Solar Technology Seminars for Congress

Wind Systems

June 8, 1979

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Technology Summary

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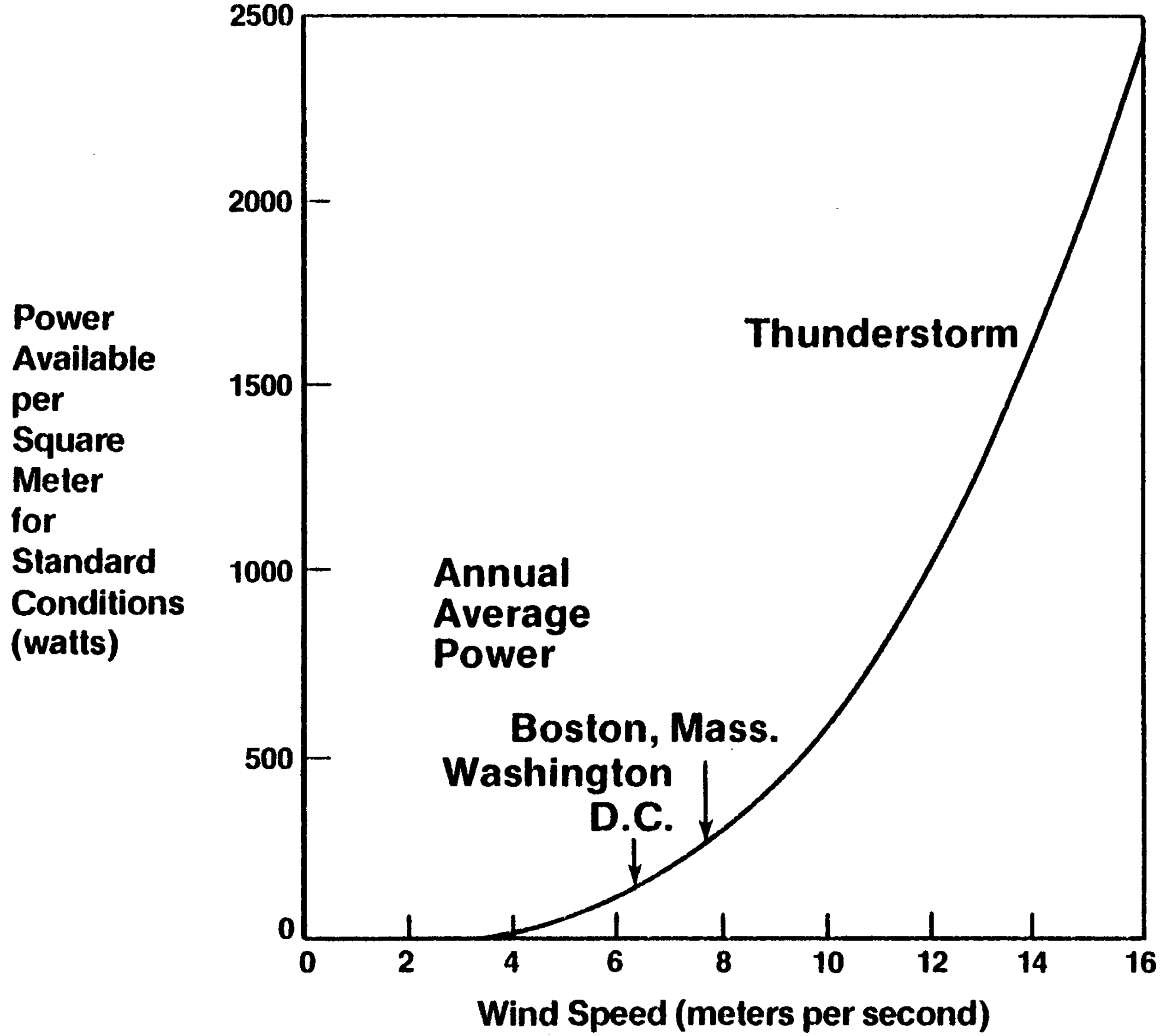


2500
2000
1500
1000
500
0
Power Available per Square Meter for Standard Conditions (watts)
Thunderstorm
Annual Average Power
Boston, Mass.
Washington D.C.
0
2
4
6
8
10
12
14
16
Wind Speed (meters per second)

A WIND TURBINE IS A SOURCE OF POWER.

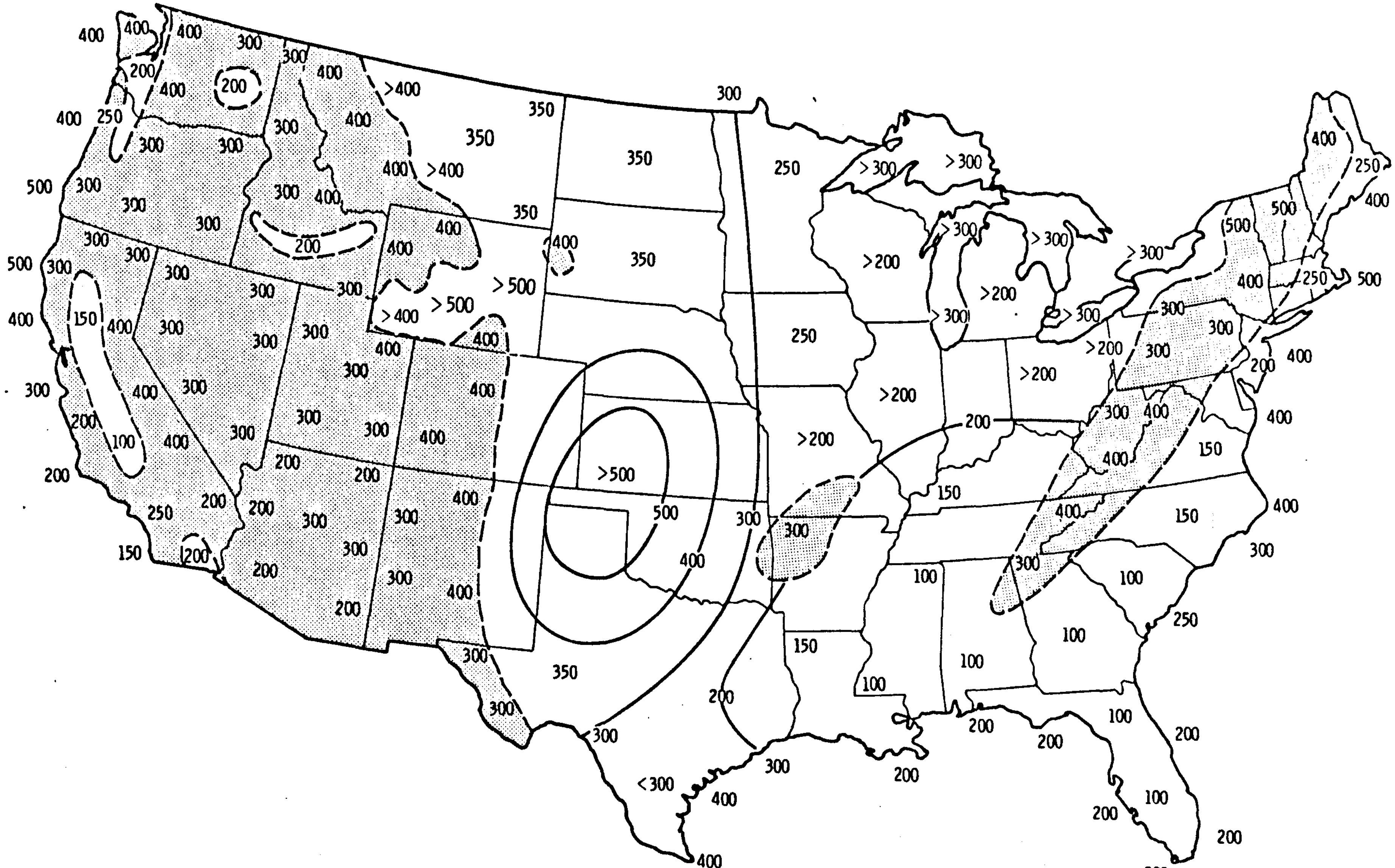
THE POWER AVAILABLE IN THE WIND PER UNIT OF CROSS SECTIONAL AREA IS

$$\frac{\text{POWER}_{\text{AVAILABLE}}}{\text{UNIT AREA}} = \frac{\text{DENSITY} \times (\text{WIND VELOCITY})^3}{2}$$

THE POWER AVAILABLE THUS INCREASES AS THE CUBE OF THE WIND VELOCITY.

THERE IS EIGHT TIMES AS MUCH POWER IN A 20 MPH WIND AS IN A 10 MPH WIND.

BECAUSE OF THIS SENSITIVITY, AND BECAUSE THE WIND IS QUITE VARIABLE GEOGRAPHICALLY, VERY GOOD WIND DATA IS REQUIRED FOR ACCURATE ANALYSIS OF WIND TURBINE POTENTIAL.



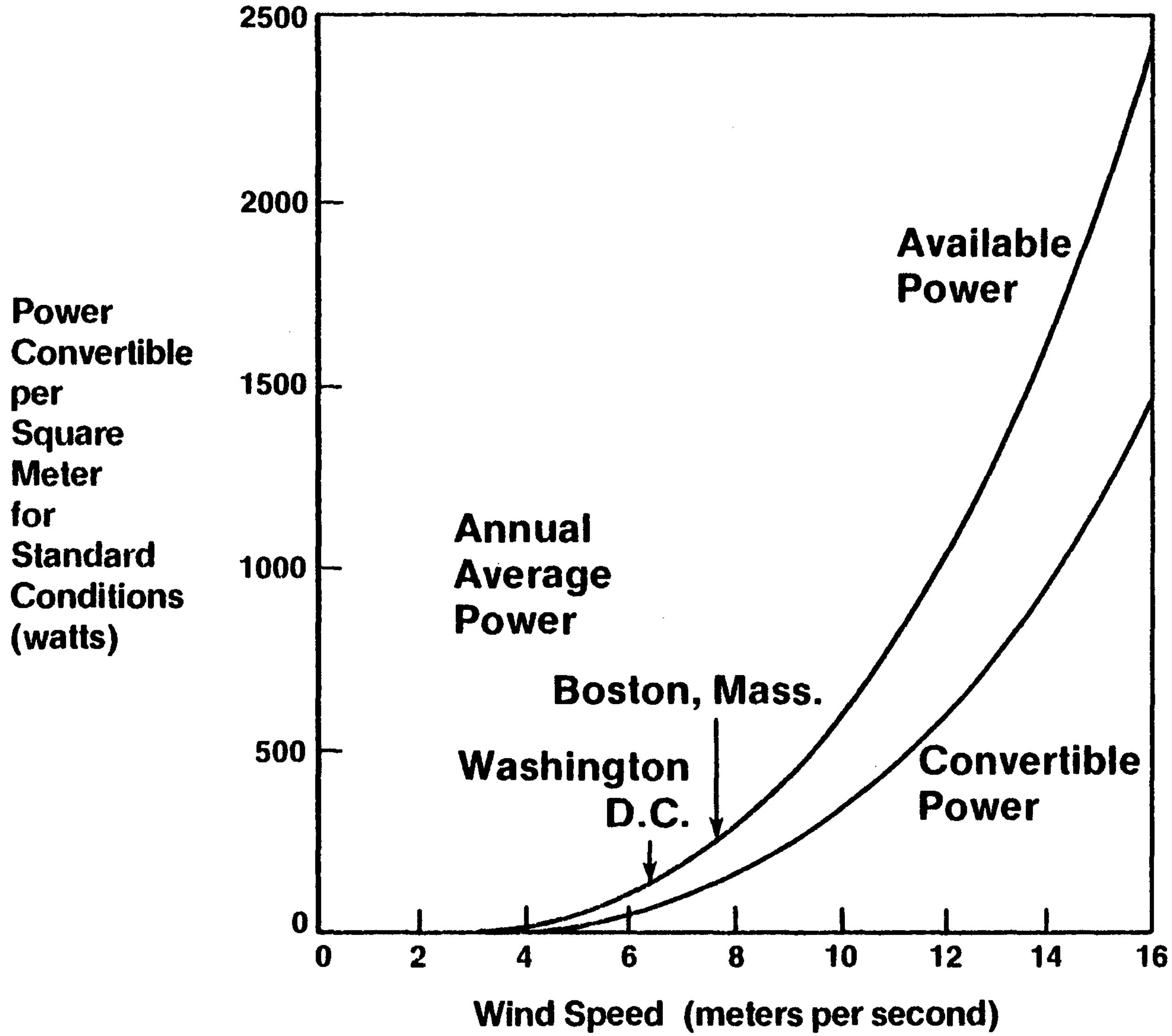
Mean Annual Wind Power (W/m^2) Estimated at 50 m Above Exposed Areas. Over mountainous regions (shaded areas), the estimates are lower limits expected for exposed mountain tops and ridges.

THERE IS A LOT OF ENERGY AVAILABLE FROM THE WIND.

THE MAP SHOWS CONTOURS OF AVERAGE WIND POWER ON AN ANNUAL BASIS PER SQUARE METER OF SWEPT AREA.

ONLY ABOUT 4/10 OF THIS POWER COULD BE CONVERTED TO USABLE FORM.

THIS STILL REPRESENTS MANY TIMES THE AMOUNT OF POWER CURRENTLY CONSUMED IN THE U.S.

