65.
11/29/80

Dr. 636

DSE-2554-78/2(Vol.1)

AN ANALYSIS OF THE MADARAS ROTOR POWER PLANT—
AN ALTERNATE METHOD FOR EXTRACTING LARGE
AMOUNTS OF POWER FROM THE WIND

Volume 1. Executive Summary

By
Dale H. Whitford
John E. Minardi
Blaine S. West
Robert J. Dominic

MASTER

June 1978

Work Performed Under Contract No. EX-76-S-01-2554

University of Dayton Research Institute
Dayton, Ohio

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

U.S. Department of Energy

Solar Energy

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy \$5.25
Microfiche \$3.00

AN ANALYSIS OF THE MADARAS ROTOR
POWER PLANT ---- AN ALTERNATE METHOD
FOR EXTRACTING LARGE AMOUNTS OF
POWER FROM THE WIND

VOLUME 1 EXECUTIVE SUMMARY

Dale H. Whitford
John E. Minardi
Blaine S. West
Robert J. Dominic

UNIVERSITY OF DAYTON RESEARCH INSTITUTE
300 College Park Avenue
Dayton, Ohio 45469

June 1978

PREPARED FOR

THE UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT
ADMINISTRATION
DIVISION OF SOLAR ENERGY
FEDERAL WIND ENERGY PROGRAM

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ERDA CONTRACT NO. E(49-18)-2554

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *eb*

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

PROJECT SUMMARY

The purpose of the program was to analyze and up-date the design of the Madaras Rotor Power Plant concept that had been developed in the 1930's to determine the technical and economic feasibility of this system to be competitive with conventional horizontal axis wind turbines. The Madaras concept uses rotating cylinders, vertically mounted on flat cars, to react with the wind like a sail and propel an endless train of connected cars around a closed track at constant speed. Electricity is generated by alternators on each car that are geared to the wheels. Electrical power is transmitted from each car to the power house by a trolley system.

A four-task program consisting of a series of wind tunnel tests, an electro-mechanical analysis, a performance analysis, and a cost analysis was conducted. Wind tunnel tests were conducted to validate rotating cylinder data in the literature and to obtain non-existing data that relates aerodynamic performance to rotating cylinder (rotor) geometry. Supporting studies included structural design, mechanical component design, and an electrical system design to provide a realistic set of inputs to a performance trade study which provided the basis for selecting a single rotor configuration and set of operating conditions which were considered to represent a good, but not necessarily an optimum design. Studies to determine the minimum spacing between cars governed by inter-rotor aerodynamic interference also were conducted.

Drawings and specifications of the system were used to estimate costs, and parametric cost/performance computer runs were made to correlate plant cost, annual output, and energy cost as a function of plant size parameters. These cost studies incorporated appropriate learning curves to account for reduction in cost resulting from improved production techniques and increased productivity.

Primary results of this study are:

- Madaras plants having circular track plan-forms probably will not be economically attractive, but those having racetrack plan-forms appear to be of interest.

- Madaras racetrack plants appear to be competitive with a farm of MOD-1 horizontal axis machines of equal total power generation capability (to within the overall accuracy of estimation for both schemes) in cost per unit rated power and cost per unit of energy delivered. Cost comparisons were based upon estimates made in this study and estimates made by Hightower¹ and General Electric² for the MOD-1 machine. A substantial economic benefit favoring the Madaras scheme does not appear, although this possibility may exist (under more "optimal" designs determined through more detailed analysis).

- Madaras racetrack plants having rated capacities as high as 228 MW and annual energy outputs of 975×10^6 kW-hr/year were studied, and analyses indicated that even larger, more efficient plants could be developed. Thus, Madaras plants can produce energy in the quantities of interest to the electric utility industry.

- Madaras plants are more complex, have higher electrical and mechanical losses, and hence will require higher operation and maintenance costs than horizontal axis machines. Further, a racetrack plant configuration for Madaras plants limits them to regions having generally unidirectional winds (including reciprocal directions) in which large expanses of relatively flat land are available. (However, similarly-sized HA-WTG plants require twice the land area as Madaras plants.)

