integration into the industry.

Mr. Jessop:

I am with the Power Plants Branch of the Rural Electrification Administration. We are probably responsible for putting more windmills out of action than any other agency. Economics is the name of the game from where I sit, I am not a policymaker; I deal with power plants and make recommendations on their cost of installation and their cost of operation. Sometimes I overestimate, and sometimes I underestimate. Nine times out of ten we've got enough funds to build the things, but that one time out of ten we run short of money. So costs are pretty important to us. I want to make clear that REA-financed powerplants are still only about 1½ percent of the total installed U.S. capacity. Even to our borrowers, we are in a minority. I should explain that our borrowers are mostly rural electrification cooperatives who have taken on utility responsibility in sparsely settled parts of the country. These cooperatives have brought up the number of connected households from 10 percent of the total in rural areas, in its inception in 1935, to about 98 percent recently.

So there is very little left that hasn't been covered. We have spread the tentacles of central station power service throughout the highways and byways of America until we have pretty well completed the job. But we are still working in a very, very remote areas. We are presently connecting plants in Alaskan villages and small settlements in the United States which are still without central power service.

As a consequence, the spread in the cost of power to these facilities is quite great. We have many borrowers who are able to generate power at around something like 1 cent, not 1 mil. And then we go up, in the remote Alaskan villages, to power costs which are more like 8 cents, 5 to 8 cents. But, if you are looking toward large applications, then I have here the Thirty-Second Annual Report of Energy Purchased by REA Borrowers. The costs have drifted down from about an average of 1.1 cent, when these figures were first compiled in 1940, to about 0.65 of a cent in 1965. After a flattening out process, they have again turned up; they are now going up quite rapidly.

But, so the past is prologue, and it isn't necessarily a good indication of what the future will be. Costwise our plants are going to cost more because of the environmental features. Large central station power generators, which we have built at a cost of about $120 to $170 per kilowatt, depending on the type of fuel we burn, are the cheapest because there are fewer environmental considerations and less fuel processing.

Coal-fired plants are more expensive; they range up to about $200 a kilowatt if we're in lignite fields. Possibly because of the things which must be added due to environmental considerations, we might have to go up to $400 per kilowatt for these central power stations. Costs for plants in remote areas, for example, Alaskan villages, have ranged from about $225 to $300 per kilowatt. These plants are small diesel powered ones.

All of these plants have one common characteristic: they can come on-line when the demand is there. They do have surplus capacity. In the case of the Alaskan plants, if one unit fails, or is taken out for maintenance, there is another unit standing by.

So these are reliable peak-supplying systems. I might make a comment on storage. Time is of the essence, and if you are dealing with a system with no storage, then you've got to compete against incremental fuel costs as far as the marketplace is concerned; this can be very, very low, even as low as 2 mils. But, again, fuel costs are going up, so here again you're aiming at a moving target. So you've got the choice, possibly, between storage competing with 2 to 4 mil power, without storage competing with 2 to 4 mil fuel costs, or with storage competing with 2 to 4 cent power costs. This is on peak power.

It seems to me, from what I've heard as an individual, that heat has the best application, because thermal transience is the longest. Not maybe as long as the transience you get with wind velocity, but they may be catching up on the deal, and thermal storage is usable feasible. Rocks are cheap, water is cheap. Put together a pool in the basement with rocks and water in it, and you've got a real good thermal tank.

Mr. Douglas:

The Boeing diversification program includes consideration of various forms of energy. One source of energy that we have worked at in some depth is that available from municipal, commercial, and industrial waste. As a systems problem, its economics depends on a balance of refuse collection, processing, and marketing of the products. Similarly, wind energy is a systems problem involving technologies, siting, and customers.

We have heard that rotor technology, suitable for wind energy plants, is available today. The real question is whether we can produce electricity at a price of 3½ to 7½ mils per kilowatt with the technology that is available and for the conditions prescribed by the power companies. If not electricity, can we pump water, run mills, or convert wind energy into useful work competitively in any market for energy?

I believe that our demonstration programs should be aimed at the systems problem rather than proof of concept of a component in isolation from its matching elements.

Mr. Mockovciak:

Our activities in the Grumman Aerospace Corporation's Energy Systems Group are twofold: one, energy conservation, and two, solar energy applications (which include the use of wind energy).

As regards our potential role in this area, we see ourselves as possible manufacturers of wind machines. From our standpoint, therefore, the existence of a market for wind energy machines is a major concern. We think that it exists or could be created, but advocates of wind energy must go out and "beat-the-bushes" to find people who really want to use it. A user motivation, I think, is a key to future wind energy usage.

For example, one of the suggestions that was made in a committee meeting last night is that perhaps there are many universities that would like to use wind energy, both as an actual energy plant supplying electrical power to its facilities and as a relevant engineering project involving both students and faculty in its design, construction, and operation. This example is illustrative of who could be real users of wind power. To reiterate, I believe that advocates of wind energy must identify the people who <u>want</u> to use it.

There are two ends to the wind generator spectrum: the small local wind generator application and the larger, utility-type wind generating machine. I personally feel that the utilities (since they are generally conservative) are going to take a "wait and see" attitude. Therefore, I believe that the place to begin is in the smaller, localized wind generator applications. When the utilities begin to see that wind machines do, in fact, provide electrical power, that people are satisfied with their performance, and that a base of operating experience is being developed across a reasonable spectrum of wind generator sizes, then I think the utilities will sit up and take notice.

Most important, in my view, are (1) acquiring operating experience and (2) establishing realistic costs. These two factors, if anything, are going to convince the utilities that wind energy can be a useful electrical power source.

One of the interesting aspects of the wind energy business is that there <u>is</u> an existing and adequate technology base. By that I mean that there is an adequate base to begin to engineer wind machines for power production. It disturbs me, however, that many advocates of wind generating machines call for more research and development. I would almost call this an "R & D syndrome." I frankly think there's an overemphasis on the amount of research and development that has to be done, and too little emphasis on finding ways to make it happen. I personally feel that we have an adequate technical base and that we should start thinking about building these machines and looking for people who want to use this energy.