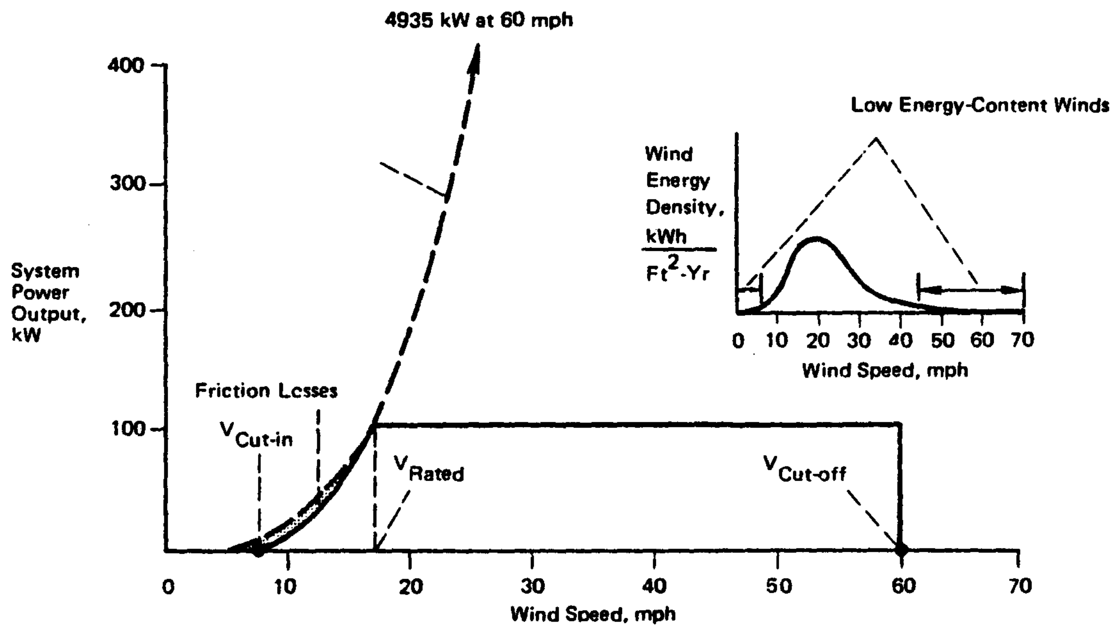

Power
Convertible
per
Square
Meter
for
Standard
Conditions
(watts)
2500
2000
1500
1000
500
0
Available
Power
Annual
Average
Power
Boston, Mass.
Washington
D.C.
Convertible
Power
0
2
4
6
8
10
12
14
16
Wind Speed (meters per second)

NOT ALL OF THE POWER IN THE WIND CAN BE CONVERTED TO USABLE FORMS. THE THEORETICAL MAXIMUM FOR POWER CONVERSION IS

$$\frac{\text{POWER}_{\text{CONVERTIBLE}}}{\text{UNIT AREA}} = .593 \times \frac{1}{2} \times \text{DENSITY} \times (\text{WIND VELOCITY})^3$$

THUS

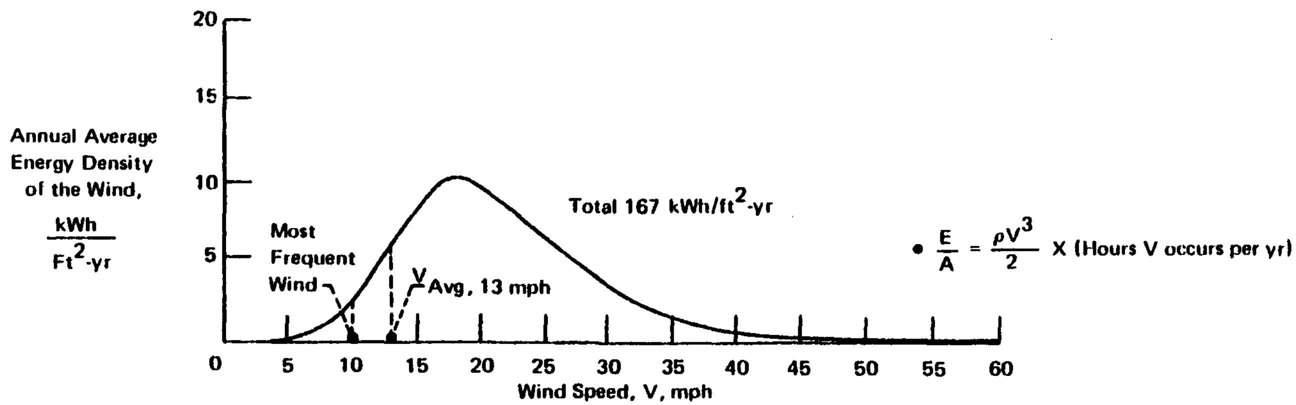
$$\frac{\text{POWER}_{\text{CONVERTIBLE}}}{\text{POWER}_{\text{AVAILABLE}}} \leq .593$$



POWER OUTPUT OF 125 FT. DIAMETER ROTOR, RATED AT 100 kW IN WINDS OF OVER 18 MPH

ANOTHER CONSIDERATION IS THAT THE POWER CONVERTED MUST BE LIMITED IN HIGH WINDS.

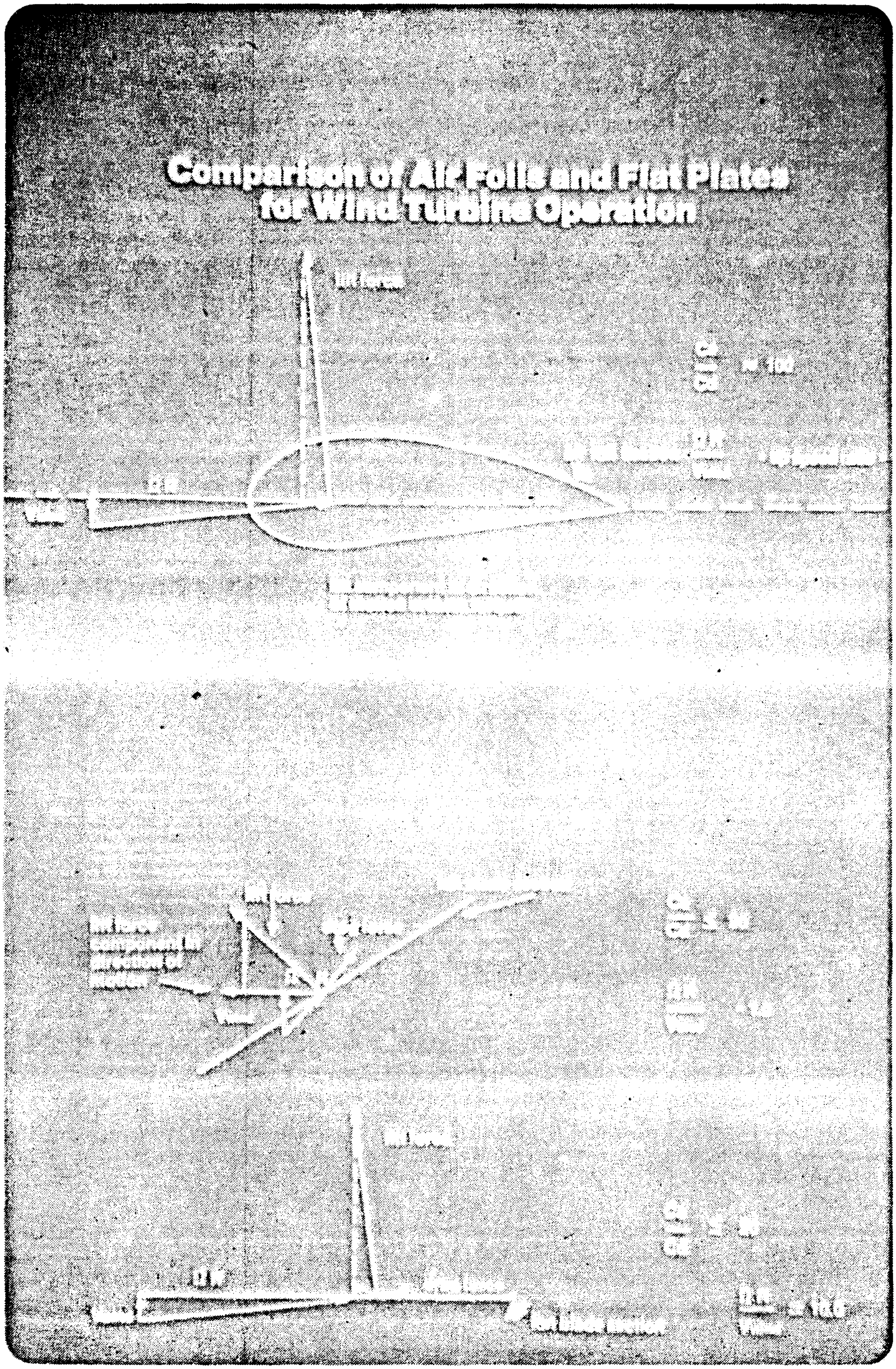
THIS IS A GRAPH OF POWER VS WIND SPEED FOR A TYPICAL WIND TURBINE. THE CUT-IN WIND SPEED, RATED WIND SPEED, AND CUTOUT WIND SPEED ARE INDICATED.



TYPICAL DISTRIBUTION OF ANNUAL AVERAGE ENERGY DENSITY OF WINDS OF VARIOUS SPEEDS

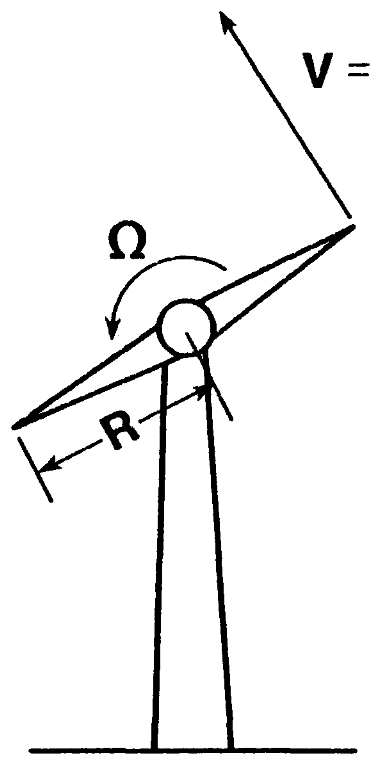
USING THE POWER CHARACTERISTICS OF A WIND TURBINE AND A WIND SPEED DISTRIBUTION CURVE ONE CAN DERIVE A POWER DENSITY SPECTRUM.

THIS CURVE SHOWS THAT, EVEN THOUGH THERE IS A GREAT DEAL OF POWER IN VERY HIGH SPEED WINDS, BECAUSE THEY OCCUR SO SELDOM, THERE IS NOT A LOT OF ENERGY IN THOSE WINDS.


Comparison of Air Foils and Flat Plates
for Wind Turbine Operation
lift force
lift force

A WIND TURBINE EXTRACTS POWER FROM THE WIND BY CAUSING A FORCE TO BE APPLIED BY THE WIND ON THE ROTOR IN THE DIRECTION OF ROTATION. THIS CREATES A TORQUE.

THE POWER PRODUCED BY THE ROTOR IS THE NET TORQUE TIMES THE ROTATIONAL SPEED. THE DIAGRAM SHOWS THESE FORCES FOR A HIGH SPEED WIND TURBINE AND AN OLD-FASHIONED FARM WINDMILL.



$$V = \Omega \times R = \text{Tip Speed}$$

$$\text{Tip Speed Ratio} = \frac{V}{V_{wind}}$$

THE TIP SPEED RATIO IS DEFINED TO BE THE MAXIMUM LINEAR SPEED OF ANY ROTATING PART DIVIDED BY THE ONCOMING WIND SPEED.

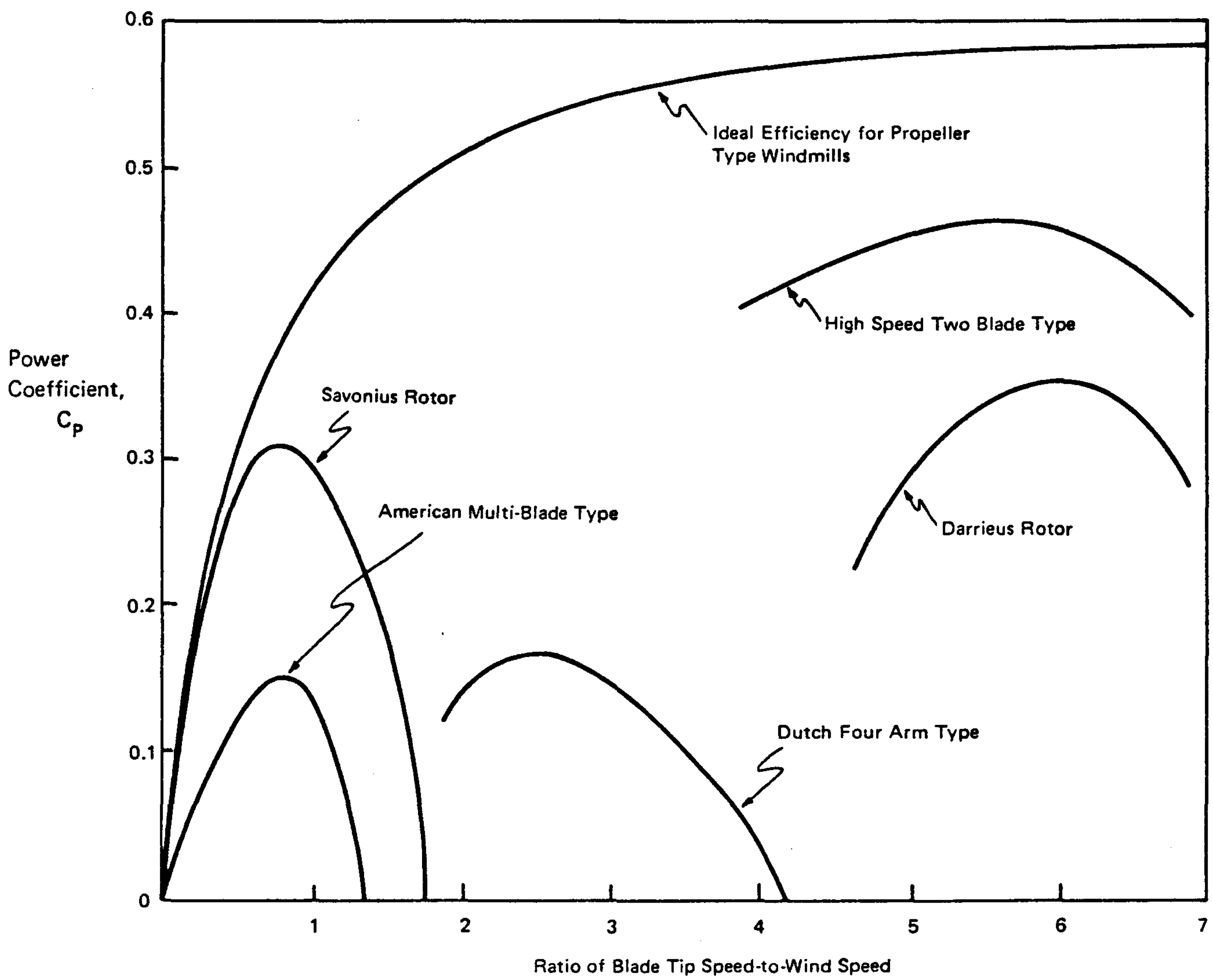
$$TSR = \frac{\text{ROTATIONAL SPEED X RADIUS}}{\text{ONCOMING WIND SPEED}}$$

FOR HIGH SPEED MODERN WIND TURBINES, THE TIP SPEED RATIO RANGES FROM 5 TO 12.

