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# Wind Energy Research at the Solar Energy Research Institute

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# Wind Energy Research at the Solar Energy Research Institute

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## INTRODUCTION

As world interest in wind energy research and development (R&D) emerged in the mid-1970s, the path to the commercialization of wind power seemed clear, straightforward, and relatively short. In the United States, a fledgling industry foresaw small, 10-kW wind machines spinning in suburban and rural backyards, providing a fully dispersed new power source that would provide low-cost electricity to thousands of Americans. The U.S. government envisioned an equal number of large, utility-owned, multimegawatt wind turbines turning majestically in far-spaced rows across the Great American Plains to supplement existing coal-fired, oil, hydroelectric, and nuclear plants. Typically, both of these visions have proven to be inaccurate, at least so far; what we have in the United States are closely spaced rows of privately owned, intermediate-sized wind turbines (numbering more than 17,000), primarily on the coastal hills and inland plains of California.

The sheer magnitude of this recent development caught us by surprise. Within four years after U.S. tax incentives began in 1979, the wind technology installation goals established by the U.S. government were exceeded. Companies were so busy building, installing, and maintaining the machines that the basic research required to advance the technology was largely ignored. Meanwhile, U.S. government researchers and private consultants began seeing mounting evidence of machine problems, confirming their fear that the industry had done too much too soon. The industry has proven that the best wind machines can provide excellent reliability and availability (the amount of time that they are available to produce power). Still, there remains a great amount of work for the wind industry and the research community before wind technology receives widespread acceptance as an energy source in the United States and elsewhere.

Unfortunately, today the situation is clouded by the large number of poorly designed wind turbines (both U.S. and foreign) still standing in some California wind farms. Many of these machines are gradually being upgraded by their operators, and the outlook is brightening. However, the road to full commercialization has not proven to be as short--nor as easy--as previously thought.

### The History of the Solar Energy Research Institute (SERI) (1976 - 1984)

The U.S. Federal Wind Energy Program, currently managed by the Department of Energy (DOE), was established in 1973. Several research laboratories were assigned to address the specific research needs of the U.S. wind industry. Figure 1 shows the current DOE laboratory organization structure. The Rocky Flats and SERI programs (which were merged in 1984) were started in 1976 and 1977, respectively.