Obviously, the people who may be interested in using wind energy are also going to be concerned with its cost. In this regard, I think that the government could play a key role. In the near term the government could offer direct subsidies in order to get the machines out where people could see them operating and performing useful functions. In other words, what I am suggesting is that the public (through the Federal government) could make wind energy "happen." If the public wants to use wind energy, the government can make it happen; the same way that we've made a tremendous highway system happen in this country, and the same way that we've provided direct subsidies for public housing where we want housing to happen! The government mechanisms are there, if the public motivation is also.

Moderator, Dr. Morse:

We will open the floor to questions. We are interested, from the point of view of industry, other government agencies, and utilities, in what role the Federal government might play in this wind energy program. What would it like to see done so that it could make the kind of decisions that it will have to make.

Are there any questions to the panelists?

Mr. Cohen:

It occurs to me that perhaps it might be worth looking into the possibility of coupling the high quality mechanical energy generated by windmills to heat pumps and storing that heat rather than degrading the energy and the heat to begin with.

Dr. Morse:

It's a thought.

Mr. Lutzy:

It's the basic role I am attempting to do. In other words, don't go through intermediate investment steps for high cost investments and gadgetry. Get that mechanical heat directly to the heat pump to improve its efficiency.

Dr. Morse:

By the way, NOAA is an agency that certainly has a role to play in that new wind energy program, and I didn't mean to exclude you.

A Voice:

I would like to ask what the proper mechanism of our existing governmental structure is for the government to decide to make it happen. They decided to make nuclear power happen, and it happened. We all have our own opinions on the way it happened, what it cost us to have it happen, but where do we start? What can we as private citizens do to make it happen?

Mr. Lines:

If I may, I will respond in general with more of a personal observation than a recount of any staff position of a Federal agency. I call to your attention two related items that might be of interest. One is in the June 1973 issue of Spectrum, the I.E.E.E. publication. It lists two pages of Federal agencies involved in energy policy and problems to some extent. The other item includes the President's energy messages of about 18 months ago and just recently. Over the past weekend, the President announced a proposed reorganization which included the establishment of a Cabinet-level agency in which energy and resources considerations would be centered and which would affect to some extent, among others, the Department of the Interior organization. There were other proposed changes. This proposal will be sent to Congress for its approval or action. The atomic energy program was established in a similar manner by the Act which established the AEC. The Joint Atomic Energy Committee is the congressional body that is actively interested in that program.

To answer your question directly, we have an outlet, through our congressional representation, to establish and make known our personal viewpoints and what we as individuals think of both the energy policy of this country and its many, many ramifications.

Dr. Savino:

As I listen, I get the feeling that among certain government agencies, such as the Rural Electrification, the FPC, and the power utilities, the attitude appears to be one of business as usual. We talk about things having to be cost effective as though we can continue supplying the public with all the power it can consume, as though we had plenty of it. Everyone here is aware of the fact that we are on more or less a collision course over the next 20 or 30 years. And there seems to be a reluctance to take the action that is necessary before we get into a real bind. I believe it was Dr. Hutter last evening who mentioned that we as individuals accept many dislocations in our lives. We have automobile accidents that cause a dislocation, or we lose our job. There are a number of such things that happen, yet when we push the light switch or decide to drive somewhere we want power available to us at that instant. We don't want any dislocations in our energy supply. Isn't it time the public utilities, as well as the agencies, tell it to the public like it is? We are going to have to start paying higher prices. We must stop chasing the demand curve. Shouldn't your companies and agencies also start getting involved in supporting alternative systems? Many of us believe we can no longer look to nuclear or fossil or any one or two systems to provide all the energy. There is going to have to be a mix, and we cannot have this mix unless we have the involvement of the utilities, the agencies, as well as the people who are proponents of this system. We, the proponents of wind power, can never create the environment necessary to move forward until you people who have the influence get involved instead of sitting back and waiting for someone to come forward and say here's a package that works -- would you like to use it?

Mr. Loftness:

As a matter of fact, that is precisely the reason EPRI was established by the utilities. They recognized that business as usual - the way it had been going on for many, many years - was no longer the case.

Obviously, EPRI will have activities that relate to conventional technologies - improvements in transmission and distribution, in nuclear power generation and related safety questions, and in fossil fuel generation - all to improve the ability to generate power with the equipment we now have. At the same time, EPRI will have a group on advanced technologies that will be concerned with evaluations, by the in-house staff, of the status of solar, geothermal, wind, ocean thermal gradient, and other alternate energy sources. Hopefully, there will be major inputs of information from individuals who are experts and who have been working in each field for a long time. These inputs will be judged, in terms of future research and development support, by the contribution each alternative might make to the total energy mix.

There is nobody I know in the utilities who feels it is possible to go on forever using oil or coal as they have in the past. There is a lot of current interest in fission power and fusion power, but there is also interest in looking for alternate sources of oil - from the liquefaction of coal, for instance - and in alternate sources of gas through coal gasification. These coal conversion processes are now more expensive than natural oil and gas, but, nevertheless, they are processes the utilities feel must be developed if they are going to continue to generate power to meet the needs of the country.

I think the utilities have given evidence of their interest in pursuing alternate energy technologies. I don't think people interested in, say, wind energy are any longer voices in the wilderness.

As I mentioned, the Institute is very much interested in having all the factual information it can possibly obtain. We can't possibly develop it all ourselves. We should proceed from the basis of information that already exists, and I would encourage all of you to submit the information you have to the Institute.

EPRI will not be alone in developing new technologies. For example, both NASA and the National Science Foundation have activities in solar energy and we will be working with them in this area. In any particular technology, we will be judging what needs to be done based on an assessment of the relative contribution of that technology. Where wind energy would come out in such an assessment, I don't know.