- At this stage of the investigation, it is not possible to state conclusively whether or not the Madaras system will significantly out-perform a similarly-sized horizontal axis wind turbine system. The Madaras system seems to outperform horizontal axis systems in the areas of structural durability, economy of scale, amount and efficiency in use of land, and possibly energy cost. Therefore, in view of this potential, it appears that an in-depth optimal design study of the system is warranted.

TABLE OF CONTENTS

SECTION	PAGE
1. BACKGROUND	1
2. WIND TUNNEL TESTS	5
3. ELECTROMECHANICAL DESIGN	13
3.1 Structural, Mechanical, Site Design	14
3.2 Electrical Design	20
4. PERFORMANCE ANALYSIS	24
5. COST/PERFORMANCE ANALYSIS	31
6. CONCLUSIONS	37

LIST OF ILLUSTRATIONS

FIGURE		PAGE
1	Madaras Rotor Power Plant.	1
2	Internal Support Tower for Madaras Rotor.	2
3	Madaras Rotor Tested in 1933 at Burlington, New Jersey.	2
4	Comparison of Lift-Drag Polars of a Rotating Cylinder and an Airfoil.	3
5	Side View, 152 mm Cylinder in Tunnel with Lower Streamlined Fairing.	7
6	Front View, 152 mm Cylinder in Tunnel with Lower Streamlined Fairing and Mirror Strut.	7
7	152 mm Diameter Cylinder and Car Ready for Simulated Boundary Test, $e/d = 3$ End Plates, $AR = 6$.	8
8	Freestream C_L and C_D versus U/V , AR of 3 and 6, and e/d Ratios of 1.25, 2, and 3, and $d = 152$ mm.	10
9	Power Required to Rotate Cylinder for Various End Cap Diameter Ratios and Two Aspect Ratios, and $d = 152$ mm.	11
10	C_L , C_D , Power versus U/V for Boundary Layer Tests for e/d Ratios of 1.25 and 2; one End Cap on Top or Two End Caps; $AR = 3$ and 6.	12
11	Typical Design Loads for 8.0 m/s (18 mph) Mean Design Wind Speed; Track Speed = 8.9 m/s.	13
12	Revised Rotor Car Configuration.	15
13	Rotor Car End Truck Assembly.	16
14	Plant Layout.	19
15	Optimum Motor Size and Maximum Power Output versus Track Diameter, 13.4 m/s (30 mph) Wind Speed.	21
16	Electrical Schematic of Circuitry on Each Rotor Car.	23
17	Net Power Output for One Rotor, Spin Motor Power, and Motor rpm versus Rotor Position on Track as Affected by Use of Viscous Braking, Regenerative Braking, and a Three-Step Transmission to Vary the Spin Schedule.	26

LIST OF ILLUSTRATIONS (Concluded)

FIGURE		PAGE
18	Net Power Output from one Rotor versus λ as a Function of Wind Speed. Performance is Presented for Both a 1370 m (4500 ft) Diameter Circular Track and a Racetrack having 1370 m (4500 ft) Diameter Ends and 4880 M (16,000 ft) Straight Sections.	27
19	Mutual Interference Loss Factor versus Wind Speed for Various Numbers of Rotors on a 1524-m Diameter Track. Constant Rotor Speed and Track Speed of 186 rpm and 13.4 m/s, Respectively.	29
20	Modified Design Wind Duration Curve to Represent Wind Conditions at a Rotor Mid-Height of 25 m (82 ft) Above Mean Terrain Level.	30
21	Power Duration Curves for the Two Plants Shown in Figure 6.14 Based on the $\bar{V} = 9.6$ m/s Design Wind Duration Curve at 25-m Height (Figure 6.13).	30
22	Unit Plant Cost versus Rated Power for Racetrack Configuration as a Function of Inter-Rotor Spacing, Length of Straight Section of Track, and Number of Rotors. DOE Design Wind Duration Curve: $\bar{V} = 8.1$ m/s @ 9 m.	32
23	Energy Cost versus Rated Power for Racetrack Configuration as a Function of Inter-Rotor Spacing, Length of Straight Section of Track, and Number of Rotors. DOE Design Wind Duration Curve: $\bar{V} = 8.1$ m/s @ 9 m.	32

LIST OF TABLES

TABLE		PAGE
1	Wind Tunnel Test Conditions	6
2	Effect of Land Cost, Learning Curves, and Mean Wind Speed ($\bar{V}$) on Plant and Energy Cost	33
3	Overall Comparison of Several Madaras and HA-WTG Plants at Two Wind Regions	36

FOREWORD

This final report describes the study conducted by the University of Dayton Research Institute on Contract E(49-18)-2554, sponsored by the Wind Systems Branch, Division of Solar Energy, United States Energy Research and Development Administration (now the Department of Energy). The program was later transferred to the Solar Energy Research Institute. Project monitors on the program were Dr. Robert Thresher for ERDA and Dr. Irwin E. Vas for SERI.