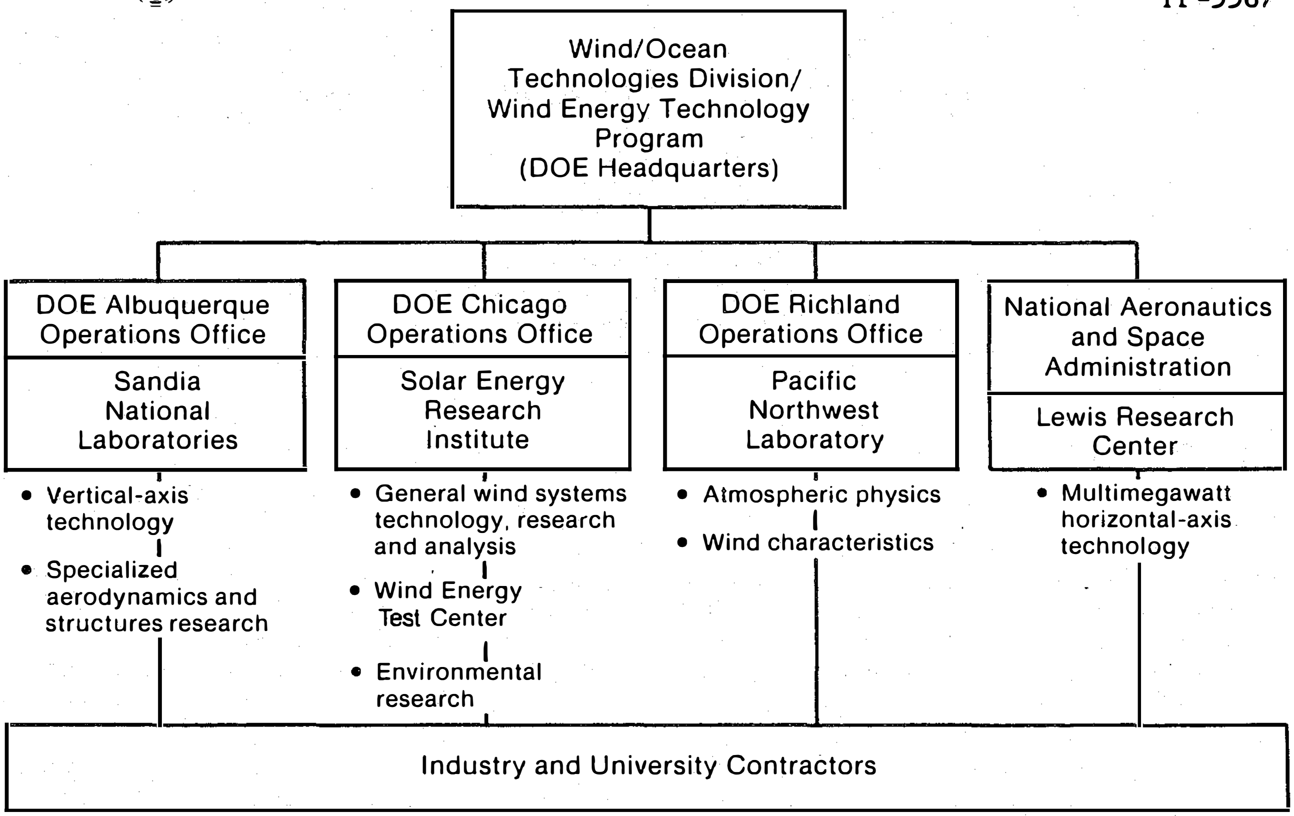


**Figure 1. Organizational Structure of the Federal Wind Energy Program**

## The SERI Research Program

SERI was created by the U.S. Congress in 1976 to serve as the primary center for renewable energy research in the United States. Operated by the Midwest Research Institute, SERI conducts research and development on the full range of solar technologies, including photovoltaics, biofuels, ocean thermal energy conversion, solar thermal, buildings, and wind energy.

Initially, SERI's primary responsibility in wind energy research was to manage the advanced- and innovative-concept elements of the Federal Wind Energy Program. The advanced concepts, which included a variety of wind turbines with ducted or augmented inflow, were investigated to determine if they could be competitive with conventional horizontal axis systems.

SERI also investigated the environmental and institutional impacts of wind power development. The most important aspect of this research was to develop techniques of aeroacoustical measurement and data analysis, which are now available to the U.S. wind industry to determine compliance with local noise ordinances. As part of its institutional activities, SERI conducted economic studies that assessed the value of wind power to utilities.

## The Rocky Flats Research Program

The Rocky Flats wind program became the broadest research and development effort under the Federal Wind Energy Program. In addition to developing and operating the national test center for small wind systems (where more than 50 wind turbine models were tested from 1977 to 1981), Rocky Flats managed 13 prototype development subcontracts for horizontal- and vertical-axis wind turbines ranging from 1 kW to 40 kW. A substantial "institutional issues" program was also begun in 1979 and included studies of wind power markets and financial issues, and an information dissemination program. Rocky Flats also implemented the DOE field evaluation program that planned the installation of 120 wind turbines throughout the United States. Applied wind turbine research was conducted in the areas of aerodynamics, structural dynamics, airfoil development, and variable-speed generation.

## THE FIVE-YEAR RESEARCH PLAN

The U.S. Department of Energy Five-Year Wind Technology Research Plan began the process of getting industry and the government laboratories working more closely together. Inputs to the plan were received not only from the laboratories, but from industry representatives who attended a series of SERI-hosted workshops across the United States. The resulting document comprises a general agreement on mutual goals and objectives. The plan has three major components:

1. Basic research in the science of wind turbine dynamics
2. Research on advanced components, subsystems, and systems
3. Cooperative research and test programs with industry.