The assessment process would involve all the individuals who are interested in making a contribution to the argument on what should be done or what should not be done. Out of this dialogue, I believe there will be a decision among interested organizations, including the Federal government, that certain technologies should be funded as a national effort - as is the case now for solar energy. As you know, such an assessment has resulted in a tripling of the solar energy budget of the National Science Foundation in the past year.

In summary, I don't think there is a lack of recognition for the importance of new energy sources either in the government or in industry.

Mr. Lutzy:

It appears that we have come from a nation of abundance to a nation of scarcity, and that involved in this is basically the national security and the question of the balance of payments problems in regard to the value of the dollar on the world market, in regards to our being able to compete in the world that exists and to maintain our standard of living. I would think that, based on our feelings in the past, we did not want to be substantially committed to surviving based on foreign energy supply, as an example; this would demand a commitment in the very near future by the national government to solve these problems and to do so by the capabilities that exist in this country. The other thought is that, in regards to capital investment, we all are schooled that we must be economically competitive and must maximize the use of an investment, good or not. In our personal lives the percent use of any investment that we put our money in doesn't have to be justified. As an example, don't buy a generator to generate a little power, but buy a boat for $1400 or a snowmobile and put them in the corner. What's the percent use of a snowmobile, plus the consumption of energy in this? There is no comparison between this, so there is a question that maybe there ought to be a play opera between personal investment and business investment whereby some of this personal investment is put to a more meaningful use.

Mr. Mockovciak:

I'd like to address myself to EPRI's future role, but I must qualify this as a personal observation. Coming from an industrial organization and being heavily involved in past research and development activities, I have observed that the basic function of (what are called) new businesses, advanced programs, or research and development organizations is to promulgate the current business line. In other words, the "new business" aspect is a misnomer. It's called new business, but it really means keep the old business going.

In this regard, I can't help but observe, when exposed to the kinds of things that EPRI is proposing to do, that they are planning to do just that - keep the old business going. EPRI appears to be largely interested in improving the operations and performance of existing electrical power systems or those that already have extensive research and development bases. Thus, I can't help but feel that there really is no motivation there to make anything new happen.

I would, therefore, suggest that EPRI strongly consider sponsoring the engineering design and development of actual wind generating machines for a number of regional locations. Since there is no new technology needed, the machines can readily be engineered. There is nothing to prove by research and development studies, but much to prove by operating the machines: namely, prove that wind generators can supply electricity reliably, can be operated for long durations, and that they are or are not economically practical.

I am very much concerned, as I mentioned earlier, about this "R & D syndrome." We always seem to approach a problem saying that we need to institute a research and development program. I don't think that's the case with regard to wind energy. I think there is an adequate technology base that can be used to build wind power machines. Once we get some operating experience under our belt across a spectrum of sizes, that experience should point the way for new research and development directions. Furthermore, if the initial wind generating plants indicate that they can be made economically competitive, the research and development would likely become more economic as opposed to technically oriented.

In the nuclear field the utilities have worked out the economics of the atomic business. Right now it's costing about $550 per installed kilowatt. This does not include the decommissioning, and it has recently come out in hearings that the decommissioning of one of these plants, so the land could be reused, would cost much more than it did to build it. In addition to that, you have each of these thousand megawatt plants producing over a million pounds of radioactive waste that has to be taken care of. I think all of these costs have to be added in when we start to compare windpower with the other forms of power.

Mr. Schwartz:

A very important point was made; that is, it is difficult to see how all this can be made to work without the government interacting with the utilities. Dr. Starr testified recently before Congress that he didn't feel the Federal government had a role in deciding what kind of energy research should be done. That's best left to the utilities and suppliers. I wonder if there is; does Mr. Loftness have a comment on that?

Mr. Loftness:

I don't recall that particular statement. Was he stating that the government should not decide what the utilities should do, or what EPRI should do, or what the nation should do?

Mr. Schwartz:

His comment was he didn't feel the Federal government should be involved in energy research related to utilities and their suppliers; they can decide better what they could carry for policy.

Dr. Morse:

I think that in fact the increased funding in solar energy would counter that statement. I think there are Federal funds going into the development of new energy sources. In MHD there are significant funds, and in geothermal the same. I think there is that indication. I think that Joe Savino's comment as to how to get the utilities to take an active role, or to get the user to take a more active role, is a relevant point.

Mr. Schwartz:

The words "significant funds" have been used several times in connection with the forthcoming budgets in certain areas. I hope we will know about that this afternoon. But I wish to ask Mr. Loftness, or anybody else who has data on the subject, if there is anyone who can characterize the funding that is going into all forms of energy sources in terms of the annual capital outlay of the utilities?

Mr. Loftness:

The figure that Dr. Stever used in testimony before Congress was a Federal budget for next year of $772 million for energy research and development: about 65 percent was for nuclear research and development and the rest was spread across all other technologies. He used a figure of $1.2 billion being spent on energy research and development in the private sector - by industry, by the utilities, and by other organizations in non-Federal, funded activities.

Mr. Schwartz:

Is that engineering of new power plants using existing concepts?

Mr. Loftness:

He didn't break this down, so I don't know how he arrived at the figure of $1.2 billion for the non-government activities. EPRI itself will have a budget next year, supported by both the private and the public utilities, of a bit over $100 million for research and development. This compares to the $772 million for government-supported research and development work. I really can't imagine that Doctor Starr said that the government should not decide what research and development is important. I am sure, however, he would say that EPRI is not looking to the government for all of its direction on what should be done, and I don't think it will. I would expect, however, that many of the programs that EPRI will have will be cooperative programs with the U.S. Government. We already have a cooperative program in coal gasification, for example, and I would guess that programs in geothermal development, if we have them, will be in cooperation with government programs. There will be a lot of joint planning of activities, even if there aren't joint programs in the sense of being jointly funded. We are talking to the AEC about several joint programs; we feel the programs are important and they feel the programs are important. No one organization has either all the wisdom to decide what needs doing - or all the money to support every program.

Dr. Morse:

I think we could go on talking for quite a while on this topic, but we do have a session coming up in which the NSF and NASA programs will be discussed. Therefore, I think we will adjourn at this point.