THE POWER COEFFICIENT IS DEFINED TO BE THE POWER DELIVERED BY THE ROTOR DIVIDED BY THE POWER IN THE WIND.

$$C_P = \frac{\text{POWER DELIVERED}}{\frac{1}{2} \times \text{DENSITY} \times \text{SWEPT AREA} \times (\text{VELOCITY})^3} \leq .593$$

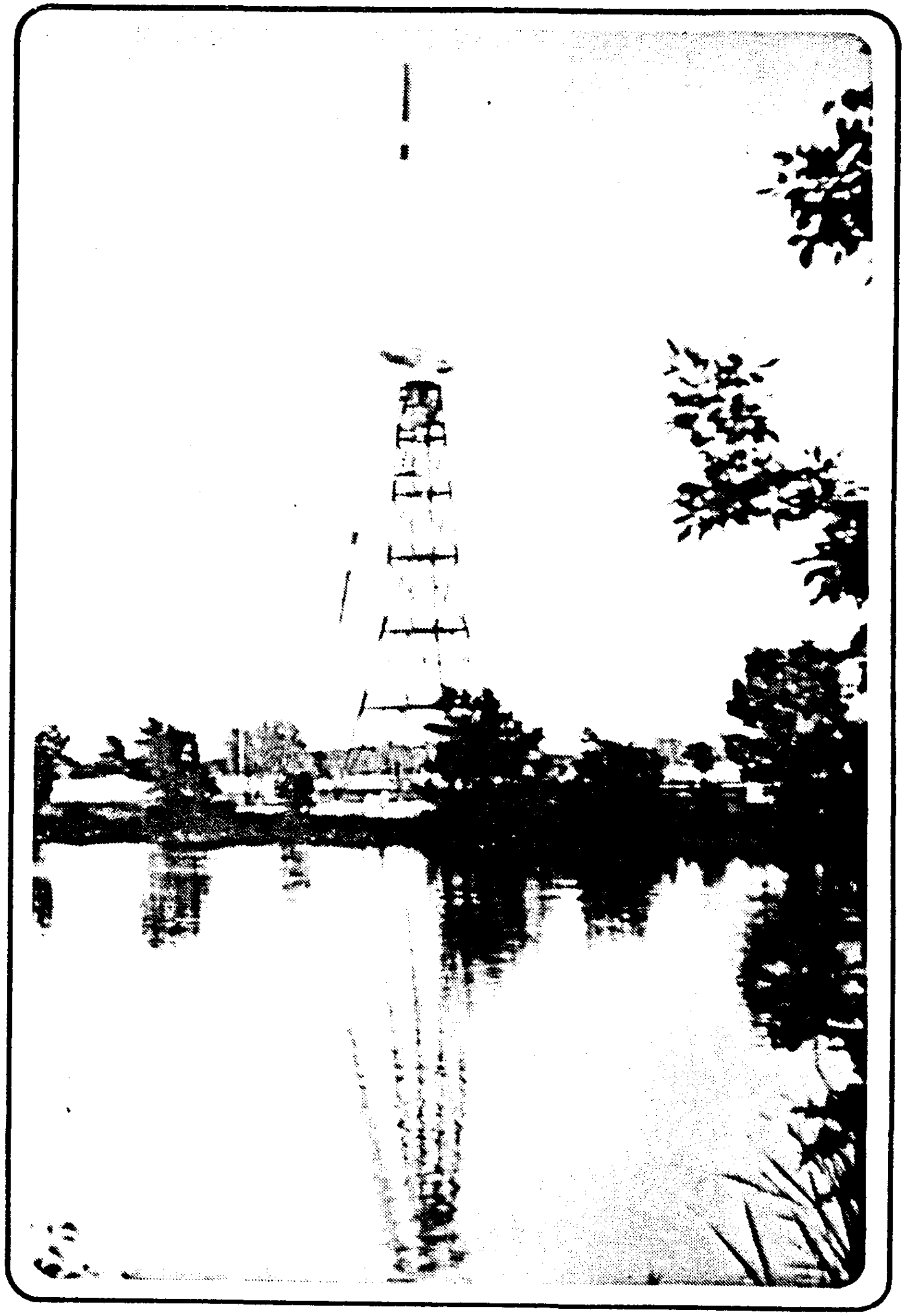
.593 IS A THEORETICAL MAXIMUM FOR NONAUGMENTED WIND ENERGY CONVERSION DEVICES. THIS IS REFERRED TO AS THE BETZ LIMIT, AFTER THE FIRST PERSON TO DEVELOP THE THEORY.

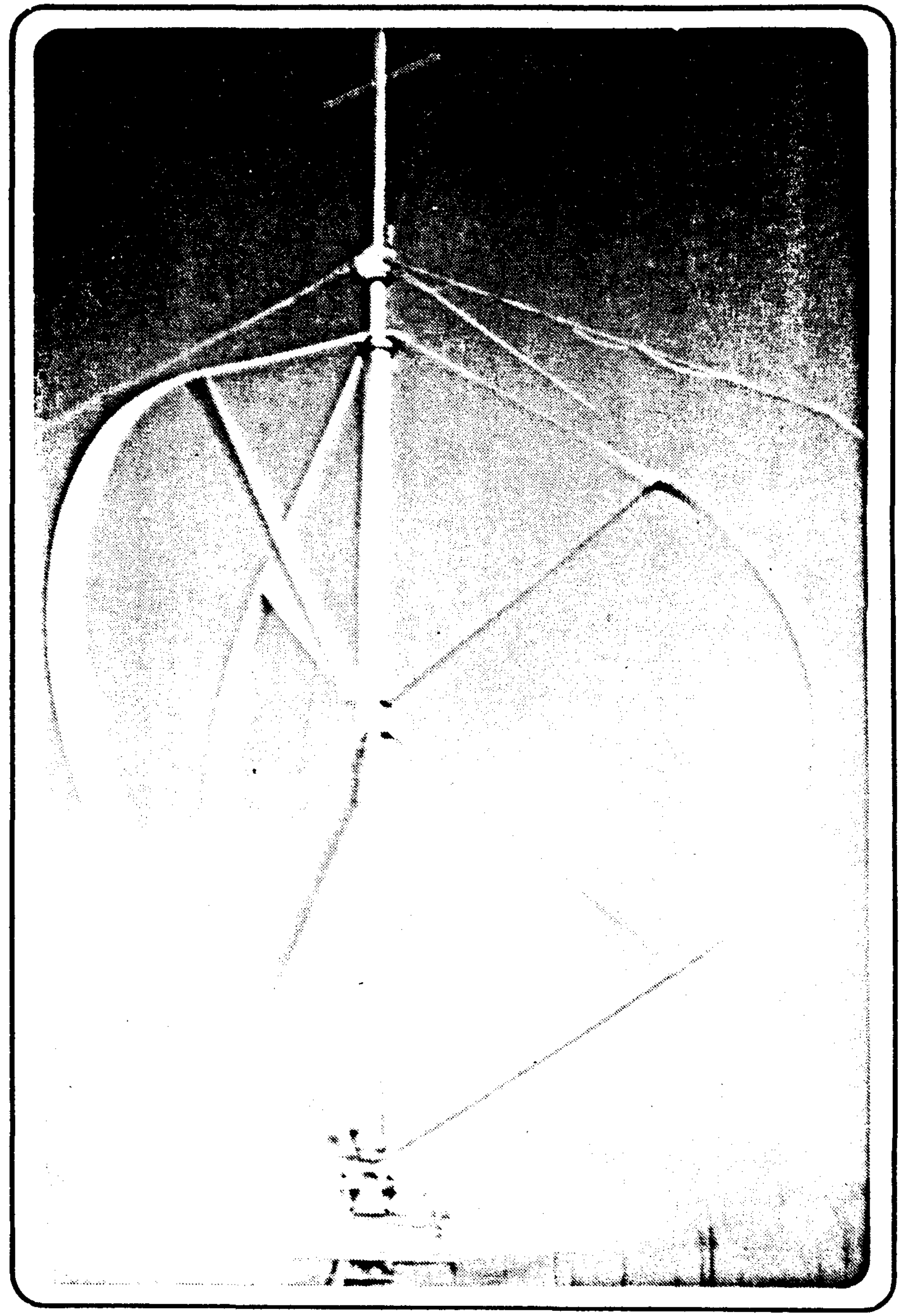


TYPICAL PERFORMANCES OF WIND MACHINES

A CONVENIENT WAY TO CHARACTERIZE WIND TURBINE PERFORMANCE IS WITH PLOTS OF C_p VERSUS TSR.

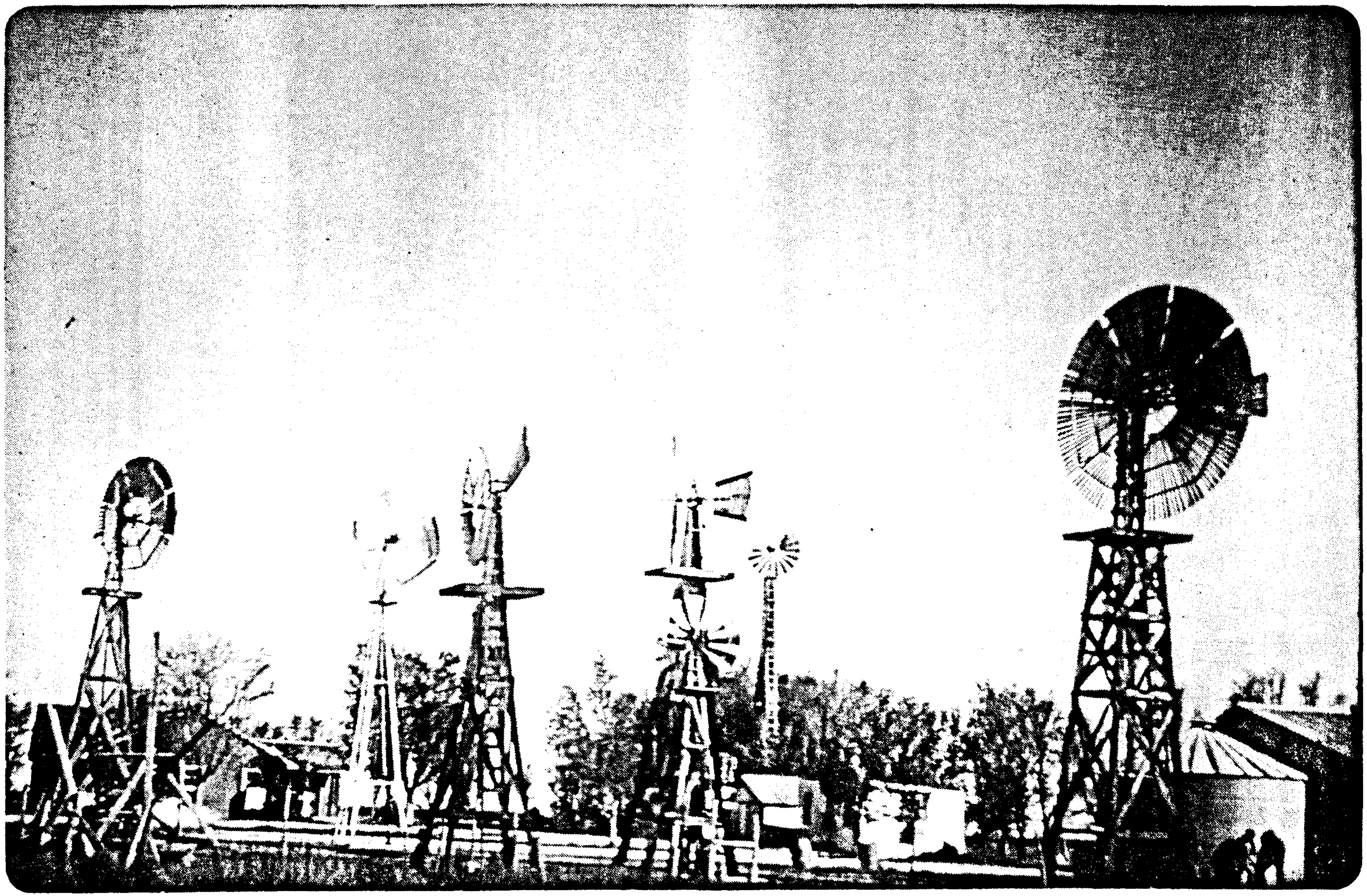
THESE GRAPHS DESCRIBE THE OPTIMUM PERFORMANCE OF VARIOUS WIND ENERGY CONVERSION DEVICES.





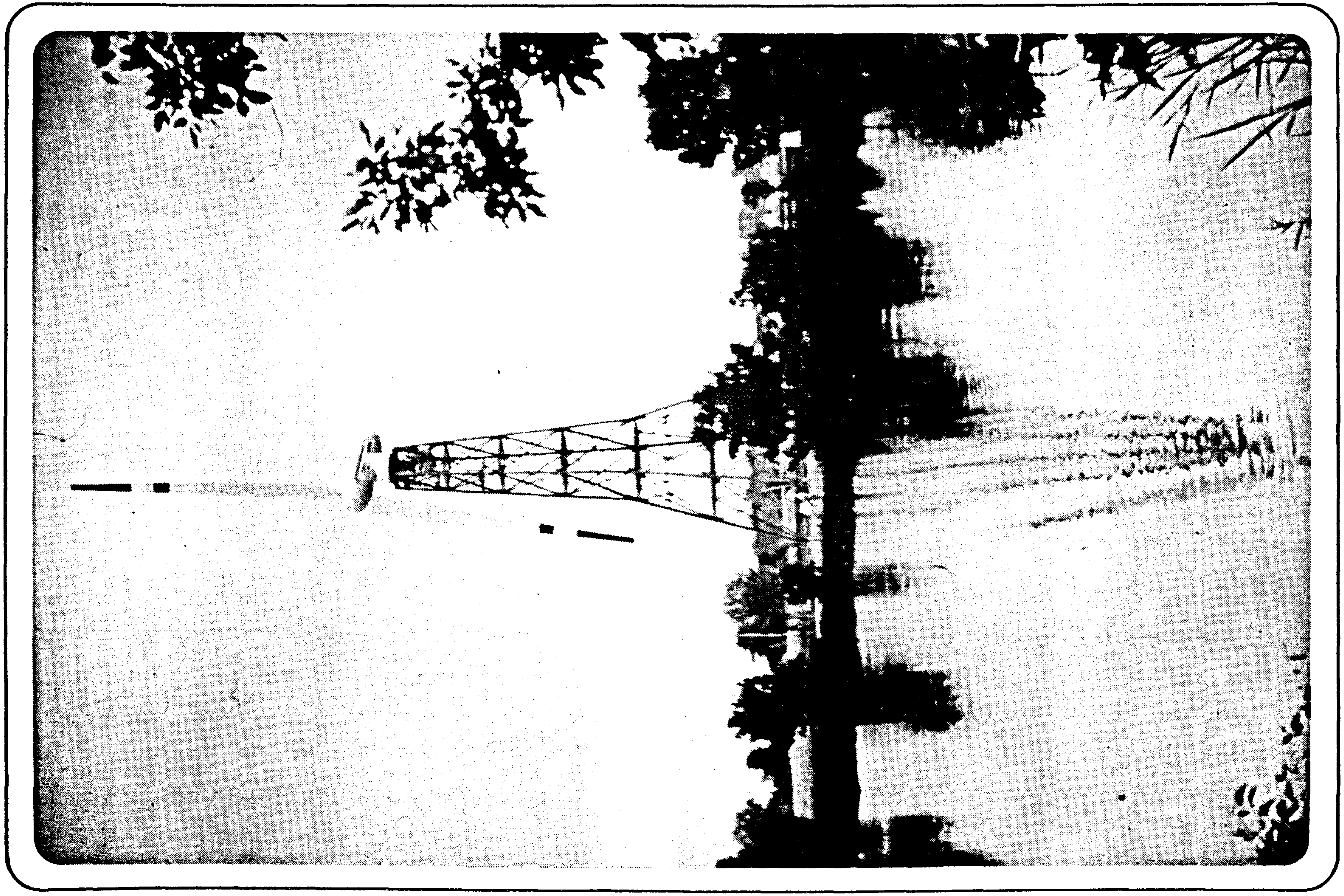
THERE ARE TWO CLASSES OF CONVENTIONAL WIND TURBINES.