The five-year plan emphasizes areas where SERI and the other laboratories can contribute to the private development of wind power. Accordingly, the primary activities to emerge have been to develop predictive and analytical tools (computer codes) for designers; conduct basic research that is beyond the capability of private firms; and conduct research and proof-of-concept efforts in high-risk areas, such as advanced airfoil development.

The U.S. wind energy program is now composed of three major laboratories. SERI is the lead laboratory for research on horizontal-axis wind turbines, including aerodynamics, structural dynamics, and supporting research. Sandia National Laboratories primarily conducts research on the Darrieus vertical-axis configuration. Pacific Northwest Laboratory manages research on atmospheric fluid dynamics and wind characteristics. The National Aeronautics and Space Administration (NASA), which managed the multi-megawatt machine program, is ending its involvement in wind energy now that tests of the MOD-5B machine have been successfully completed in Hawaii. SERI had already assumed many of NASA's responsibilities in 1985, including the operation and decommissioning of the large experimental MOD-2 wind turbines.

## THE PRESENT U.S. WIND INDUSTRY

From more than 50 manufacturers in the early 1980s, the size of the U.S. wind industry has dwindled to 5 or 6 manufacturers of commercial wind turbines. The largest firm is Westinghouse Electric, the builder of a 600-kW, intermediate-sized machine being used in a 15-unit wind farm in Hawaii. The largest volume manufacturer, U.S. Windpower, is the largest wind turbine company in the world; it installed 600 units in 1987. These firms are served by several dozen component suppliers. The primary competition for U.S. firms is with foreign manufacturers from Denmark, The Netherlands, West Germany, Great Britain, and Japan.

Most of the U.S. firms have their own research and engineering staffs, with which SERI tries to maintain communication through subcontracts, cooperative test activities, and regular professional contacts. Many of the companies are actively exploring the possibility of exporting their products to developing countries.

## CURRENT SERI RESEARCH

### Program Highlights

Our primary challenge at SERI has been to be responsive to industry needs under a government program with increasingly limited and uncertain resources. As a result, we've tried to identify problem areas faced by the entire industry and focus our resources to address those areas and thereby benefit the industry as a whole. Figure 2 presents a breakdown of how we have allocated resources to the various research disciplines under the SERI program since the five-year plan was initiated in 1985.

Robert Lynette and Associates recently completed a study for SERI that identifies research areas needed to solve current industry problems. We will use the results of this study, together with input from an industry technical review team, to ensure that our program is addressing the most critical R&D needs of the wind industry.

Eventually, the combined research efforts of SERI and industry will culminate in the development of advanced third-generation wind turbines--often referred to as the "1990s Wind Turbine." These machines will be lighter, more powerful and reliable, and cheaper to build and operate than wind turbines using existing technology, and they are absolutely essential to the success of wind power development. The current designs are serviceable and economical where wind speeds are very high and energy prices are advantageous. But they are not sufficient to make wind power ultimately competitive with conventional