The study was under direction of Mr. Dale H. Whitford, who, with Dr. John E. Minardi, conducted the preliminary performance analyses, planned the wind tunnel tests, and analyzed the wind tunnel test data. Mr. Levere F. Starner and Mr. Blaine S. West were responsible for the structural analysis study, and Mr. Robert J. Dominic conducted the electrical analysis.

The authors wish to express their appreciation for the excellent contribution to this program made by the personnel of the Gas Dynamics Laboratory, Aerospace Engineering Department, University of Michigan. Overall guidance, assistance in developing the test plan, development of the method for generating the simulated atmospheric boundary layer, and coordinating all aspects of the University of Michigan effort was provided by Professor William W. Willmarth. Test supervision and scheduling of support for the tests was provided by Mr. David R. Glass. Mr. Daniel O. Scharf was responsible for directing tests and processing the data, and Mr. Charles Hogan, Mr. Leo Griffin, and Mr. Cletus Iott were responsible for instrumentation, model installation, and operation of the wind tunnel.

We also want to acknowledge other major contributions: the vortex analysis study conducted by Professor Harold Larsen of the Air Force Institute of Technology; the detailed structural and mechanical design layout done by Mr. Francis Shannon of Maier and Associates; the economic analysis conducted by

Mr. John L. McClellan; and the aerodynamic consultation provided by Dr. Frank L. Wattendorf.

We are especially appreciative of the support of the Detroit Edison Company and the assistance given by Mr. Walker L. Cisler, former Chairman of the Board of that Company; the consultation provided by Mr. Russell F. Hardy, former Chief Engineer of the Madaras Rotor Power Project; and the helpful comments and critique of this work given by Dr. E.E. Lapin of the Aerospace Corporation.

EXECUTIVE SUMMARY

1. BACKGROUND

Analytical studies, wind tunnel experiments, and full-scale aerodynamic tests of the wind-powered, Madaras Rotor Power Plant were conducted in the 1929 to 1934 time period. This system invented by Julius D. Madaras consisted of 27.4-m high by 6.8-m diameter cylinders which were vertically mounted on flat cars and rotated by electric motors to convert wind energy to Magnus-effect forces. The forces propelled an endless train of 18 cars around a 457-m diameter, closed track (Figure 1).

Figure 1. Madaras Rotor Power Plant.

Alternators geared to the car axles were calculated to produce up to 18 MW of electric power at a 8.9 m/s track speed in a 13.4 m/s wind. Twice during each orbit of a rotor car around the track (at points $\pm 90^\circ$ from the wind), each spinning rotor in turn must be de-spun to a stop, and then spun-up in the opposite direction. This cycle is necessary in order to assure that the propulsive force changes direction so that all rotors are propelling the train in the same angular direction.

Force measurements obtained from a full-size rotating cylinder mounted on a stationary platform (Figures 2 and 3) proved that the concept was technically feasible, but the project was discontinued prior to pilot plant demonstration because of the Depression. The reason for using a rotating cylinder instead of an airfoil to propel the train is that a rotating cylinder generates a lift force about ten times larger than that of an airfoil (Figure 4 shows lift-coefficient, C_L , versus drag coefficient C_D .)

Figure 2. Internal Support Tower for Madaras Rotor.

Figure 3. Madaras Rotor Tested in 1933 at Burlington, New Jersey.