THEY ARE THE VERTICAL AXIS MACHINES AND THE HORIZONTAL AXIS MACHINES.



HORIZONTAL AXIS WIND TURBINES ARE BASICALLY OF TWO TYPES, UPWIND AND DOWNWIND.

THE UPWIND TURBINES HAVE THE ROTOR PLACED UPSTREAM OF THE TOWER AND VICE VERSA FOR DOWNWIND TURBINES.

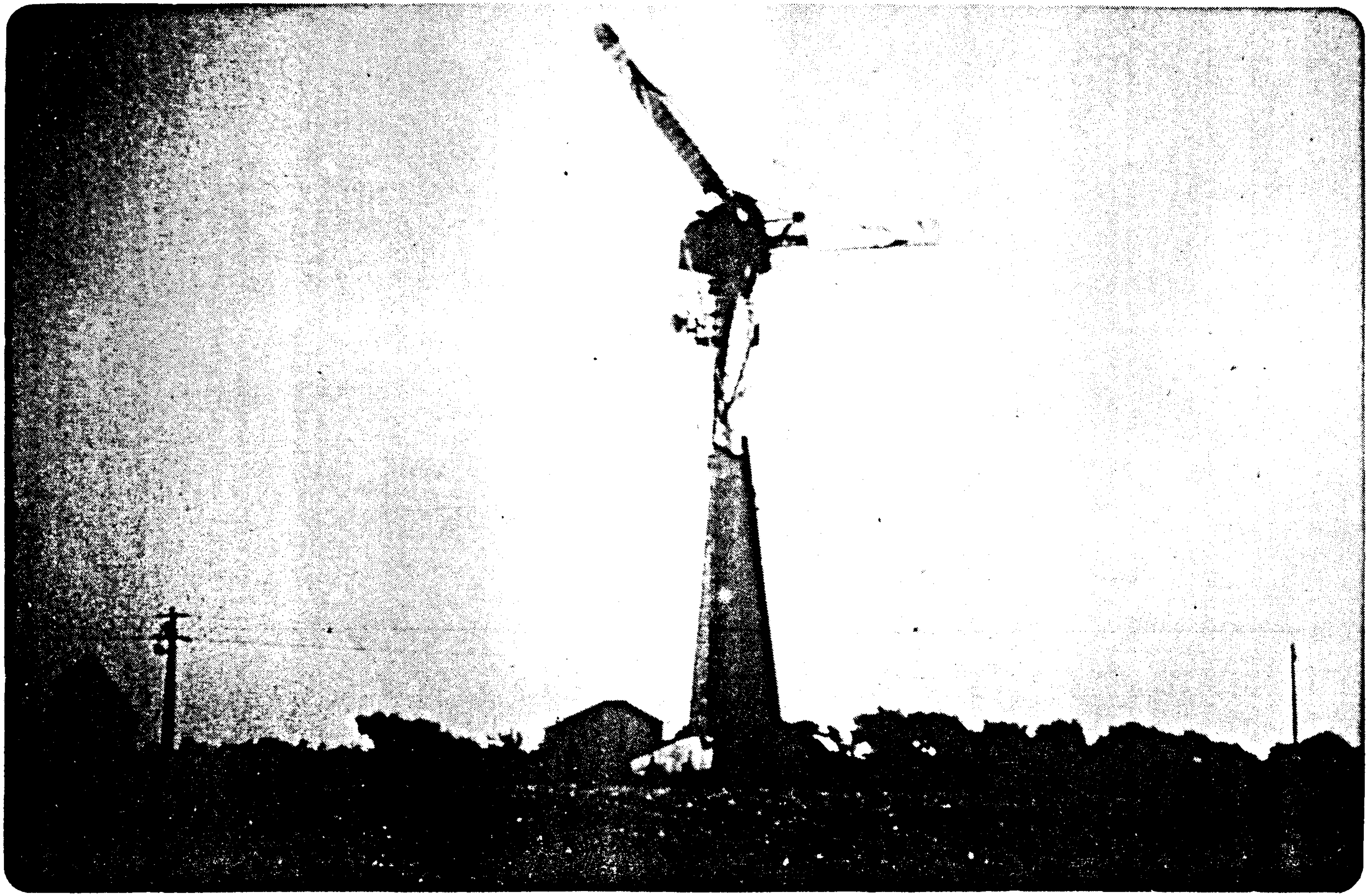


THE MOD-OA MACHINE, BUILT UNDER CONTRACT TO NASA LEWIS RESEACH CENTER, IS A LARGE, DOWNWIND HORIZONTAL AXIS WIND TURBINE.

ITS OUTPUT IS LIMITED TO 200 KILOWATTS OF ELECTRICITY AT A WIND SPEED OF 20 MPH.

THE GRUMMAN WINDSTREAM 25 IS A SMALL, DOWNWIND HORIZONTAL AXIS WIND TURBINE.

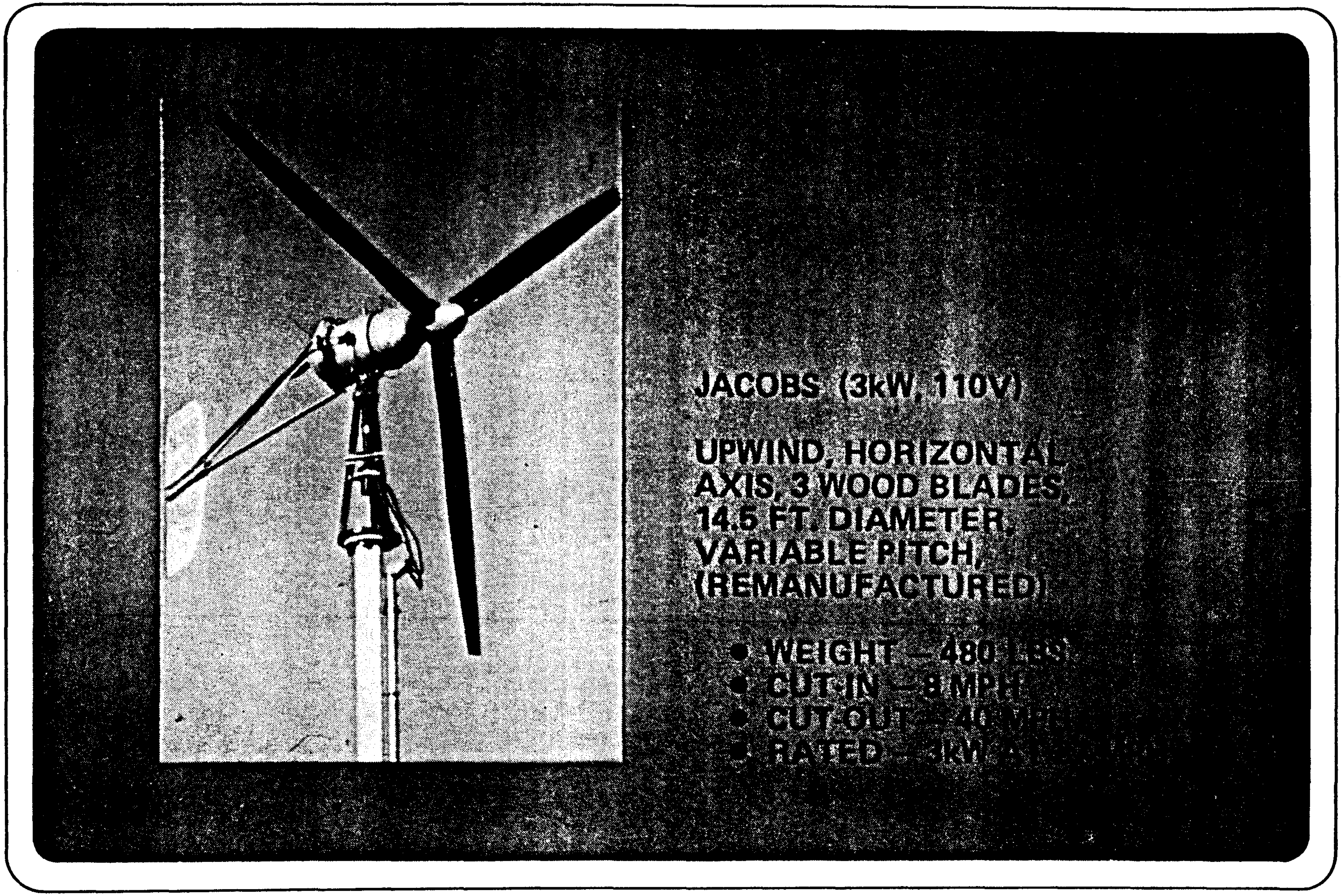
ITS OUTPUT IS LIMITED TO 15 KILOWATTS OF ELECTRICITY AT 26 MPH.



THE GEDSER WIND TURBINE IS A LARGE UPWIND, HORIZONTAL AXIS WIND TURBINE.

IT WAS BUILT BY THE DANES DURING THE 1950'S AND ROUTINELY GENERATED ELECTRICITY FOR MANY YEARS.

IT HAS RECENTLY BEEN REFURBISHED FOR TESTING, PARTIALLY FUNDED BY THE FEDERAL WIND ENERGY PROGRAM.



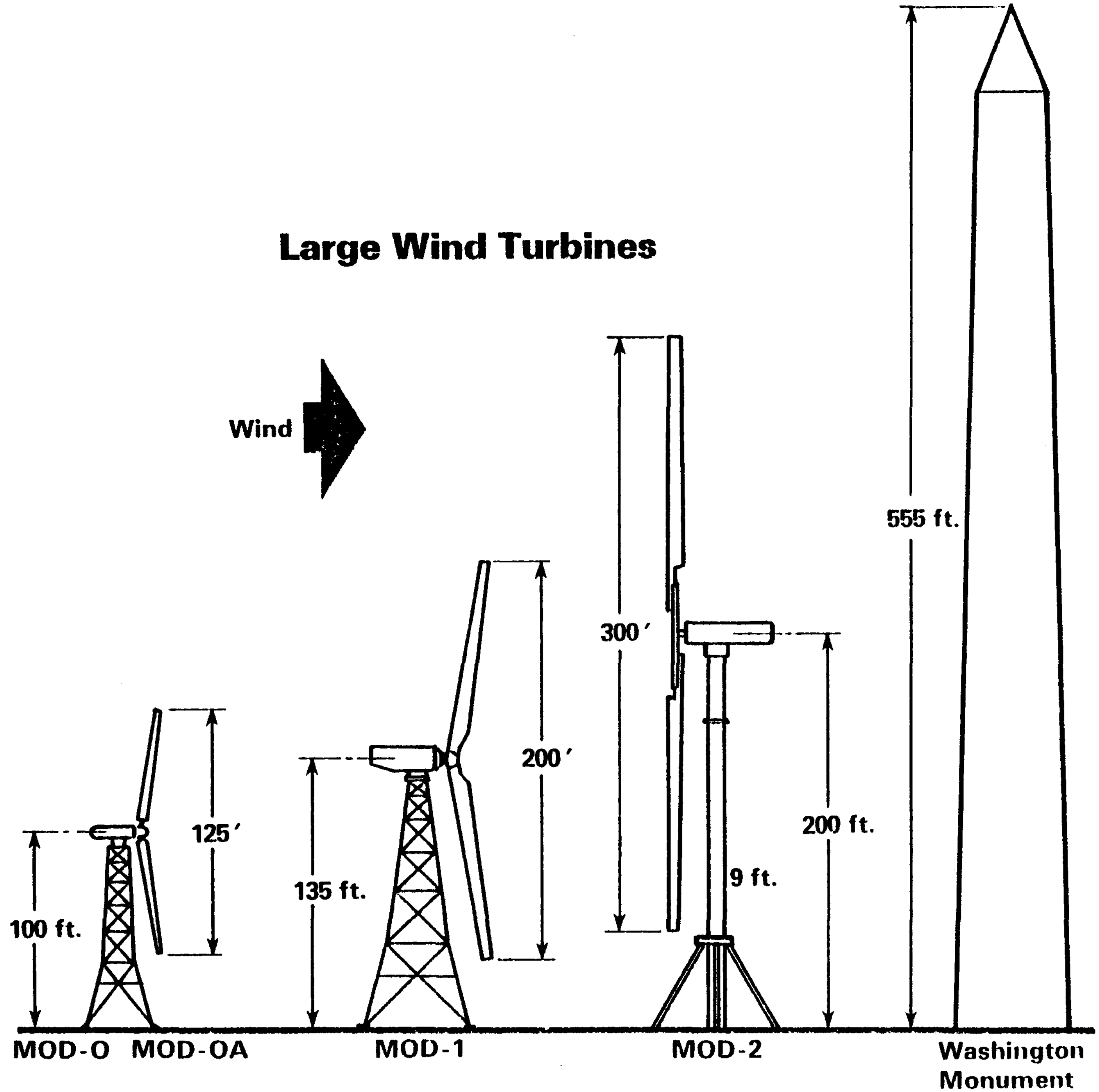
JACOBS (3kW, 110V)
UPWIND, HORIZONTAL AXIS, 3 WOOD BLADES, 14.5 FT. DIAMETER, VARIABLE PITCH, (REMANUFACTURED)
• WEIGHT — 480 LBS
• CUT-IN — 8 MPH
• CUT-OUT — 40
• RATED

THE JACOBS WIND TURBINE IS A SMALL, UPWIND, HORIZONTAL AXIS WIND TURBINE.

THIS WIND TURBINE WAS AVAILABLE IN MANY MODELS DURING THE THIRTIES AND FORTIES.

IT WAS USED PRINCIPALLY FOR POWERING ISOLATED FARM BUILDINGS.