NSF PRESENTATION

Frederick H. Morse*

National Science Foundation
Washington, D. C.

The following is a brief summary of the National Science Foundation's energy conversion program, which is one part of the NSF solar energy program. Also included is a comment on NASA's involvement in the wind energy program.

Perhaps the best way to begin is to look at NSF, then the RANN (Research Applied to National Needs) program, the solar energy program, and, finally, within the solar energy program, the wind energy conversion program. For the purposes of managing research programs addressed to national needs, the National Science Foundation has organized components of its coordinated and problem-focused research into the Directorate of Research Applications. A major activity in this Directorate are the RANN programs. The Director of the RANN programs is Dr. Eggers. The authority of the NSF to become involved in research that is directly related to the problems of society and the environment was enhanced by the provisions of ammendments to the NSF Act in 1968. The NSF is therefore directly engaged in research programs that are related to social and environmental problems as well as the potential impact of future technological development. Solar energy is just one example of the new technology in which NSF, through RANN, is deeply involved.

While the emphasis of the RANN programs is on problem orientation, NSF supports fundamental and applied research through the divisions of the NSF Research Directorate. In many cases, programs within the Research Directorate are related and complimentary to certain RANN programs. For example, within the Research Directorate there is a program of global atmospheric research; also, there is a wind engineering program which is concerned with the interaction of wind with structures.

Within RANN there are four divisions: Environmental Systems and Resources, Social Systems and Human Resources, Exploratory Research and Problem Assessment, and Advanced Technology Applications. The Advanced Technology Applications Division is concerned with new or improved technologies that can enhance economic productivity, exploit the potential contributions of advances in science and technology, or stimulate those applications that will contribute to the solution of

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some major national problem, such as the energy problem. The solar energy program is centered within the ATA Division. The NSF solar energy program was initiated in fiscal 71. In July 1971, the President, in a special energy message to Congress, called for programs to provide the nation with adequate sources of clean energy. Shortly after that message, the Office of Science and Technology, through the Federal Council of Science and Technology formed eleven panels, in the various energy areas, to establish Research and Development goals for those energy technologies. The National Science Foundation and NASA were asked to jointly organize a solar energy panel. This panel was established in January of 1972.

The Solar Energy Panel consisted of 40 individuals from universities, industry, and government, with backgrounds in electrical engineering, mechanical engineering, solid-state physics, chemistry, biology, and architecture. Also included were a sociologist, an environmentalist, and an economist. The panel assessed the potential of solar energy as a national energy resource. The scope of the Panel included direct solar energy applications as well as the indirect applications - wind and ocean thermal energy and renewable organic fuels. In December 1972 the report of the Solar Energy Panel was released. This report is available from the Solar Energy Panel, Department of Mechanical Engineering, University of Maryland, College Park, Md. 20904.

The panel's key recommendations are that the Federal Government take the lead in developing research and development program for the practical application of solar energy as an alternative energy supply to meet the heat and power needs of the United States and that this program be a simultaneous effort in three areas - economical systems for heating and cooling buildings, economical systems for reducing and converting organic materials into solid, liquid and gaseous fuels, and economical systems for generating electricity. The Solar Energy Panel identified seven areas, as most promising from technical, economic, and energy standpoints. These are the following:

(1) Heating and cooling of buildings
(2) Photovoltaic energy conversion
(3) Solar thermal energy conversion
(4) Wind energy conversion
(5) Ocean thermal energy conversion
(6) Photosynthetic production of organic matter
(7) Conversion of organic matter into fuels

Sometime after the panel's release of the report, the National Science Foundation presented a 5-year program to the government, and it was given the responsibility for the terrestrial solar energy program. The objective of this program is to develop, at the earliest feasible time, the many applications of solar energy as alternative energy sources. An interagency panel was recently convened to inform and coordinate the activities of other agencies such as NASA, NBS, NOAA, DOD, AEC, and others in terrestrial solar energy applications. This interagency panel presently meets on a monthly basis.

A brief comment on the funding. In fiscal 71, \$1.1 million was spent on terrestrial solar energy projects. In fiscal 72, that funding was \$1.6 million; in fiscal 73, it was \$3.8 million; and in fiscal 74, the estimated budget is \$12.2 million.

There are many ways of collecting and converting solar energy into electrical energy. Solar energy is collected naturally in the Earth's atmosphere, which gives rise to the wind. It also warms the surface of the ocean, thereby establishing the temperature gradients therein. And it is collected on the surface of the Earth, a fraction of which is captured by the photosynthesis process.

In addition, man can construct collectors, such as solar cells, to convert solar radiation directly into electrical energy, or concentrators to convert solar radiation into electrical energy by means of heat engines such as those operating on the Rankine cycle.

Let us now turn our attention to the wind energy conversion program. The objective of this program is to develop reliable and cost competitive wind energy conversion systems that are capable of rapid commercial expansion to produce significant quantities of energy on a national scale.

There are many technical challenges to face in meeting this objective, such as performance predictions, configuration tradeoffs, failure mode analysis, development of low-cost structures, etc. There are also many environmental, social, and economic programs involved in the large-scale extraction of energy from the wind; for example, the environmental impact at these systems on the marine or plains ecology, or the institutional constraints on these systems, and so on. Time does not permit a full discussion of these types of problems.

In fiscal 73, the NSF wind energy conversion program initiated three projects. One project was a grant to the NASA-Lewis Research Center to organize and conduct this workshop. The second project, at Montana State University, will identify the major technical problems of the tracked airfoil system that were previously described at this meeting. A grant to Oklahoma State University was also awarded for the development of a variable input-constant output generator and an electrolysis units in the 10-kilowatt size, suitable for integration in a wind conversion system. In fiscal 73 these three projects totaled about \$300,000. In fiscal 74, a funding level of the order of a million dollars is anticipated.