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

The University of Dayton Research Institute has conducted studies of the Madaras system to verify the initial computations made by Madaras and his co-workers. These studies have included

a thorough review of the literature of the Madaras program (contained in a set of 14 unpublished technical reports obtained from Detroit Edison) as well as discussions with two key men who

Figure 4. Comparison of Lift- Drag Polars of a Rotating Cylinder and an Airfoil.

had worked with the original Madaras project. One of these men is Mr. Russell F. Hardy who was the Chief Engineer of the Madaras Rotor Power Corporation, and the other is Mr. Walker Cisler, who recently retired from the position of Chairman of the Board of the Detroit Edison Company. Our studies also have included a review of all wind tunnel tests on rotating cylinders conducted since the mid 1920's, performance simulation studies, and economic analysis.

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

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

The research into the Madaras system conducted by the University of Dayton Research Institute (UDRI) prior to this program lead to several unanswered questions concerning the system. These questions were:

- What is the fewest number of rotors required to extract the maximum amount of power per unit land area from the wind?
- What aerodynamic performance can be expected from full-sized cylinders operating in the lower levels of the atomospheric boundary layers in terms of the various geometric and operational design variables which affect performance?
- What are the design requirements for structural, electrical and mechanical subsystems; and what performance of a Madaras system can be expected when modern, commercially-available electrical and mechanical components are used?
- What is the capital cost and the cost of electric power generated by modernized Madaras plants of different sizes in various climatic areas of the United States?

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

- This was a conceptual design trade study of the basic system proposed by Madaras. Only off-the-shelf hardware and available technology were to be used. Thus a system design optimization analysis was beyond the scope of the program.
- Design wind conditions included:
 - Wind duration curves having 8.1 m/s mean wind speed at 9 m height above ground.
 - Structure must withstand winds of 53.6 m/s with the rotor train standing still on the track.
 - Structure must be able to operate in wind gusts to 26.8 m/s while operating at the rated wind speed of 13.4 m/s.
- Design life of 30 years for rotating parts and 50 years for static parts.

- System must withstand hail up to 2.5 cm diameter, operate in a temperature range of -51°C to $+49^{\circ}\text{C}$, and operate in snow, rain, lightning, icing, salt vapor, and windblown sand and dust.

2. WIND TUNNEL TESTS

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

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

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

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

Over 200 test runs were conducted in the overall test series. A summary of the test conditions is presented in Table 1.

A unique aspect of the test series was the series of tests conducted in a simulated atmospheric boundary layer. For these tests, a boundary layer similar to that of wind blowing over grassy plains was simulated by wooden quarter-round strips

TABLE 1
WIND TUNNEL TEST CONDITIONS

Test Variables	Test Combinations	
	50 mm	152 mm
Cylinder Diameter		
Aspect Ratio (AR)	4	3,4,5,6
End Plate Diameter to Cylinder Diameter Ratio (e/d)	1, 2, 3	1.25,2,3
Free-Stream Reynolds Number Range	2×10^4 to 7.4×10^4	7×10^4 to 3×10^5
Cylinder Surface Speed to Wind Speed Ratio (U/V)	0 - 6	0 - 6
Number of End Plates	1, 2	1, 2
Type Flow		
Free Stream	x	x
Atmospheric Boundary Layer	x	x
Cylinder on Model Car	x	x
Cylinder and Car on Embankment		x

placed traverse to the wind flow along the floor of the tunnel. These strips which were placed at 0.3 m intervals from the entrance to the 6.1-m-long test section up to the model, simulated the boundary layer profile quite well across the width of the tunnel.

Typical photographs of the 152 mm test model during the free stream tests are shown in Figures 5 and 6, and a typical boundary layer test model is shown in Figure 7.

It can be seen that the free stream tests were conducted with either a bottom fairing or both a bottom and top fairing. Actually, the bottom fairing was used to isolate the model support sting (which was mounted to the balance system) from the air flow. The top fairing was merely a mirror-image strut that was not fastened to the model, but which cleared the top of the model by about 0.8 mm. By comparing data obtained with the single and double fairings, the effect of the fairing on the aerodynamic coefficients was ascertained, and then the data were corrected accordingly. No correction of this sort was required for the boundary layer tests.

Figure 5. Side View, 152 mm Cylinder in Tunnel With Lower Streamlined Fairing.

Figure 6. Front View, 152 mm Cylinder in Tunnel With Lower Streamlined Fairing Only and Mirror Strut.