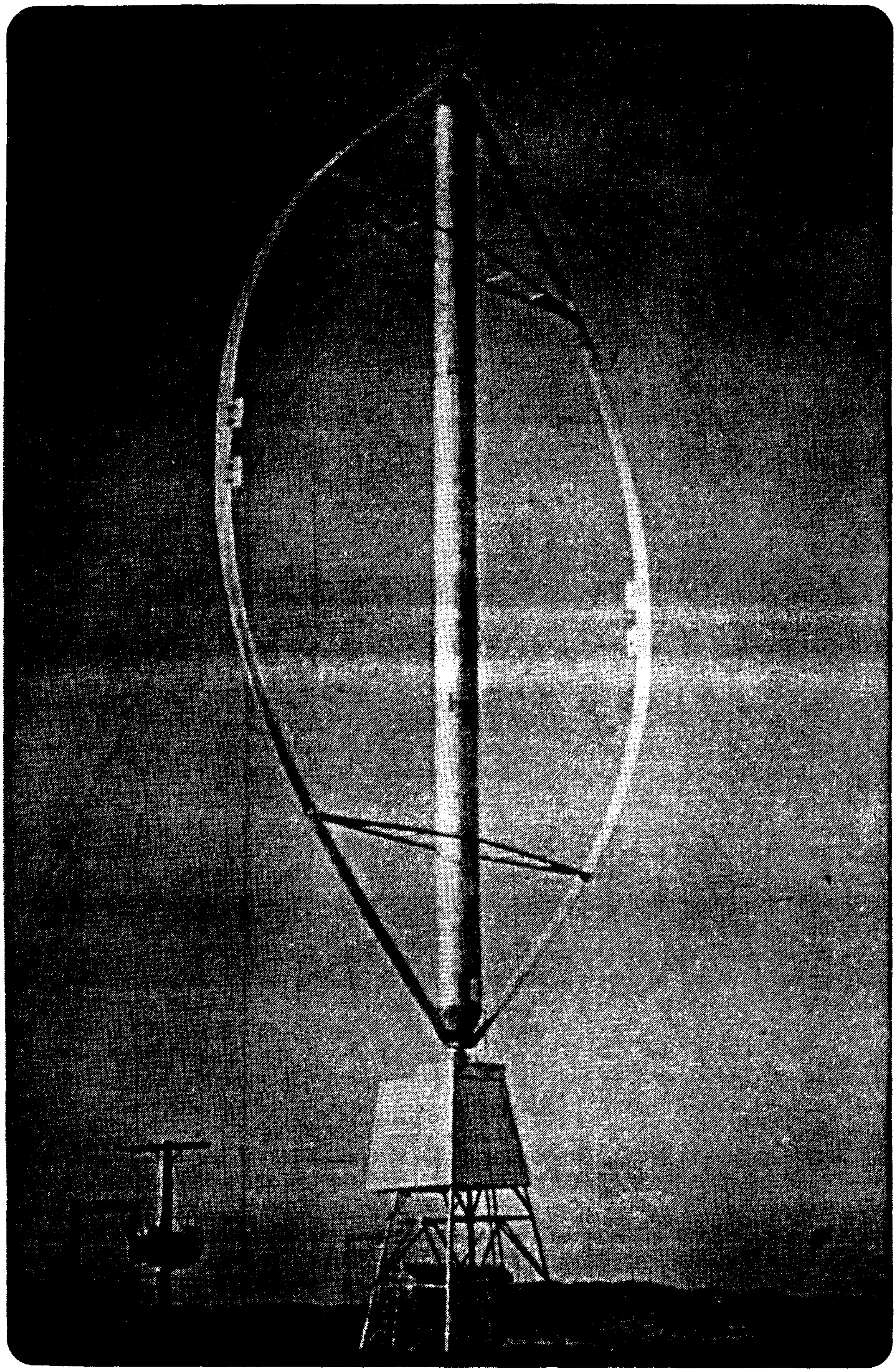
Large Wind Turbines



THIS SLIDE SHOWS THE MOD'S 1 AND 2, CURRENTLY BEING BUILT UNDER CONTRACT TO NASA-LEWIS RESEARCH CENTER, COMPARED TO THE WASHINGTON MONUMENT.

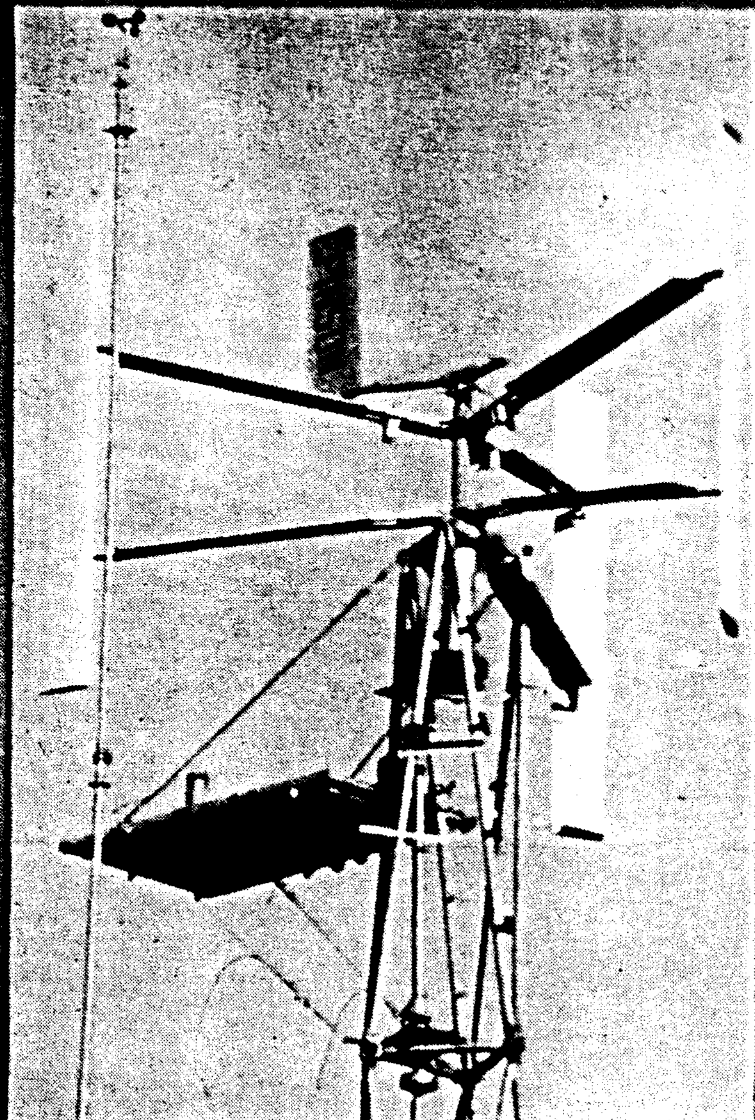
THE MOD 1 IS A DOWNWIND MACHINE RATED AT 1000 KILOWATTS ELECTRIC.

THE MOD 2 IS AN UPWIND MACHINE RATED AT 2500 KILOWATTS ELECTRIC.



VERTICAL AXIS WIND TURBINES ARE OF TWO PRINCIPAL TYPES.

THE DARRIEUS ROTOR SHOWN WAS ERECTED BY HYDRO QUEBEC AND WAS CAPABLE OF GENERATING 200 kW OF ELECTRICITY.



PINSON (C–2)

VERTICAL AXIS, 3
ALUMINUM BLADES, 12 FT.
HEIGHT, CYCLICALLY
PITCHED

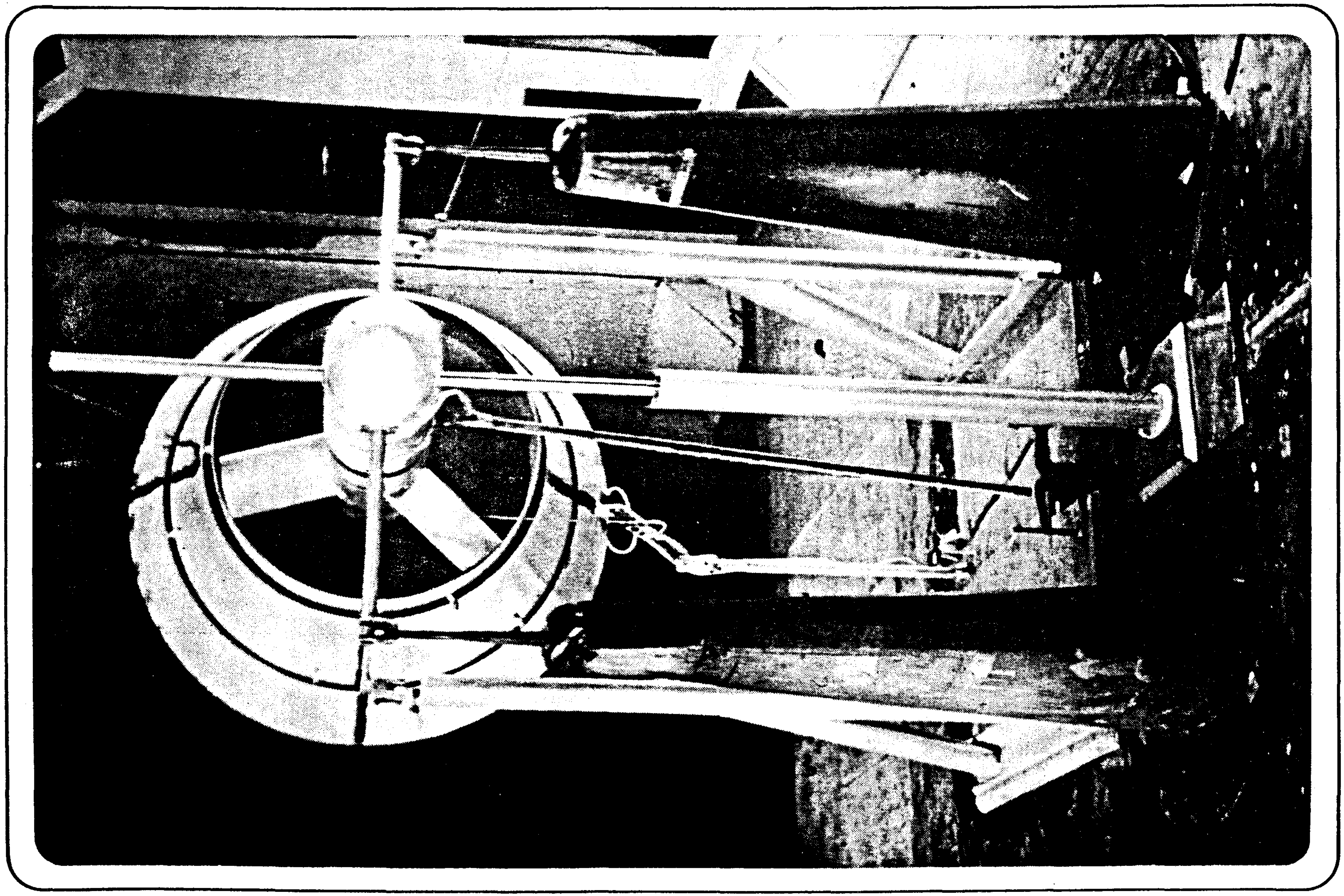
- WEIGHT — 150 LBS
- CUT-IN — 9 MPH
- CUT-OUT — N/A
  GOVERNS AT [illegible]
- RATED — 2 [illegible]
  MPH

THE GIROMILL SHOWN IS MANUFACTURED BY PINSON ENERGY SYSTEMS AND IS CAPABLE OF PRODUCING 2 KILOWATTS OF ELECTRICITY IN A 24 MPH WIND.

Wind Energy
Innovative Systems

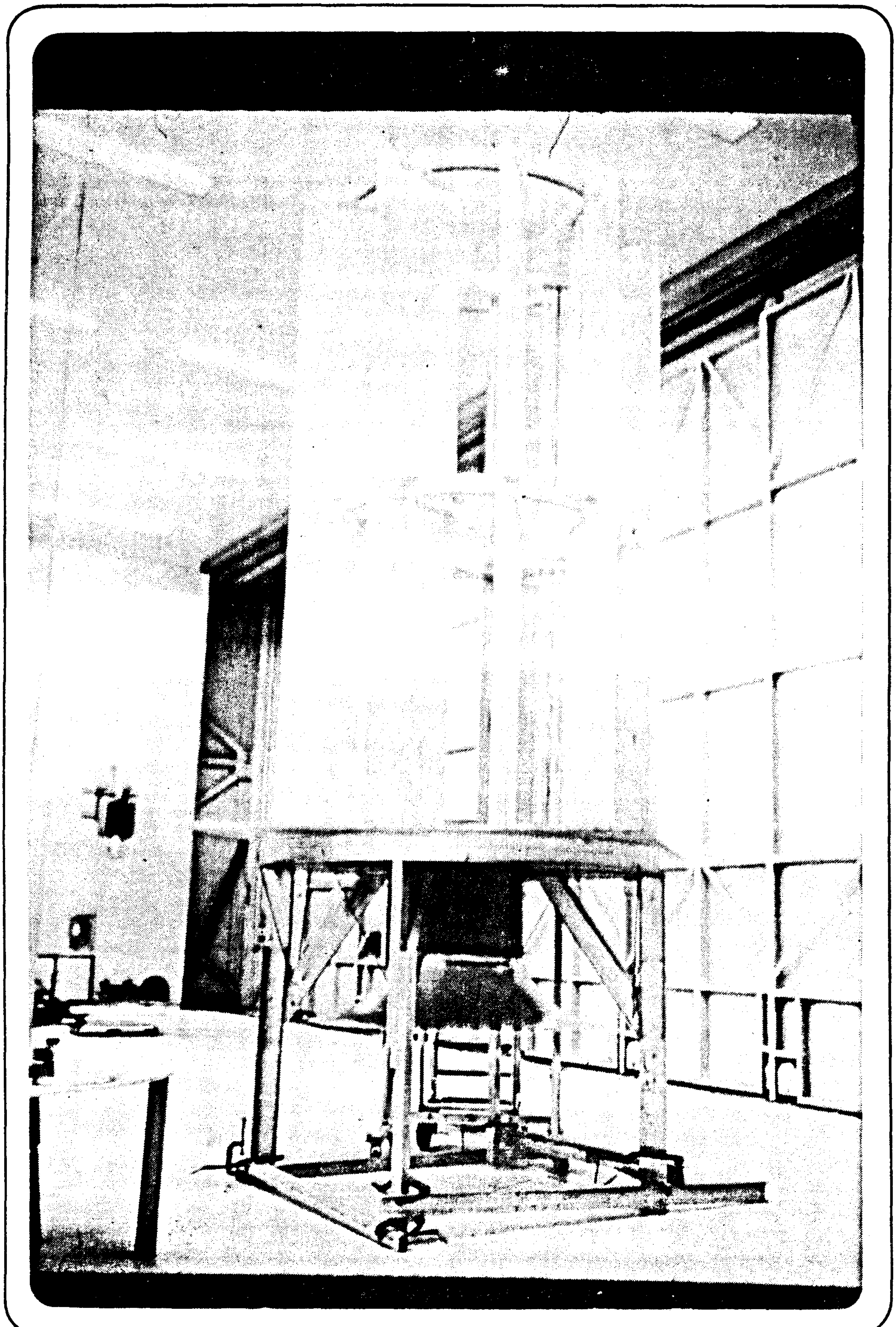
THE WIND ENERGY INNOVATIVE SYSTEMS PROGRAM IS MANAGED BY SERI.

SERI'S RESPONSIBLITY IS THE DEVELOPMENT OF INNOVATIONS WHICH MAY LEAD TO REDUCED COST OR INCREASED PERFORMANCE.