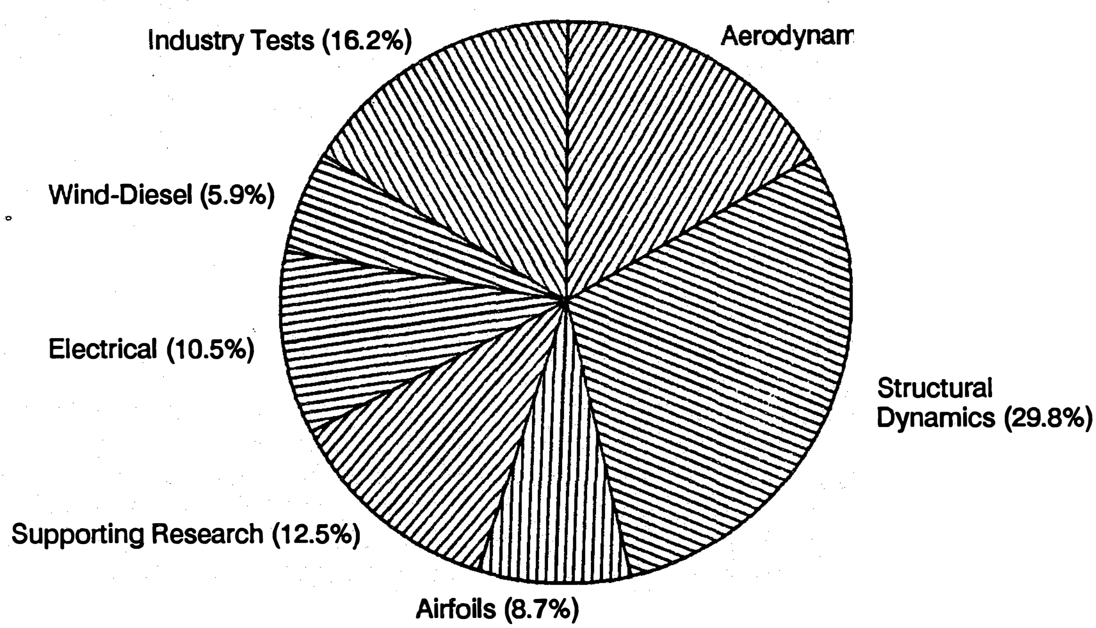


**Figure 2. Allocation of SERI Research Funds for 1985-1988**

energy sources at sites with moderate wind speeds. Most wind energy applications are located in areas with moderate wind speeds.

What will the 1990s Wind Turbine look like? The Northern Power Systems (NPS) 125-kW wind turbine is one example of the light, flexible, and efficient rotors that have been developed by U.S. companies. This rotor incorporates a teetering hub and special hinges to absorb and dampen rotor loads, particularly the cyclical fatigue loads that cause material fracture and failure. To date, few of these advanced rotors have been completely successful on intermediate-sized machines. SERI has tested the NPS rotor, which is still in the development stages, to acquire dynamic-response data. Later in 1988, we will be performing a cooperative test with NPS to obtain fatigue data. Such measurements are the essential first step in helping industry realize the great potential of the flexible self-regulating rotor. These data can be used to refine analytical design tools by incorporating teetered hubs, innovative hinges, and other load-control devices in the basic computer models.

All of SERI's basic and applied research is ultimately aimed at making such advanced turbines a reality. Studies of yaw dynamics will help designers improve the behavior of sophisticated new rotor designs. Structural-dynamics codes will assist designers in predicting the loads that different types of rotor designs will experience under similar conditions, helping to determine the best design configurations. Figure 3 presents results from one of these computer programs, the Force and Loads Analysis Program (FLAP). This computer run predicts loads at the root of a wind turbine blade in the presence of turbulent winds--something that previous codes could not do. Although this code requires additional refinement (it accurately predicts peak loads at lower frequencies but underpredicts loads at higher frequencies), we are confident that it will soon become the most accurate design tool available to the U.S. wind industry. The next challenge is to develop