NSF will use the phase-project-planning approach. This approach consists of an orderly progression from Phase Zero, in which the conceptual design and performance requirements are specified, into Phase One, where the preliminary design is made and the critical subsystems are researched, designed, and tested, and finally into Phase Two, where the proof of concept experiments are conducted. In the NSF wind energy conversion program we expect to be through Phase Two within our 5-year program. The remaining phases, Phase Three (demonstration system design, construction, and testing) and Phase Four (commercial system design constructing and testing) are left to the user. In parallel with Phases One and Two, research on components and advanced concepts will be conducted on a continuing basis.

In carrying out its responsibility for the solar energy program, the National Science Foundation will involve universities, industries, and government agencies on the best-performer basis. As you know, NSF can and does award grants to universities. In addition, the NSF/RANN program can award contracts to profit-making industry. It is no longer necessary for industry to join with a university, as a subcontractor, in order to receive support; however, in many cases the resulting joint effort is stronger than either alone. In the wind energy program, as well as other areas of the solar energy program, NSF/RANN will continue to encourage and accept unsolicited proposals which represent the ideas generated by people in universities and industry. In addition, NSF/RANN forsees the release of program announcements and RFP's as the program develops. Unsolicited proposals should continue to be sent to NSF. NASA Lewis Research Center has reviewed all proposals in solar energy and will continue to do so.

In the area of wind energy conversion, the NASA Lewis Research Center has expressed a strong interest in the program and has been asked to prepare a plan indicating how they would support the wind energy conversion program. While the details haven't been finalized, it seems quite certain that the NASA Lewis Research Center will play a very major role in the implementation and execution of this national wind energy program. In the following presentation, NASA will describe some of the details of their proposed plan.

NASA PRESENTATION

Ronald L. Thomas

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

Good afternoon, ladies and gentlemen. I will briefly go through a program plan here that we've worked up. We've been taking a hard look at this area for the past year, and also other solar energy areas; and we have put together a preliminary program plan in wind energy which we have discussed with the NSF.

Obviously, as a result of our workshop, there are going to be a lot more inputs into this plan than you're going to see now. This plan, I want to stress, is tentative. But it will give you an idea of this five-year program. First I will briefly review the objectives, the approach and the planned accomplishments for this program.

The objective is to develop a wind energy system that supplies reliable energy at a cost that is competitive with other energy systems. This is a government-directed industry program with strong university support. We plan to set up a review board which would consist of utilities, manufacturers, consumers, and the appropriate municipal, state, and federal agencies. This board would be like an advisory board. It would meet and review the program from time to time, and offer valuable inputs as to the way we are proceeding and so forth, which areas should go forth faster, which slower, that type of thing.

We feel very strongly that there would be an effort, within our national laboratories, to provide the basis for program direction.

We would study, build, and test wind energy conversion systems and components without storage. We would also study, build, and test energy storage systems. And I will go into the reason here: We feel that we should get on quickly with the job of the wind energy conversion system, and not necessarily tie it directly in with the storage right at the beginning.

A very important facet is that we will conduct meteorological studies in cooperation with other agencies, particularly with NOAA, to estimate the wind energy potential and determine favorable regions and sites for wind power. Another important part of this overall program is to study and identify the suitable applications for a demonstration test -- just what is the overall potential and what are these applications? At the end of 5 years we hope to have identified cost-effective wind energy conversion systems, not necessarily with storage tied to them. And we would have these systems in operation and have some data to back this up. Not only will we have some of these prototype subsystems in operation, but we will have had bench tests and subsystem tests of the key components going on within industry and within universities or the laboratories.

Demonstration systems for selected applications and some of these, hopefully, with storage would be at the point where we would be ready to begin tests at the end of 5 years. It is unlikely that in 5 years, we would actually have systems complete with storage and for actual applications ready to go.

At the end of five years we hope to have determined the potential for wind energy in this country. We would also plan to have under development analytical techniques for selecting sites for wind conversion plants.

Next, I will discuss several action diagrams to point out the key phases of the overall program. The key phases are the wind energy conversion system, the meteorological studies, the energy storage system, and environmental impact studies.

In the overall program (fig. 1) you can see we would be carrying on a number of steps in parallel, starting in the first year. This would be the study, design, build and test of wind energy conversion systems, without storage. We gather and assess wind data to come up with the favorable site selections and what is the potential of wind energy. We would study, design and build and test energy storage systems. We would identify and study the suitable applications for wind energy, concentrating on the most favorable ones in the beginning and coming up with what are the practical applications for wind energy.

Then, we need to determine what the requirements are for major facilities. We are encouraged by what came out of the workshop here. It looks like a lot of the components and sub-systems can be adequately designed with simulations and modeling.

All the above phases are parallel and will focus on the design and demonstration for those favorably selected applications. We would then construct and test those demonstration systems. That completes the overall program.

Now in figure 2, looking at the wind energy conversion systems which are primarily the towers, the rotors and the electrical generation. Where should we begin, and how can we put a wind generator together that meets our requirements. First we started with systems design studies of wind conversion systems. We would concentrate on those without storage at this point, and these would be to identify the size of machines that makes sense, hopefully focusing these into applications.

We then select the ones with the most promise to actually have prototypes running within the 5 years. We may pick out one or more combinations for detail design of these prototypes. Once we have a detail design of these prototypes, we would then select the most promising one and proceed with construction of that prototype. We would also at that time begin bench testing and in-house testing of the components and subsystems.

Also in the systems designs we would come up with some advanced concepts. These would be split out and paralleled to start studying these advanced concepts, deciding which of these should be built and tested, primarily at the component level.

What we have is a program going down three paths leading toward the construction of prototypes as quickly as possible, probably building very heavily on the technology that was discussed by Dr. Hutter, and breaking off in parallel component tests and modeling of rotors and the key electrical conversion and also with advanced concepts.

We would test these prototypes within the 5 years, and all of this would be input, then, into the design of the demonstrations for selected applications.