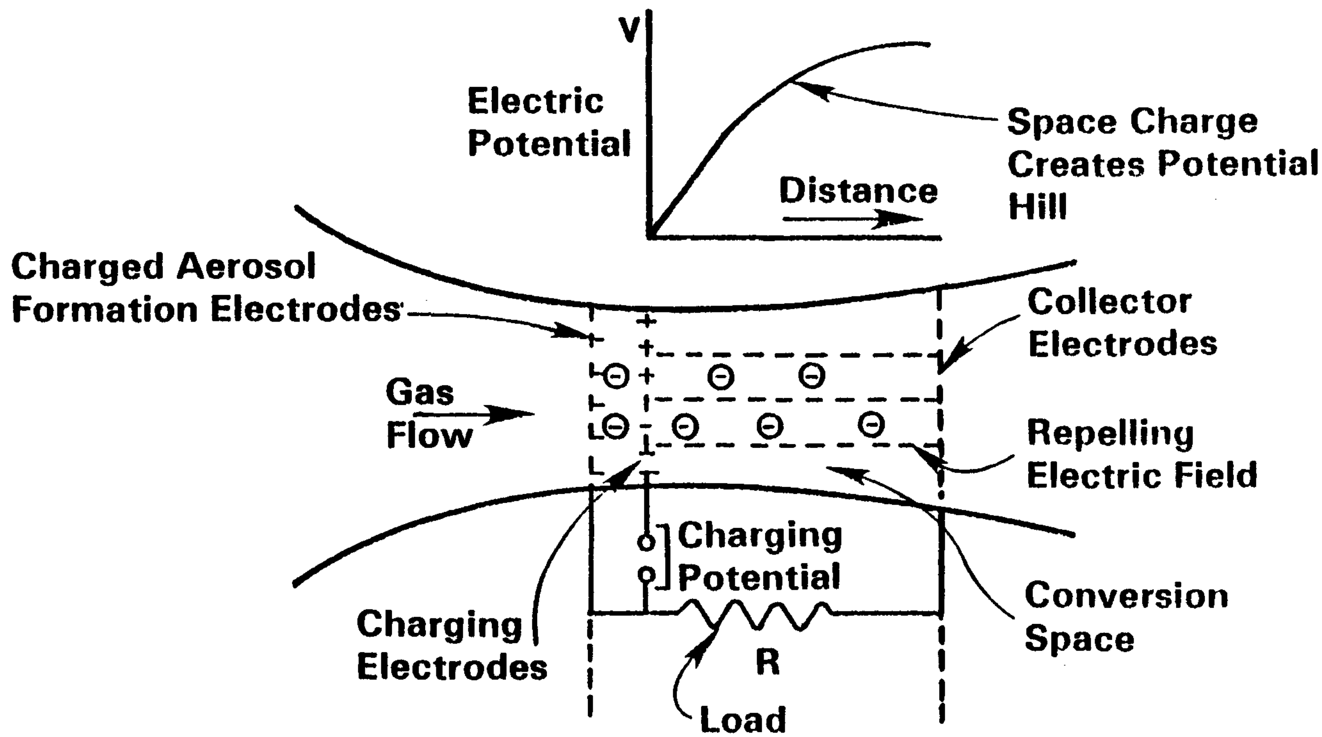
THE DIFFUSER AUGMENTED WIND TUBINE IS SHOWN.

THE DIFFUSER INCREASES THE WIND SPEED THROUGH THE ROTOR AREA INCREASING THE POWER GENERATED BY THE WIND TURBINE.



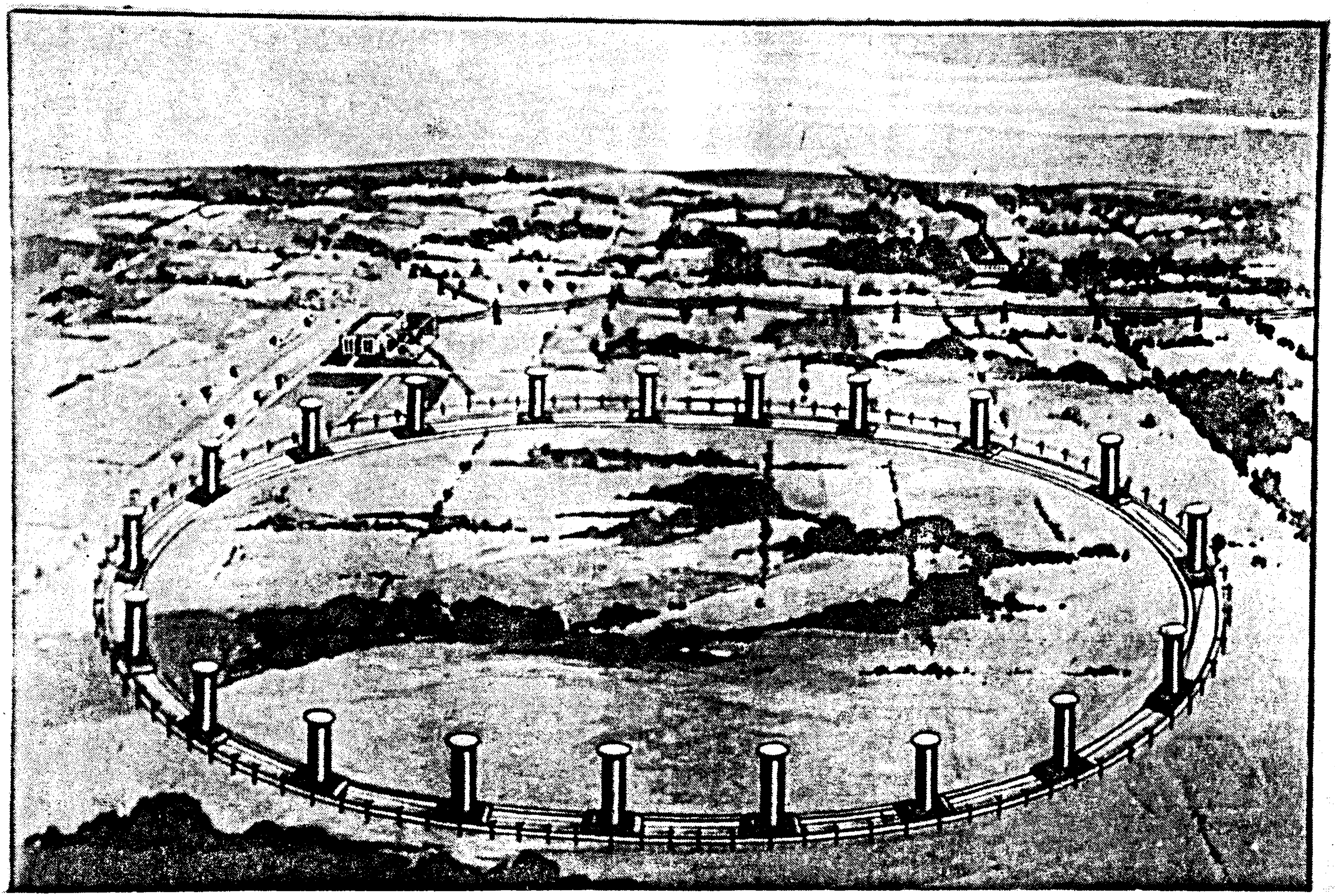
THE TORNADO WIND TURBINE ATTEMPTS TO USE ATMOSPHERIC WINDS TO GENERATE A HIGH SPEED (TORNADO-LIKE) VORTEX IN THE CENTER OF THE STRUCTURE.

THIS AREA OF LOW PRESSURE MAY THEN BE TAPPED TO SUCK AIR THROUGH A WIND TURBINE, INCREASING THE POWER PRODUCTION OF THE TURBINE.



Theoretical Model of Charged Aerosol (EFD) Generator

THE ELECTRO FLUID DYNAMIC WIND ENERGY CONVERSION SYSTEM IS A DEVICE WHICH WILL CHANGE THE MECHANICAL ENERGY OF THE WIND DIRECTLY TO ELECTRICAL ENERGY.



The Madaras rotor uses the "magnus effect" to enable an electricity generating device to move around a track generating power.

An experimental Madaras rotor was built in the thirties by a New Jersey utility to test the concept.

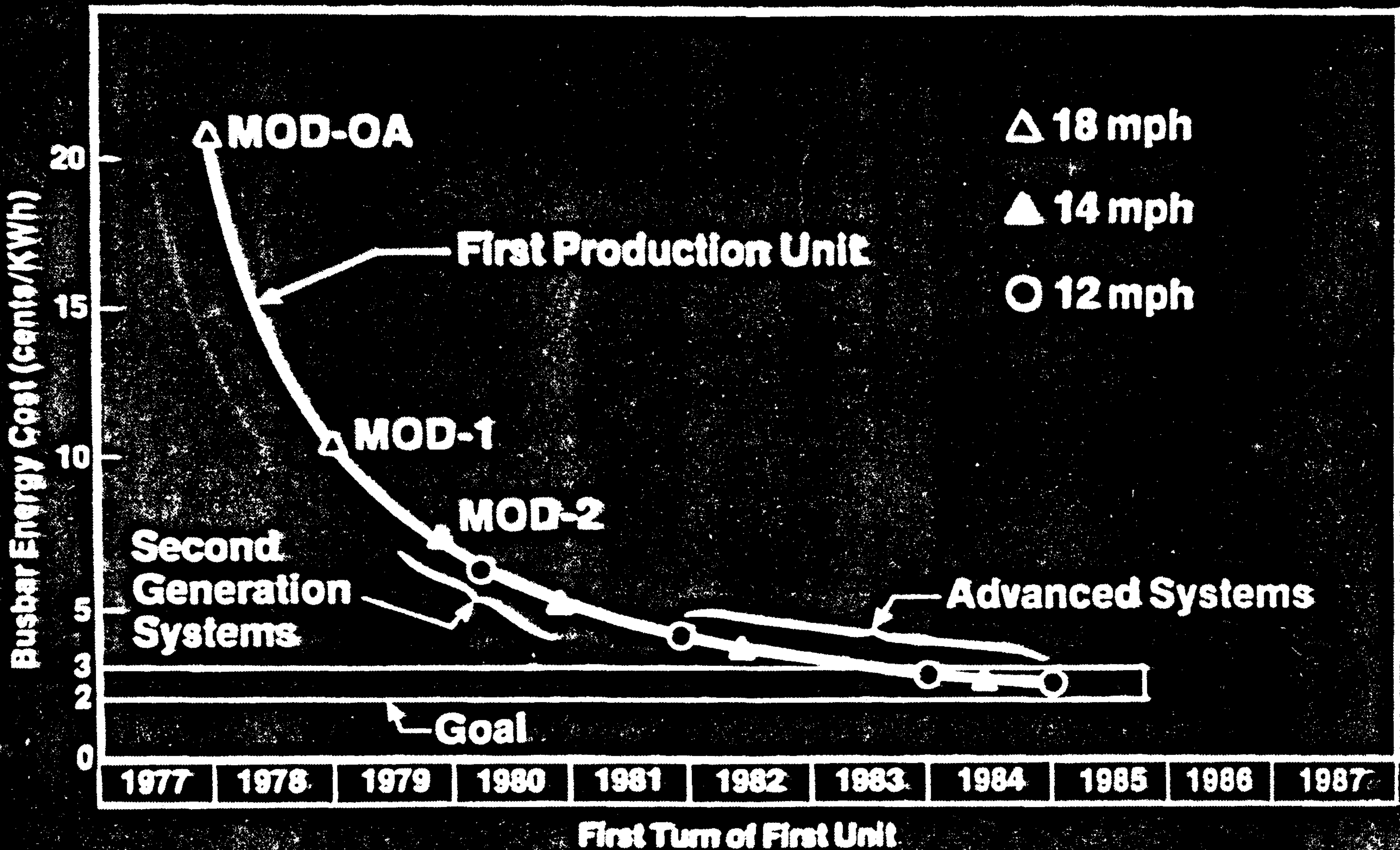
THE WIND POWER CAN HAVE MANY APPLICATIONS.

WIND POWER HAS BEEN USED TO

- GENERATE UTILITY GRADE ELECTRICITY
- PUMP WATER
- HEAT HOUSES
- POWER REFRIGERATION EQUIPMENT
- GRIND GRAIN
- POWER SHIPS

THE SLIDE SHOWS A HYBRID DEEP-WELL PUMP BEING TESTED BY THE USDA IN BUSHLAND, TEXAS.

Large WECS Cost Goal and Trend in First Production Unit Costs



THIS SLIDE REPRESENTS THE COST GOALS FOR THE FEDERAL WIND ENERGY PROGRAM.

POINTS DEPICTED ARE FOR EXISTING AND PROJECTED MACHINES.

ONCE THESE COST GOALS ARE REACHED, THE WIND GENERATED ELECTRIC POWER WILL BE COST COMPETITIVE IN MANY MARKETS.

THERE ARE STILL SOME INSTITUTIONAL ISSUES WHICH SHOULD BE ADDRESSED RELATING TO WIDESPREAD WIND TURBINE USAGE.

THESE CONSIDERATIONS MAY BE CONVENIENTLY BROKEN DOWN INTO LEGAL AND ENVIRONMENTAL ISSUES.

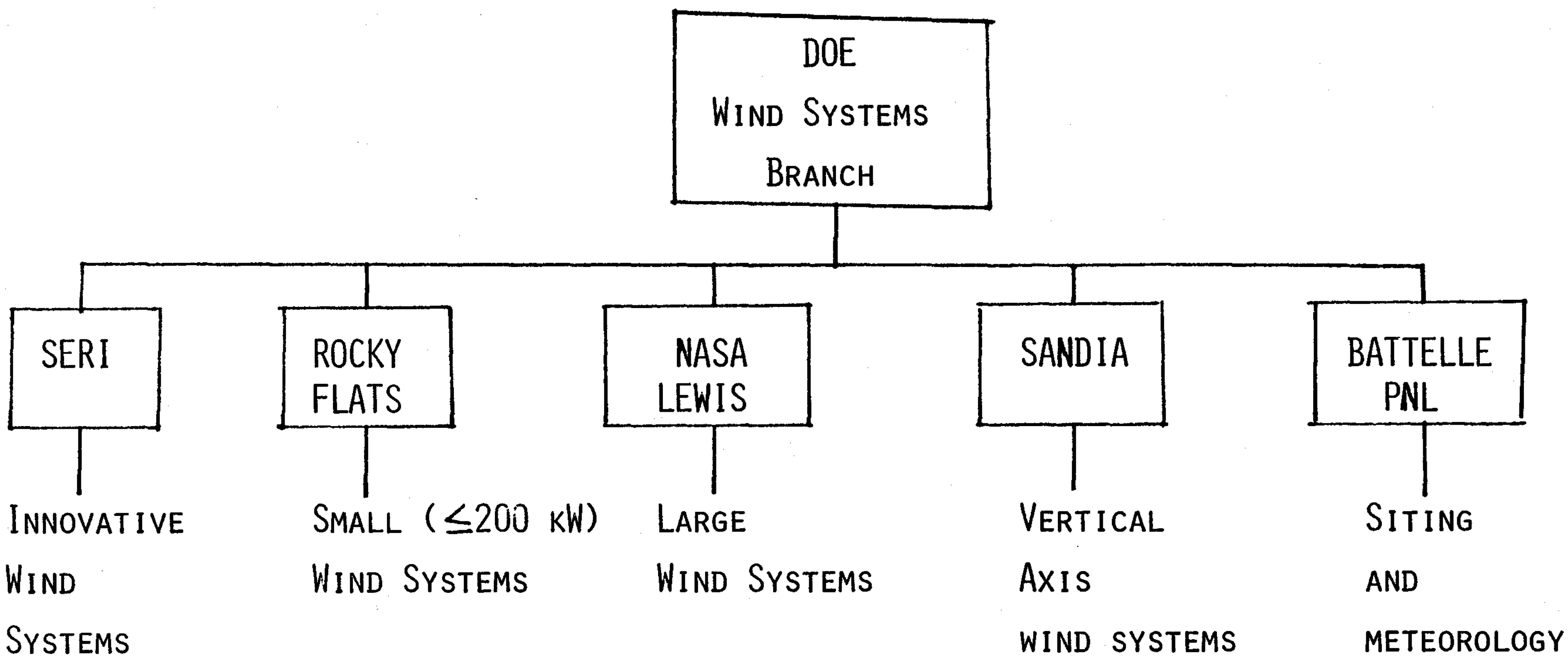
THE LEGAL ISSUES INCLUDE

- LIABILITY
- BUILDING CODES
- ZONING
- RIGHTS OF ACCESS TO THE WIND
- EXCHANGE OF ELECTRICITY WITH A HOST UTILITY
- TAX INCENTIVES