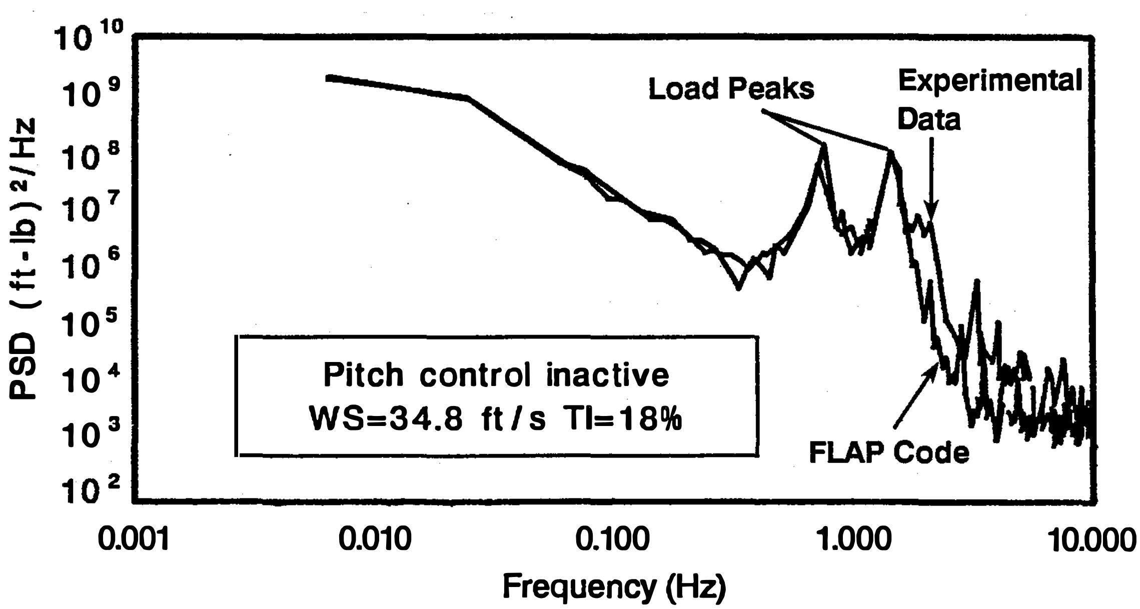


Figure 3. FLAP Code Predicted Root Moment Spectra (Turbulence Case) Compared with Experimental Data

fatigue models that use these predictions to help industry increase the service life of wind turbines. This will require an improved understanding of the properties of complex composite materials used in the rotors of advanced wind machines.

In this paper, we will focus on three specific research activities to demonstrate key areas where progress is being made at SERI: the Combined Experiment, advanced airfoil development, and wind-diesel research (an area of particular interest to developing countries).

### Combined Experiment

Despite years of government and private research, the basic physical processes governing wind turbine rotor operation and dynamic response are still not understood sufficiently to allow designers to predict structural behavior and system life with a reasonable degree of confidence. Loads associated with deterministic processes such as gravity and centrifugal forces are relatively predictable. However, stochastic loads caused by turbulence and wind shear, and the various aerodynamic, aeroelastic, and dynamic phenomena associated with these loads, have proven difficult to predict. When a rotating wind turbine blade stalls in the presence of complex or chaotic phenomena, all analytical predictions break down. For example, horizontal-axis wind turbines actually produce more power and experience higher loads in high winds than standard analyses predict. This is a problem for designers, who must attempt to optimize wind turbine operational characteristics at different sites with different wind regimes and turbulence intensities. If a mistake is made, improper component selection (for example, choosing a generator that is too small) can ruin the economics of an entire wind farm.

There have been a number of unsuccessful attempts to obtain the required three-dimensional data: pressure measurements, flow-visualization measurements, and associated wind input and structural-response data. The SERI Combined Experiment represents the first time that these measurements are being made simultaneously to produce a useful integrated data set. A 10-m-diameter wind turbine is being used for the experiment, which combines research on wind inflow, aerodynamics, aeroelastics, and structural dynamics--all on one wind turbine. Inflow is measured by a vertical-plane array of anemometers placed upwind in the prevailing wind direction. Flow patterns over the blades are recorded by a high-speed video camera mounted on the rotor. The camera records the position of small, dynamically balanced tufts mounted on the blades to help researchers determine how the flow changes under various conditions.

SERI has developed pressure transducers and custom-made probes to directly measure lift coefficients and corresponding angles of attack. These measurements will help us isolate the various three-dimensional phenomena (dynamic stall, delayed stall, and span-wise or lengthwise flow along the blade) that are suspected of invalidating predictions. When the dominant physical process is isolated, subsequent detailed test programs can focus on understanding the process and developing guidelines for industry designers who want to modify or overcome the process. Using such guidelines, designers could meet operation goals to achieve superior component matches and thereby increase overall operating efficiency and annual energy output. Developers could also use such guidelines in advanced designs that reduce the fatigue loads that are causing so many problems for the industry.