In the area of the meteorological studies (fig. 3) we have mainly started out to assess what the existing wind data are. Obviously, we will need very close cooperation and coordination with an agency like NOAA. The purpose is to identify sites for these first prototypes and pick out the favorable sites. We must get the wind data we need to do the the detailed designs of the prototypes.

Also we want to determine the wind energy potential in the U. S. Using the existing data we would try to determine that potential. We would determine the favorable wind sites in the U. S. Also we would develop analytical techniques for wind prospecting so you don't have to smother the landscape with anomometers.

We would make additional measurements, wind measurements that are required in areas where there isn't sufficient data and feed this back to up-date the wind energy potential estimates.

In the area of energy storage (fig. 4) we would again look at the various types of energy storage systems that are available. We would do some design studies and select the systems that look the most promising for fabrication and evaluation. In parallel, there are going to be some advanced storage systems identified. We will do design studies on these systems also and build and test those advanced components. All of this, again, leads into the demonstration systems occurring after 5 years.

For the conversion systems in Fiscal 1974 we would immediately start with several systems design studies, followed by a detailed design of the prototypes that appear to be the most promising. Remember that we have a key point here where we bring in the advisory groups to help in the selection of this. We begin construction of that prototype at the beginning of Fiscal 1976, and should be able to have a prototype and start testing at the beginning of Fiscal 1977. We also build and test the prototype components and sub-systems as soon as we've identified the system that we have selected.

The meteorological studies are an on-going program. We envision these studies would assess and make use of existing wind data, set up instruments for making additional wind measurements as required, and develop analytical techniques for wind prospecting.

The key points are that by the middle of Fiscal 1975 we would have those prototype sites, and have made an up-dated determination of just what the wind potential is in the United States in these selected areas. By here we would identify these suitable sites for selected applications.

I haven't gone through all of the program here but very briefly have tried to give you what we see as the approach at this point to getting on with the job. The key thing is to do these things in parallel, carrying them out, and to constantly be evaluating the direction we are going in.

DISCUSSION

Q: When do you expect to be able to make announcements on this or a similar program being started?
Dr. Morse: I would say within the next several months.

Q: You announced the NSF funding program. How about the NASA?
Dr. Morse: The funding is for wind energy conversion. The projects or part of the program that NASA would conduct for NSF and the grants or contracts that it would issue and manage would be from those funds.

Mr. Thomas: And as I'm sure you are all aware, NSF is the lead agency. They have the solar energy program. What NASA is willing to contribute at this point is manpower and facilities. We have laboratories, experimental capability, and analysis and project management. That would be NASA's contribution.

Q: Out of this million dollars from NSF?
Mr. Thomas: Yes.

Q: What is left over?
Dr. Morse: It's all left over. They are not going to pay their salaries out of that. NASA Lewis is contributing the manpower, the facilities, and the experience to the program. The money that I mentioned that NSF has will be spent partially through NSF and partially through NASA Lewis. Again, this is a program with strong university and industry involvement. We expect the bulk of that money to be spent externally.

Q: Are there any sorting criteria that you can give us for which type of proposals go to which, or do all of the proposals go to NSF for this time period?
Dr. Morse: All RFP's and program announcements will state clearly on whether that should be directed to Lewis or to NSF. At the moment, unsolicited proposals should go to NSF. They will be reviewed in the usual way except that now Lewis will be included as a reviewer on all proposals. I might also mention that proprietary proposals will be handled accordingly.

Q: There seems to be an incompatibility -- maybe it's only by inference -- between system design and your technology in the position phase. You have a systems design that goes right on into the concept. You have a technology phase which says there are some technology gaps which have to be identified. Are you fellows getting together on this?

Dr. Morse: Yes, we are.

Q: That's one question. The second question is: Is your objective merely to demonstrate a large rotor that can effectively turn out so much power in some kind of wind, regardless of what you use it for? Or is it to integrate an objective as to how you will use this energy in a system?

Mr. Thomas: The objective is to discover how you use the energy and whether or not it can be practical and competitive.

I think the other point is, too -- I mean, you can sit back and show all these little magic blocks up there on the Vu-graph. The way those were arrived at is: What is a reasonable objective and goal to get accomplished by the end of 5 years?

We set down our plan, what we thought we could do. Then those blocks are really backed up by the actual tasks that have to be required in each one of those areas, in terms of manpower and dollar expenditures and what the hopeful output will be for each one of those blocks. It would be a number.

Now, I won't go into detail on those, because, if I put up the definition of those tasks, give you the outline of a work statement and told you what the manpower was and what the dollars were, there wouldn't be much sense in putting out a competitive RFP because all proposals would come with the same costs and the same amount of manpower.

Now, obviously, what's come out of this meeting, we are going to get criticisms, good and bad; depending on how much money NSF is going to divert to this NASA effort depends on how fast we go down this path. But we look on this as a joint venture with NASA and NSF, and to go down those parallel paths together in the best and the optimum way overall.

Q: Dr. Morse, does this mean that the proposals which have been submitted this year already on the subject are -- to use a word of Mr. Zeigler's -- inoperative?

Dr. Morse: No, that isn't so. We have ten unsolicited proposals, two of which have been reviewed. The other eight are in various stages of discussion and formalization. Some of these proposals may very well be supported, based on their own merits. It may be that some of these proposals fall very close to what we have in mind for an RFP, in which case we would not go ahead with that, and indicate to the principal investigator that, at the moment, we are going to hold off on that.

Q: Will the storage facilities or the mechanism for the program selected for storage involve a concept of shipping?
Mr. Thomas: Can you elaborate on that? I'm not sure I know what you mean.

Q: Does the use of wind energy involve shipping in any way?
Dr. Morse: You mean like producing hydrogen and shipping it in some form?

Q: No. For sail, the idea being if the storage mechanisms were practical enough -- is that ruled out?
Mr. Thomas: We haven't really considered that, although the FCST panel on transportation did recommend that the old sailing ships may hold a lot of application today and that work be done in that area.