Figure 7. 152 mm Diameter Cylinder and Car Ready for Simulated Boundary Layer Test, $e/d = 3$ End Plates, $AR = 6$.

Typical free stream test results for the shortest aspect ratio ($AR = 3$) and longest ($AR = 6$) cylinder for all of the three end plate sizes (e/d ratio) are presented in Figure 8. Here, the lift and drag coefficients are plotted as a function of U/V , the surface speed of the rotor divided by the wind speed. This parameter is analogous to the angle of attack of an airfoil. Results conformed with our expectations, and curve shapes and magnitudes correlated well with previously-published data for comparable geometries. Primary observations of importance are:

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

The power required to rotate the cylinder is presented in Figure 9. Two observations are of particular importance:

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

Thus, by combining the observations from Figures 8 and 9, it appeared that a good design would be achieved for a rotor having $AR = 6$ and $e/d = 2$. This combination would provide high lift, low drag, and reasonable power levels for spinning the rotor. We also concluded that aspect ratios greater than 6 might be even more attractive; however, since wind tunnel size prevented testing a larger cylinder, data for larger aspect ratios would have to be obtained by extrapolation and use of the conventional induced drag equation which is a function of C_L^2 and AR .

Although not presented in the interest of brevity, measurements of lift moment and drag moment also were obtained

Figure 8. Freestream C_L and C_D versus U/V , AR of 3 and 6, and e/d Ratios of 1.25, 2, and 3, and $d = 152$ mm.

Figure 9. Power Required to Rotate Cylinder for Various End Cap Diameter Ratios and Two Aspect Ratios, and $d = 152$ mm.

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

Typical boundary layer data are presented in Figure 10. As with the freestream results, the data trends and accuracy are satisfactory, and the data verified well our predicted centroid positions by our model.

Figure 10. C_L , C_D , Power versus U/V for Boundary Layer Tests for e/d Ratios of 1.25 and 2; One End Cap on Top or Two End Caps; $AR = 3$ and 6.

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

3. ELECTROMECHANICAL DESIGN

Design loads on the rotor, rotor support, tower car, and track were developed from inputting the design criteria into our Madaras performance simulation program, which predicts the forces on the various components as a function of angular position on the track. Typical aerodynamic loads normal and tangential to the track for an operational wind condition are shown for one-half of the orbit in Figure 11. The loads for the other orbit half are the same.

Figure 11. Typical Design Loads for 8.0 m/s (18 mph) Mean Design Wind Speed; Track Speed = 8.9 m/s.

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

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

3.1 Structural, Mechanical, Site Design

The rotor car design concept which evolved from our studies is depicted in Figure 12. A summary of the overall design follows:

- Dimensions
 - $AR = 8$
 - $e/d = 2$
 - Cylinder length = 38.1 m (125 ft)
 - Cylinder diameter = 4.9 m (16 ft)
 - End cap diameter = 9.8 m (32 ft)
 - Track gauge = 11.0 m (36 ft)
 - Car length = 19.2 m (63 ft)
 - Car height = 3.8 m (12.5 ft)
 - Car width = 17.4 m (57 ft)
 - Gross car weight = 328,000 Kg (723,000 lb)
- Structural Configuration and Materials
 - Rotor: Semimonocoque, longer on trusses, circumferential truss stiffeners, and circumferentially corrugated skin. All 2024-T4 Alclad aluminum alloy.
 - Cap: Semimonocoque, radial trusses at 45° increments, stressed skin. All 2024-T4 Alclad aluminum alloy.

Figure 12. Revised Rotor Car Configuration.

The primary consideration given to materials for the rotor was reduced weight and reduced stresses caused by high body stresses resulting from the high centrifugal forces resulting from rotation at 186 rpm. Alclad aluminum alloy provided the best design from the stress and corrosion resistance standpoints.

Weight was not a problem for the car and the rotor support tower, so steel was used. Corrosion resistant steel was used on all weather surfaces.

The design condition governing overall car weight was completely unexpected: the weight of 328,000 Kg (723,000 lb) was required to provide a sufficiently large wheel normal force and hence frictional force to drive the 250 kW generator without slipping.