The environmental issues include

- Microclimate distrubance
- Noise
- Water and air quality degradation
- Topsoil disturbance
- Aesthetic objections
- Decommissioning of units
- Electro magnetic interference

ORGANIZATION OF FEDERAL WIND ENERGY PROGRAM



Wind Energy Systems Costs

SERI

Joseph A. Lavender

TOPICS

- Fuel Savings
- Applications
- Cost of Small Systems
- Cost of Intermediate Systems
- Cost of Large Systems
- Implementation Rates
- Cost Factors Unique to Wind
- Areas for Cost Reductions
- Summary

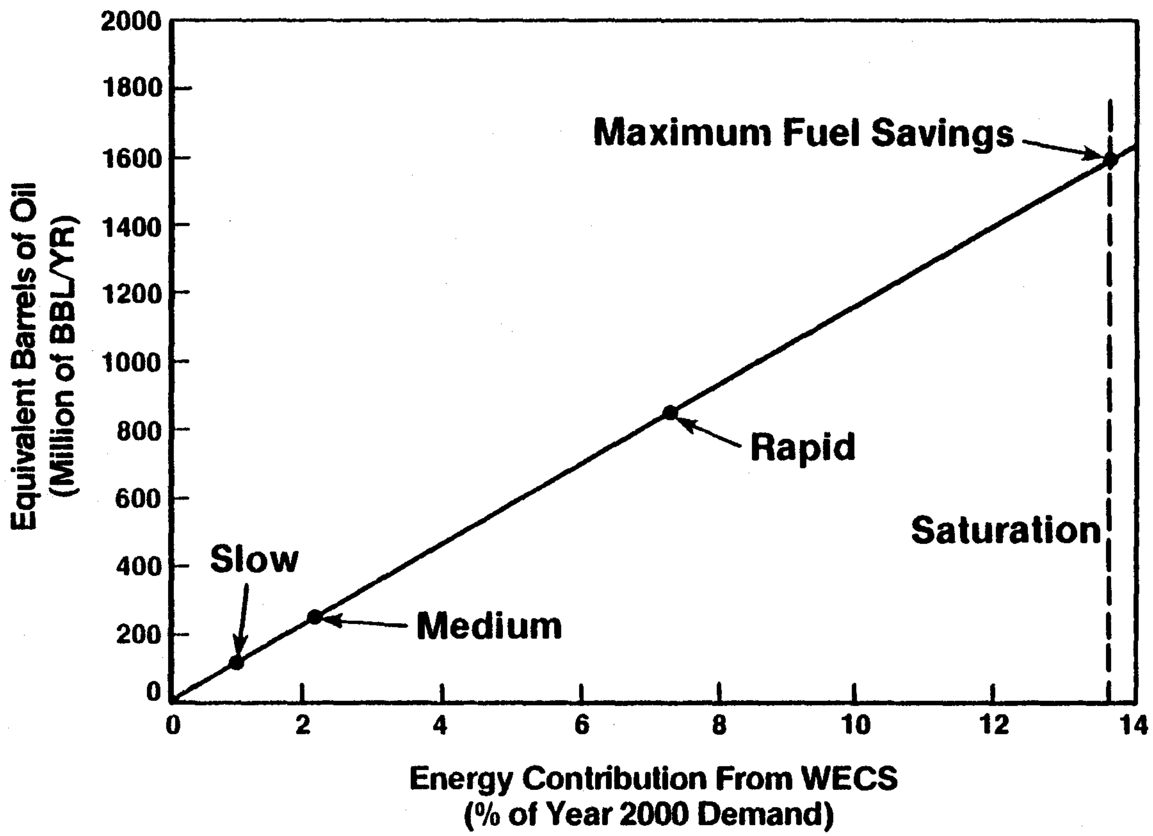
FUEL SAVINGS

Fuel savings arise primarily from displacements of the conventional fuels (nuclear and coal) and to a smaller degree, from displacements of the higher cost fossil fuels, oil and natural gas.

Over the twenty year period of RAPID implementation, (1980-2000) the cumulative savings would be 4.1 billion equivalent barrels of oil. The actual savings of oil during this time period would be 260 million barrels.

The potential fuel savings, in the year 2000 A.D., is shown in Figure 1 as a function of WECS energy contribution. The savings corresponding to SLOW, MEDIUM, and RAPID implementation are shown to illustrate the impact of implementation rate. (Ref. 3)

Fuel Savings



Annual Fuel Savings From WECS in the Year 2000 A.D.

APPLICATIONS

The single most important potential application of WECS which will yield maximum national impact is in electric utilities. This is because the utility sector annually consumes a very large portion of the nation's energy resources and serves all sectors of the economy.

WECS can be classified as an intermittent load device since it can provide power only when the wind blows. It will be used to displace generating equipment and it will be necessary to provide supplemental backup capacity to provide adequate overall system reliability. This backup capacity would most likely be in the form of gas turbines because of their low capital costs.

Between the years 1980 and 2000, WECS has the potential for a cumulative saving, depending on the implementation rate,

- between 270 million and 4 billion barrels of oil (equivalent) in nuclear, coal, oil and natural gas fuels.
- between 18 and 260 million barrels of oil.

The present cost of WECS is greater than the breakeven cost which would make it attractive to the utilities. Incremental revenue requirements are funds required to off-set the difference between WECS production costs and breakeven costs. These could be obtained in various ways-including guaranteed low cost loans, direct subsidy, or increases in the price of electricity.

RESIDENTIAL APPLICATION

The residential sector is potentially a sizeable market, conservatively estimated at 9.3 million small WECS units. With a potential for producing 207 billion kwh/year, it is the second largest application investigated. WECS will be competing with electricity at 3¢/kwh (in 1975 dollars) resulting in a high breakeven cost, and escalation in residential electricity prices over the next few years will increase the value of WECS to the homeowner even further.

The breakeven cost of value of the residential WECS depends on the investment approach of the homeowner. A conservative (low) estimate has been made by assuming WECS is financed through a conventional home mortgage and the incremental mortgage cost for the year is off-set by the savings in utility bills.

In general, adding storage capability to WECS produces a combined breakeven value above the breakeven cost of WECS alone. Storage will be most effective with large mismatches occurring between houseloads and wind availability.

Without adequate energy storage, the utility will be required to supply full electrical power to residences during wind outages. Therefore, the capital investment by the utilities in power generation equipment may not be diminished by residential use of WECS. Resolution on this issue will have an important bearing on the success of implementation in the residential sector.

PAPER INDUSTRY

The paper industry is made up of almost 600 individual plants which produced, in 1973, 62 million tons of paper and paper board. It is the fourth ranking manufacturing consumer of fuel and energy in this country, and relies heavily on on-site power generation. It has been estimated that approximately 150 plants could use WECS, and the maximum number of 1500 kw WECS units approaches one thousand.

The WECS breakeven cost in the paper industry will be very low ($186/kw) because it will be competing with low cost electricity purchased by the industry. With this low breakeven cost, and small market size (1000 units), WECS will not become cost effective in this application. Further, considering the low energy output (2.9 billion kwh) the incremental revenue requirement ($201M-$522M) is quite large.

To be successful in this application, electricity prices would have to increase considerably, or, a commitment would have to be made for implementation in the utility sector. This would increase mass production and would reduce WECS unit costs before introduction into the paper mill industry.

AGRICULTURE

The estimated size of the agricultural market for WECS is 780,000 units. Its principal use would be for irrigation pumping, crop drying, space and hot water heating, and refrigeration. This is the third largest application investigated, and has the potential for producing 43 billion kwh/year. WECS will be competing with electricity at 2.77¢/kwh (in 1975 dollars) and will reach breakeven after mass production of only 649 units (0.08% of the total market) with an incremental revenue requirement of $2.5M. This can be reduced by $1.7M, if R&D can reduce the present cost of WECS by 25%.

Serious barriers to be contended with include the possibility of penalties imposed by the utilities on farmers who use WECS, the purchase cost, and the current status of WECS as an unproven product.

REMOTE COMMUNITIES

The total market potential for wind energy in communities remote from utility service is limited; an estimated 1000 WECS units would serve most suitable candidates into the next century. Candidates include native American villages, small farm and ranch communities, island communities, rural towns and condominium or vacation home complexes. It is an excellent application for an early use of WECS, since it has the highest breakeven cost of all the applications evaluated, and can serve as a vehicle for the development of utility class WECS. Its contribution to national energy needs is small however.

WECS will be competing with on-site diesel generated electrical power costing 3.9¢/kwh, and the breakeven cost has been estimated as $626/kw.

With this high breakeven cost, breakeven occurs at 156 units with a total revenue requirement of $44.8M. If the initial cost of WECS can be reduced 25% through R&D, the incremental revenue requirement is reduced to $13M, and breakeven occurs with the 46th WECS unit.

Barriers to implementation include possible utility penalties (in those communities where, in the future, utilities may supply power), and the current status of WECS as an unproven product.

Applications: Market Size

(Saturation)

	Size of Unit (KW)	Number of Units	Capacity (GW)
Electric Utilities	1500	313,500	470
Residences	10	9,300,000	93
Agriculture	35	780,000	27
Paper Mills	1500	1,000	1.9
Remote Communities	1500	1,000	1.0

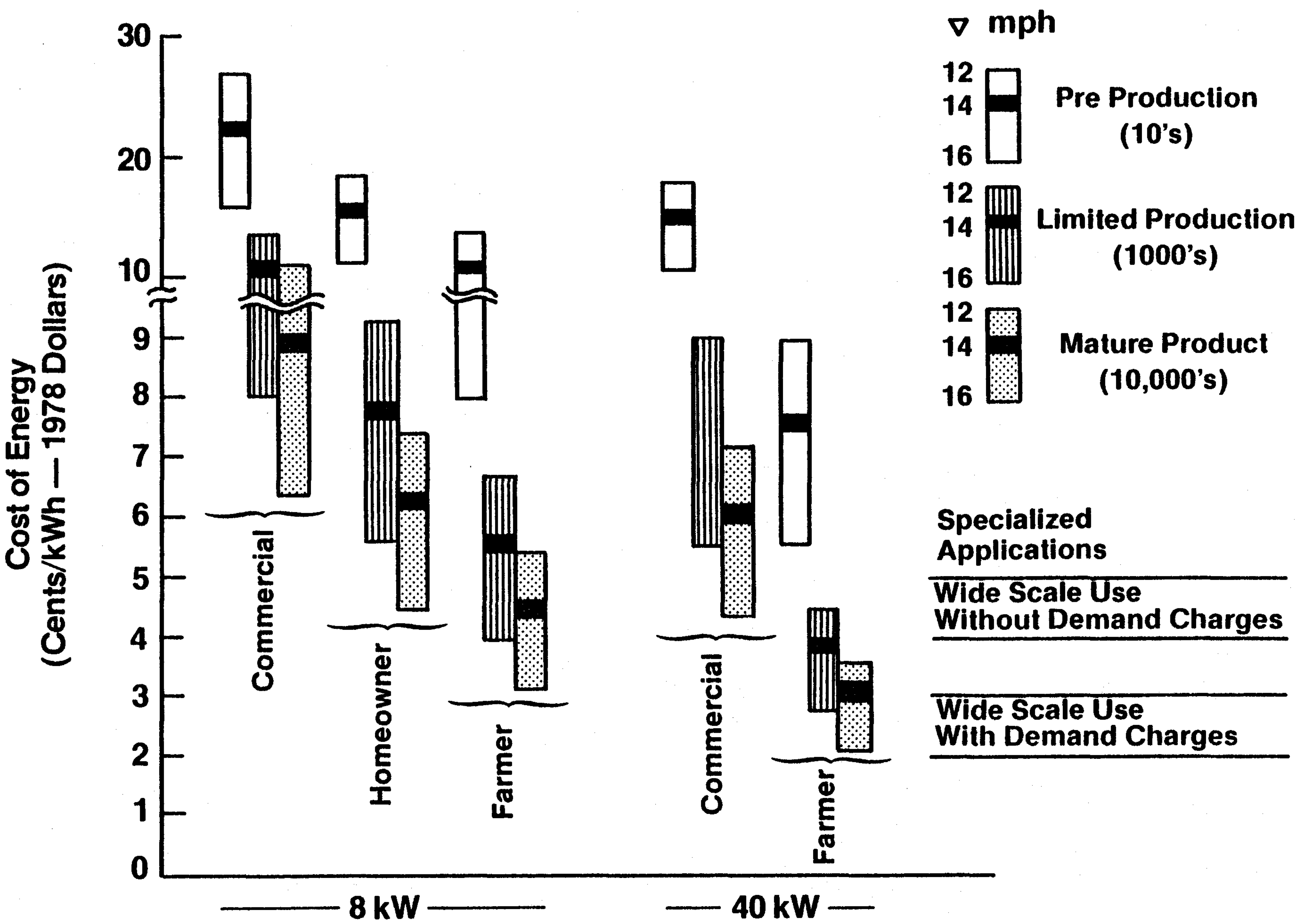
Applications: Annual Energy Output

(Saturation)