## Airfoil Development

Until recently, it was common for designers to assume that one of several aircraft airfoil shapes would be the best selection for wind turbines. SERI was the first research organization to explore alternatives that offer superior operation and performance characteristics for horizontal-axis wind turbines. After compiling a catalog of all appropriate airfoils and determining that some radically different aircraft airfoils provided limited advantages, we began, in 1984, to develop special-purpose airfoils designed specifically for wind turbines. At first, higher performance was the goal, but other considerations were soon included. Manufacturers began reporting serious degradation in energy output with the old aircraft airfoils because of insect buildup on the blade leading edge. Therefore, insensitivity of performance to the surface roughness caused by insects was added to the list of criteria. SERI studies of U.S.- and European-built, stall-regulated (fixed pitch) wind turbines revealed that their rotors were being operated at nonoptimum pitch to avoid higher-than-predicted performance and subsequent generator burnout at higher wind speeds.

SERI, together with our subcontractor, Airfoils, Inc., has developed three special-purpose airfoil families: one "thin" airfoil family for rotor diameters of less than 12 m, and two "thick" airfoil families that should provide desirable operating characteristics in the thicker blade planforms required by wind turbine rotors over 12 m in diameter. The airfoil families specify an entire series of airfoils designed for specific portions of the blade. This is done because the structural and performance requirements of the blade root, for example, are much different than those for the blade tip. The SERI approach to airfoil development is to test representative sections of the airfoils in low-turbulence wind tunnels (specifically, the one at Delft University, The Netherlands), refine the airfoils based on the results of those tests, and then fabricate and test blades incorporating the airfoils on U.S. industry wind turbines. The new airfoils developed are somewhat machine-specific in terms of rotor size, mean annual wind speed, and rotor control design (fixed pitch, variable pitch, or variable speed).

Atmospheric tests of the thin airfoil family are scheduled to begin in October 1988, with tests of the thick airfoil family scheduled for the spring of 1989.

## Wind-Diesel Research

Wind-diesel systems have attracted considerable industry attention because of their potential worldwide application. Such systems are attractive to developing countries because they offer a rapid way of providing reliable power to areas still far from central power grids. The fact that many such areas are already serviced by diesel generators makes the application doubly attractive: the addition of a wind turbine can reduce diesel fuel costs and increase reliability by relieving the diesel unit of many hours of operating time. Together with a battery storage system, a wind turbine can also increase reliable peak power production for brief periods. But wind-diesel system design is hampered by the inability to predict what will happen when these two very different power devices operate together. Experiments in the United States have shown that high penetrations of wind energy on a diesel system can result in high fuel usage and unacceptable system characteristics--from both an operational and economic standpoint.

SERI's wind-diesel research is aimed at improving the understanding of the control characteristics and component behavior so that system designers can improve the cost-effectiveness of energy production. The research approach is to coordinate model development efforts with the cooperative experiments of industry that provide data to be used to test model results. AeroVironment and the University of Massachusetts are working to adapt and validate a previously developed system and economic model to predict wind-diesel performance with different component sizes, operating characteristics, consumer loads, and wind environments. Data acquired from wind-diesel systems operated by NPS and Atlantic Orient Corporation will characterize the system stability as a function of the penetration of wind energy. These data will be used to check the accuracy of the model.

Once the model is completed, a system planner will be able to develop a preliminary design by entering primary component characteristics, known consumer loads, and the local wind characteristics. Selecting an appropriate wind turbine would then be relatively straightforward.

## CONCLUSION

From two separate programs addressing different concerns, the SERI wind research program has emerged as the primary horizontal-axis wind turbine research center in the United States. In SERI's view, the flexible high-performance wind turbines developed by U.S. manufacturers offer great potential for the U.S. and world markets. This includes the potential for scaleup to the larger sizes (250 kW to 1 MW). Our principal research challenge in the next few years is to acquire the data, develop the analytical design tools, and explore the advanced component and systems concepts that will help improve the performance and reliability of these systems and help usher in a new era of wind technology to meet world energy needs.