Another consideration in the structural design was to divide the rotor and car structure into modules and segments so that factory prefabricated units could be mass-produced and delivered to the site for final assembly. For example, the rotor cylinder and cap would be fabricated in eight 45° segments (relative to the circular cross-section) in lengths that could be shipped by truck or railway car.

Major mechanical components in addition to the suspension system shown in Figure 13 include the rotor spin system gearing, drive shaft, drive gears, and the rotor bearings, shown in Figure 12. Of particular interest are the upper and lower rotor support bearings, which are very large. The upper bearing supports the entire rotor weight and supports the relatively small amount of radial load present at this location, whereas the lower bearing reacts only radial loads. Bearings sizes are:

- Upper bearing: 256 m (8.39 ft) OD by 2.01 m (6.60 ft) ID, roller bearing.
- Lower bearing: 3.39 m (11.11 ft) OD by 3.21 m (10.55 ft), ID, cylindrical roller bearing.

All bearing loads will be transmitted to the tower, and thence to the rotor car.

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

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

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

A typical site layout, road bed, and rail configuration is shown in Figure 14. A racetrack configuration is envisioned; however, actual track length and diameter will be larger than that shown in Figure 14. The site included:

- Cross-section service road around the outside of the track.
- A spur track leading to an assembly-maintenance, and a control building.
- Drains, utilities, roadbed, and track.
- Trolleys, power distribution, and telemetered control system.
- Two viaducts under the track to facilitate access to the "in-field" portion of the track in order that the land can be used for agriculture.

The roadbed will consist of two parallel independent tracks. Each track will be built as follows:

- An excavated, well-compacted soil base.
- A 1.6-m high ballast foundation of crushed coarse and fine aggregate.

Figure 14. Plant Layout.

- A 36-cm-thick by 2.4-m-wide pavement of steel reinforced concrete.
- A flat rail made of 51-cm wide by 10-cm thick steel bolted to the concrete pavement every 1.2-m of track length.

3.2 Electrical Design

The electrical design considered four components.

- Rotor Spin System
- Control and Instrumentation System
- Generator System
- Electrical Interface System

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

One of the major results of the spin motor study was the discovery that there were three sources of spin motor losses, that these losses were highly significant, and that Madaras considered only one of these loss mechanisms. These loss sources are:

- Power required to overcome the viscous friction of the rotor caused by spinning (the only one considered by Madaras).
- Power required to overcome rotor inertia while accelerating the rotor from 0 to 186 rpm, and the loss in power during rotor deceleration (Madaras assumed complete recovery of the inertial energy of the spinning rotor by regenerative braking).

- Power lost in heating motor windings during the low speed, acceleration stage during which time the motor is operating at very low efficiency (i.e., from 0 to 45 percent efficiency as the motor speed increases slowly from 0 to 70 percent of no-load speed).

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

Madaras also erred when he assumed full capture of the spinning rotors inertial energy by regenerative braking. However, even during braking, viscous friction absorbs considerable amounts of power before it is available for regenerative braking, and then the "motor-turned-generator" heating losses (like the third type of motor heating loss above) absorb so much power,

that there is only about 3 percent of the power originally input to the spin motor can be recovered during regenerative braking. Thus, we elected to use natural viscous forces to de-spin the rotor in order to save wear on the spin motor and to reduce the cost of power transfer equipment.

Figure 15. Optimum Motor Size and Maximum Power Output versus Track Diameter, 13.4 m/s (30 mph) Wind Speed.

The selection of the 450 kW size for the spin motor was governed by a trade study utilizing our Madaras plant performance simulation study. The results of this study are shown in Figure 15. From this study, we decided that a good design point occurred at a 450 kW motor size and a 1372 m (4500 ft) track diameter. This curve is for a circular track; however, as will

be described later, a racetrack pattern improves performance considerably over that in Figure 15.

The generator selected for the Madaras system was sized for 1 MW rated output from each rotor car at a rated wind speed of 13.4 m/s. A three-phase, 60 Hz alternating current induction generator was considered to be the best for a Madaras plant. Although a synchronous generator is more efficient, the problems of aligning and maintaining precisely in phase all generators on all rotor cars in a plant seemed to outweigh the added efficiency one would gain from a synchronous generator. Since it is planned to use four 250 kW generators on each rotor car (because of wheel drive torque limitations mentioned in the structural section) the alignment problem is more severe. Then, because of possible variations in car speed caused by stretching and contracting of the interconnecting cables as well as possible wheel slippage, additional circulating current power losses could be realized.