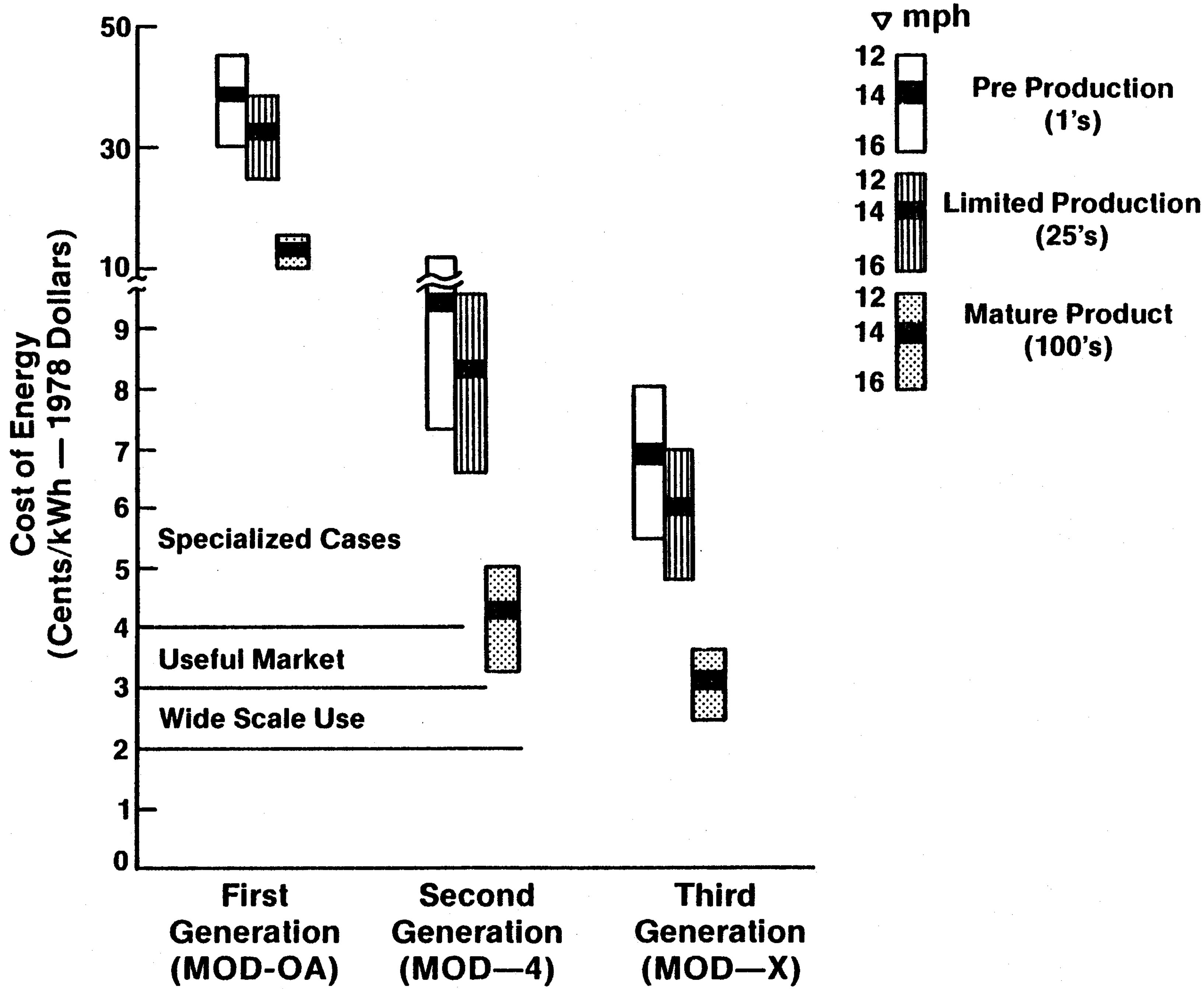
	Billion (KWH)	Quads
Electric Utilities	1070	10.7
Residences	207	2.1
Agriculture	43	.43
Paper Mills	2.9	.029
Remote Communities	2.5	.025
		13.284

U.S. Total Consumption in 1978 was approximately 78 quads.

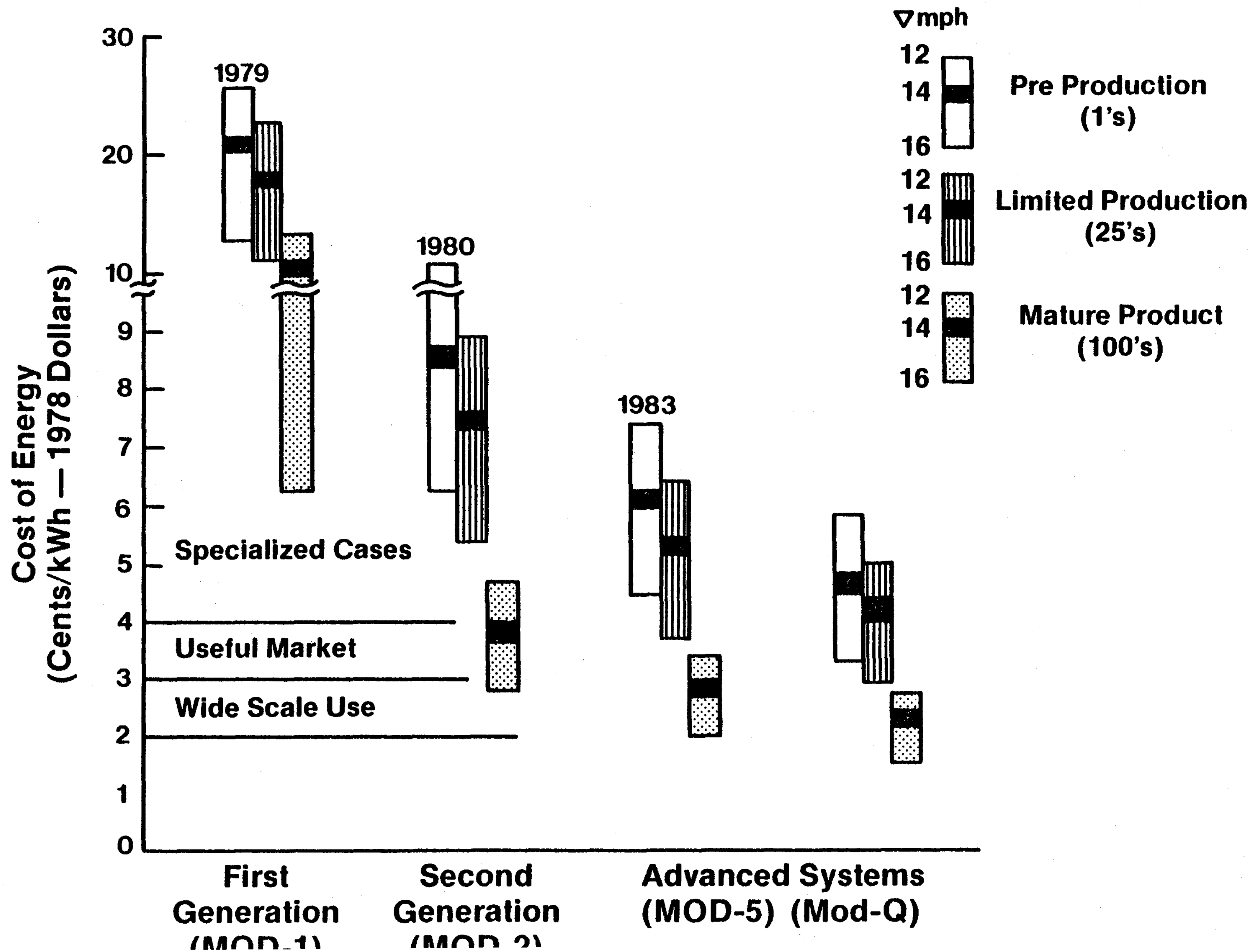
Effect of Cost-of-Money on Goals
Small Wind Systems



Cost Trends
Intermediate Wind Systems

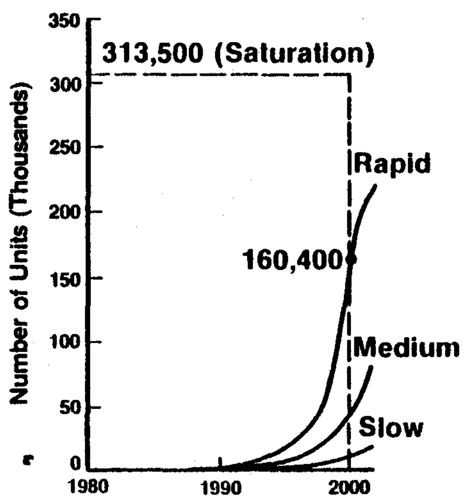


Cost Trends
Large Wind Systems

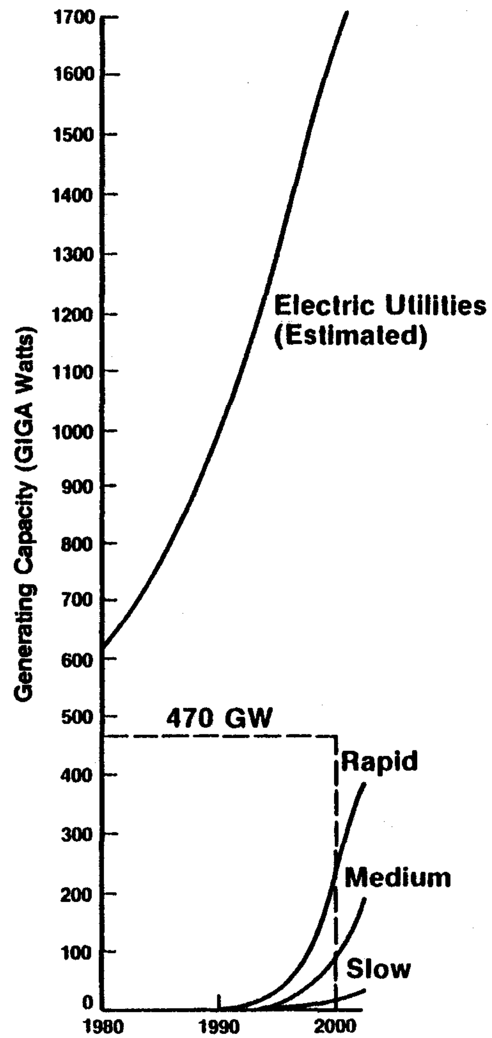


Implementation
Electric Utility

WECS Implementation Curves in Utility Sector
(Number of 1500 KW Machines)



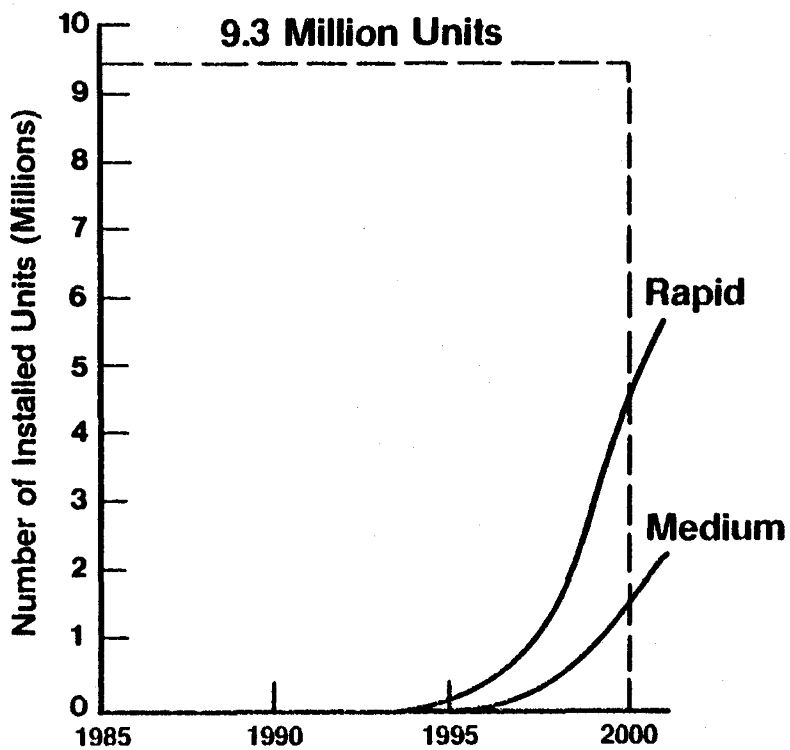
WECS Implementation Curves in Utility Sector
(WECS Installed Capacity)



Implementation

Residential Applications

WECS Implementation Curves in the Residential Sector



AREAS OF POSSIBLE COST REDUCTION

- REFINEMENT OF BLADES (STEEL, ALUMINUM, FIBERGLASS, WOOD, ETC.)
- OPTIMIZING DESIGNS AS DATA IS GATHERED FROM MOD OA AND MOD 1 PROGRAM.
- NEW INNOVATIVE CONCEPTS
- DESIGN MACHINES FOR SPECIFIC APPLICATIONS AND WIND VELOCITIES.
- THE POTENTIAL OF LARGE VERTICAL AXIS MACHINES HAS NOT BEEN EXPLORED.

COST FACTORS
(LIFE CYCLE BASIS)

COST CHARACTERISTICS WHICH ARE UNIQUE TO WIND ENERGY SYSTEMS:

- THE MOST SITE SPECIFIC OF ALL SOLAR TECHNOLOGIES (REMOTE LOCATIONS WILL RESULT IN LARGE CONSTRUCTION INDIRECT COSTS)
- HARDWARE COST IS VERY SENSITIVE TO QUANTITY OF PRODUCTION (100 OR MORE UNITS FOR LARGE SYSTEMS).
- MULTIPLE SITE INSTALLATIONS.

SUMMARY

- Wind energy can provide power to both small user and large at a cost which is becoming more competitive each day.
- Applications are numerous.
- Two types (horizontal axis and vertical axis) are being built.
- Innovative concepts are being pursued.

REFERENCES

1. Cost data from various wind manufacturers

2. Progress report, Wind Powered Distributed System Analysis
   Mitre Corporation Metrek Division, December 1978

3. Wind Energy Mission Analysis
   General Electric Space Division, February 1977

4. Wind Energy
   A Series of presentations given at the Technology Seminar for Public Constituents
   January 1979, SERI

TECHNICAL INFORMATION DISSEMINATION

BY

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INFORMATION ON WIND ENERGY

FEDERAL R&D PROGRAM IN WIND ENERGY IS PRODUCING A WEALTH OF INFORMATION CONSTANTLY.

AN INFORMATION TRANSFER SYSTEM MUST MEET FOUR MAIN CHALLENGES IN ORDER TO PROMOTE FURTHER DEVELOPMENT AND ACCELERATED COMMERCIALIZATION. THESE ARE:

1. COMMUNICATING THE RESULTS OF PUBLICLY FUNDED R&D TO ALL OTHERS INVOLVED IN RESEARCH DEVELOPMENT, MANUFACTURING AND INSTALLATION OF WIND MACHINES, SO THAT THEY MAY BENEFIT FROM THAT EXPERIENCE.

2. INFORMING THOSE WHO ARE IN A POSITION TO AFFECT TIMELY DEPLOYMENT OF WIND ENERGY OF THE LATEST RESULTS OF THE R, D AND D PROGRAMS, SO THAT THEY MAY ACT APPROPRIATELY.

3. PROVIDING INFORMATION TO THE END USER OF THE TECHNOLOGY IN A FORM USEFUL FOR DECISION-MAKING.

4. RESPONDING TO INQUIRIES FROM THE GENERAL PUBLIC ABOUT WIND ENERGY TO ENHANCE THE UNDERSTANDING OF THE PROBLEMS AND PROMISE OF WIND ENERGY.