Q: I noticed in your 5-year plan you didn't have any kind of estimates or projections on what kind of money would be allotted for wind research. Will you comment on that?
Dr. Morse: I really don't think it is appropriate to comment on that, since one never knows how those will turn out. We do have a 5-year program. We have worked out a budget for all those areas, and the only figure that is really a pretty real one is $12.2 million for next year.

Q: It appears that you really intend mostly study programs the first years, instead of hardware. Is that true?
Mr. Thomas: That's true, but those study programs are the first step in really defining and identifying which way to go on the hardware.

Dr. Morse: Although I might indicate the program at Oklahoma State is looking at two key components of the system, and that is a hardware type of a program, the bulk of it is systems studies.

Q: You mentioned earlier you have provisions or are you making plans for industry-university participation? Where in that program is the flexibility to do that sort of thing?
Mr. Thomas: It seems very clear to me, since I drew all the diagrams, but at the end of the first systems studies which will be in the first fiscal year, we plan to do several parallel studies in the same area. Each of these studies would probably have several different concepts. The point then is to pick out the system or systems that have the potential for practical completion within the 5 years. Those systems would be reviewed by the advisory board. The advisory board would be composed of representatives from the industries and universities that are working in this area and representatives from the utilities or other potential users.

Dr. Morse: I might also add that the problem of universities responding to RFP's, if they have a 2-week response time or a very short response time, is one that we have discussed and considered. We intend to maintain a strong university involvement as far along the program as it is appropriate to. So we're concerned with maintaining the involvement of the universities and industry. We would like to see a growing industrial involvement. We would like very much to have them pick up the ball and make something of it and the sooner the better.

Q: Is the planning information that you included here going to be included in the proceedings of the workshop?
Dr. Morse: I would think a summary of what we said will be.

COMMENT: May I point out that we received recently from NSF two RFP's, both two months after the deadline for response.

Dr. Morse: Right, that's the gentleman from Alaska.

COMMENT: Airmail takes one day.

Q: What do you see, if anything, as the place in this program for small-scale developments? In other words, on demonstrations and perhaps the type of thing I was talking about the other day--a demonstration of the home heating plant based on wind power.
Dr. Morse: I think it's in there, and I think that shows the power of these workshops. We have been focused pretty heavily on a way to make major impact using wind supplied energy in a major way. It's become apparent from this meeting and other discussions that perhaps one way to attack the problem is through the small size user located type of a system. We are going to give small users serious consideration in our planning, but you're right, it was not a major part of our thinking.

Mr. Thomas: In all fairness, it really wasn't left out completely. The original systems design studies have been encompassed in the range of 50 kilowatts on up. And maybe we have to go down a little further than 50 kilowatts, but that was the size that we were looking at.

There would be application studies in there. The whole point is to identify those applications that can do the job. If it turns out to be 50-kilowatt machines and you have to put up thousands and thousands of them to do the job, that would very much influence the program.

But at the same time you wouldn't go just that way. You'd be looking at the large ones, too.

Q: Do you expect there will be anything in your RFP's on this, or will this be handled on the basis of unsolicited proposal type of thing?
Mr. Thomas: My own feeling is that that would be part of the RFP route.

Dr. Morse: I would agree with that.

Q: Would you clarify one point on your charts -- the difference between energy systems, energy resources, and solar energy?
Dr. Morse: Solar energy is a resource, and you need systems to use it. NSF had a program while solar was in its infancy, in which we were looking at energy systems of the United States -- for example, a report by Dr. Szego's company, several volumes on energy systems.

We were looking at geothermal, at coal gasification, at a variety of other problems. Solar energy grew to the point where it has now been singled out as a separate program area. This doesn't mean that it's distinctly different from the resources systems.

Q: Is the $300,000 being granted to Montana State and Oklahoma State a total figure for the both?
Dr. Morse: No, for the three -- for NASA Lewis for this workshop, for Montana, and for Oklahoma State. I'm sorry, that comes to $200,000 not $300,000.

Q: Are these FY 1973 funds?
Dr. Morse: Yes.

Q: Is it illegal for a privately financed corporation to earn a profit on proposals that are submitted in response to RFP from NASA or NSF for this wind generator?
Dr. Morse: I'm not a lawyer. It's my understanding that that is legal.

COMMENT: In response to solicited proposals, I believe all the things that normally have been going on, such as the fee, are perfectly legal. It's only in response to an unsolicited proposal submitted that we must have some kind of a cost-sharing as there is no fee allowed.

Mr. Thomas: We are going down that route right now with some of our RFP's, and these are either going to be cost plus fixed fee or just a fixed price contract with a few in there. That's the way NASA does business. Now, on the unsolicited proposals, I'm not quite that sure, but even there there are some ramifications. I know that some contracts let for unsolicited proposals have included a fee.

Q: Will NASA or NSF be handling the RFP's?
Dr. Morse: We haven't decided, but, since NASA is going to implement this program, it seems reasonable that they will issue RFP's, evaluate them, award the contract, monitor it, and follow it up. That doesn't mean that NSF will not do the same. There is still a difference between the total NSF program and the total NASA program.