It is believed that the efficiency of the induction generator would be in the 80 percent to 85 percent range, with a leading power factor of from 0.8 to 0.9. This power factor would be corrected by a synchronous reactor system at the control building distribution station.

A schematic diagram of the complete electrical system on each rotor car is presented in Figure 16.

The control system will include the following components:

- A minicomputer-based primary controller in the control house.
- A microcomputer-based controller on each car.
- A two-way radio telemetry system to link all the car units to the primary controller.
- A wind sensor network dispersed around the track and hard wired underground to the primary controller.
- Monitoring instruments and control actuator circuits on each car and on system network components.

Figure 16. Electrical Schematic of Circuitry on Each Rotor Car.

- An operators station in the control house consisting of monitoring instruments and manual over-rides of the primary controller.

Standard equipment would be used for these items, so further description is not warranted in the summary. Power plant control would be automatic; however, CRT, panel displays, and hard copy readouts would be available for monitoring and manual control modes also would be provided.

System network elements required to interface with the various electrical subsystems include:

- Car trolley and feeder bus (4160V, 3 phase, 500 ampere capacity).
- Distribution circuit to the trolley feeder bus (power pick-off from the trolley every three-and-one-half rotor car spacings to limit trolley amperage to 500 amperes).
- Synchronous reactors for power factor correction.
- Utility feeder circuits.
- Substation.

The system network components would be 4160V, 60 Hz, 3 phase equipment. The substation would include transformers to interface the system with the commercial power grid as well as those to produce 480 V, 3 phase and 120 V 1 phase power for utility circuits used for lighting and plant equipment.

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

4. PERFORMANCE ANALYSIS

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

Objectives of the major investigations in the design trade study were to select for final cost analysis:

- Most efficient rotor geometry and size
- Spin motor size and track diameter (already described in Figure 15).
- Track speed and rotor rpm.
- Spin motor schedule.

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

Our Madaras plant performance simulation program was used for this study. This program has provisions for inputting all data, geometrical and operational parameters, and all losses developed in the earlier studies, and simulates plant performance for any set of these conditions for any wind speed. Output in the terms of power output/rotor for a circular track of diameter D , and for a racetrack having straight section S of any length required.

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

- Rotor Geometry
 - $AR = 8$
 - $e/d = 2$
 - height = 38 m (125 ft)
 - diameter = 4.9 m (16 ft)
 - end plate diameter = 9.8 m (32 ft)
 - two end plates
 - area = 186 m^2 (2000 ft^2)
- Spin Motor Schedule (see Figure 17 for 1/2 of cycle)
 - Maximum angular acceleration at 450 kW to 186 rpm
 - Constant 186 rpm until track position of 245°
 - Viscous drag braking to stop
 - Reverse rotation direction and repeat cycle
- Track Speed
 - Circular Track = 8.9 m/s (20 mph)
 - Race Track = 13.4 m/s (30 mph)

Figure 17. Net Power Output for One Rotor, Spin Motor Power, and Motor rpm versus Rotor Position on Track as Affected by use of Viscous Braking, Regenerative Braking, and a Three-Step Transmission to Vary the Spin Schedule.

- Track Size
 - Circular Track = 1372 m (4500 ft)
 - Racetrack - 1372 m end diameter with 3050 m (10,000 ft) to 19,210 m (63,000 ft)
- Wind Speeds
 - 13.4 m/s (30 mph) max
 - 3.0 m/s (10 mph) min

A plot showing typical performance of a circular and a racetrack plant is presented in Figure 18. It is interesting to note that the loci of optimum performance of the racetrack and circular plants occur at all wind speeds at track speeds of 13.4 m/s and 11.2 m/s, respectively. (The parameter λ represents the track speed (V_L) to windspeed (V_W) ratio.) A lower than optimum track speed for the circular plants was selected to improve annual energy yield by reducing inter-rotor, mutual interference, losses.

The data in Figure 17 do not include the reduction in performance caused by multiple rotor mutual interference.