Figure 1

FIVE-YEAR WIND ENERGY PROGRAM

Overall Program

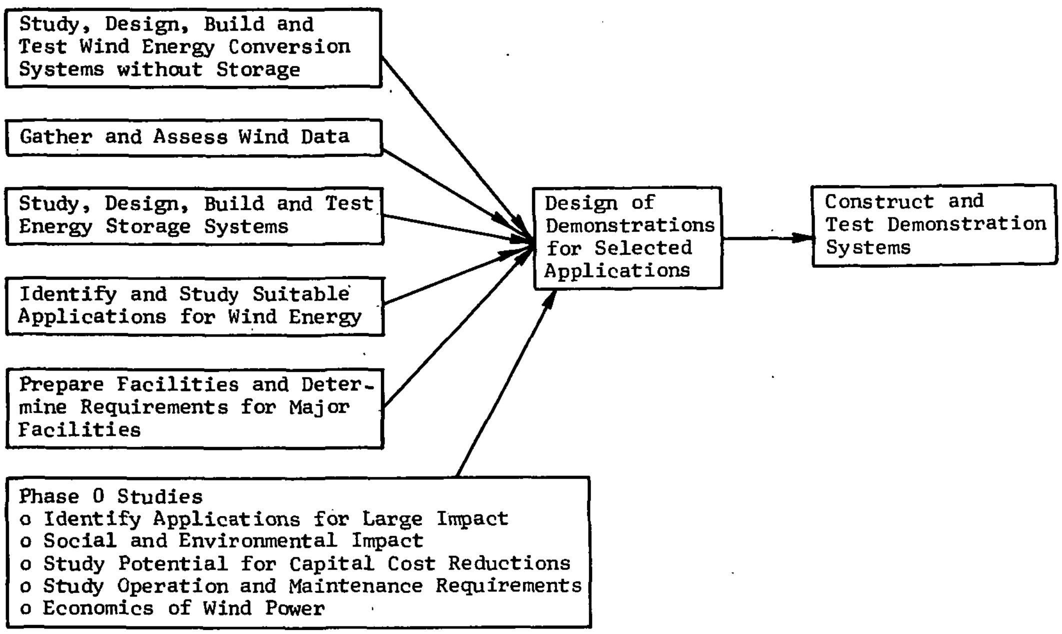


Figure 2

WIND ENERGY CONVERSION SYSTEMS

Action Diagram

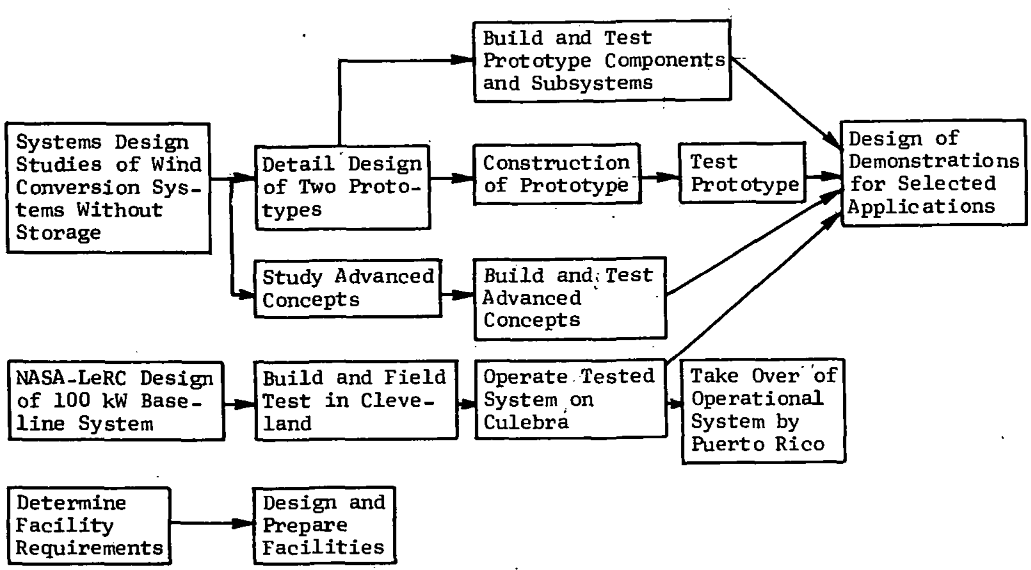


Figure 3

METEOROLOGICAL STUDIES

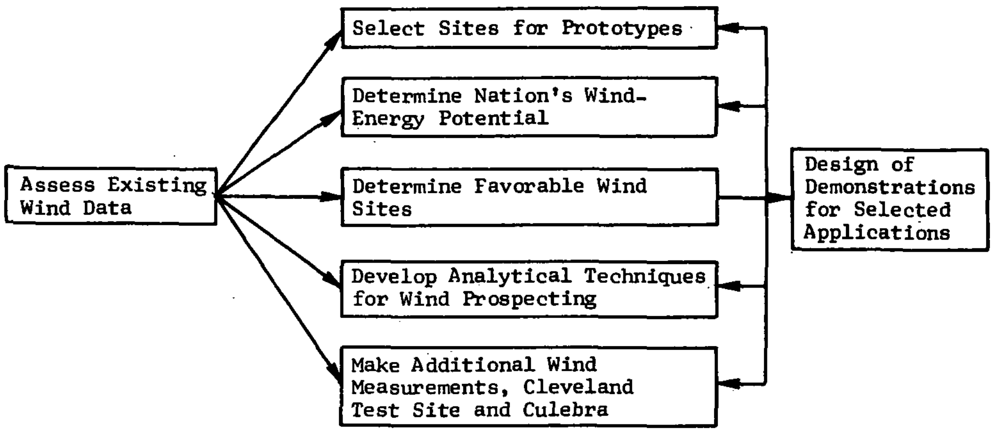
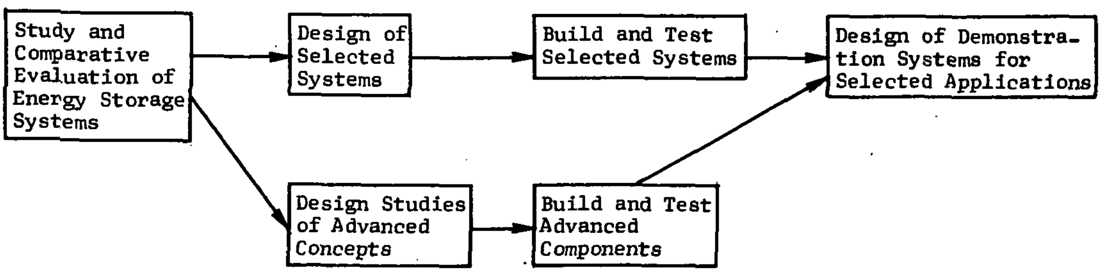


Figure 4

FIVE-YEAR WIND ENERGY PROGRAM

Energy Storage Systems



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