Figure 18. Net Power Output from one Rotor versus λ as a Function of Wind Speed. Performance is Presented for Both a 1370 m (4500 ft) Diameter Circular Track and a Racetrack having 1370 m (4500 ft) Diameter Ends and 4880 m (16,000 ft) Straight Sections.

The mutual interference study, conducted by Professor H.C. Larsen of the Air Force Institute of Technology, made use of the vortex analysis which he developed for analyzing the Giromill, now under development by the McDonnell Aircraft Company.¹

Since the Giromill and the Madaras system are essentially comparable in concept, and since the analysis has been validated by wind tunnel studies, the method was considered appropriate for the Madaras rotor mutual interference study.

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

The effect of interference is intensified as the number of rotors, N increases and wind speed decreases. The wind speed at which a curve ends represents the cut-in wind speed. Beyond that point, output power is undefined. The data from Figure 19 were used in conjunction with data from Figure 18 to develop the net output from a total Madaras plant taking into account all electromechanical, aerodynamic, and mutual interference losses.

The last aspect of this study was to develop power duration curves for various-sized Madaras plants. These power duration curves were obtained from the standard wind duration curve having a mean wind speed of 8.1 m/s at a height of 9 meters in accordance with our design specifications. This curve was uprated to a height of 25 m (the center height of the Madaras rotor) by the usual 0.167 power law. An additional wind duration curve for Medicine Bow, Wyoming, also was used to provide a means for comparing Madaras plant performance with that of a large array of MOD-1 wind turbine generators at Medicine Bow. These wind duration curves and the resulting power duration curves from two Madaras plants is presented in Figures 20 and 21, respectively.

Figure 19 . Mutual Interference Loss Factor versus Wind Speed for Various Numbers of Rotors on a 1524-m Diameter Track. Constant Rotor Speed and Track Speed of 186 rpm and 13.4 m/s, Respectively.

Figure 20. Modified Design Wind Duration Curve to Represent Wind Conditions at a Rotor Mid-Height of 25 m (82 ft) Above Mean Terrain Level.

Figure 21. Power Duration Curves for the Two Plants Shown in Figure 6.14 Based on the $\bar{V} = 9.6$ m/s Design Wind Duration Curve at 25-m Height (Figure 6.13).

5. COST/PERFORMANCE ANALYSIS

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

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

On the other hand, large racetrack plants appear to be quite attractive. Figures 22 and 23 contain parametric plots, respectively, of cost/kW and cost/kW-hr versus rated power. These plots indicate the relationship of the following parameters on cost and rated power output:

- $b \equiv$ inter-rotor spacing in number of rotor diameters, d ,
where $d = 4.9$ m (16 ft)
- $S \equiv$ length of the straight section of the racetrack
- $N \equiv$ number of rotors

These curves do not reflect the effect of learning curves, do not include land cost, and Figure 23 is based on annual costs equal to 16.5 percent of total plant cost.

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

Figure 21. Unit Plant Cost versus Rated Power for Racetrack Configuration as a Function of Inter-Rotor Spacing, Length of Straight Section of Track, and Number of Rotors. DOE Design Wind Duration Curve: $\bar{V} = 8.1$ m/s @ 9 m.

Figure 22. Energy Cost versus Rated Power for Racetrack Configuration as a Function of Inter-Rotor Spacing, Length of Straight Section of Track, and Number of Rotors. DOE Design Wind Duration Curve: $\bar{V}=8.1$ m/s @9m.

Table 2 presents cost and performance data for the two largest Madaras plants studied. Plant numbers indicate size; i.e., for Plant 49-60, inter-rotor spacing is 49 rotor diameters ($d = 4.9$ m), and the length of the straight track section is 60,000 ft (18,300 m). The suffix M indicates a Medicine Bow, Wyoming, wind duration curve. Sea level air density was used for Table 2 configurations.

TABLE 2

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

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

(1) Does not include land cost

(2) Based on annual cost = 16.5% of plant cost.

The separate and combined effect of learning curves, land cost, and mean wind speed on Madaras plant and energy cost are shown in Table 2. Costs are in 1978 dollars. These data indicate that land cost has an insignificant effect on energy cost because plant cost is high relative to land cost, and also because we elected to purchase only that land required for the track and road, the power station, and the area enclosed by a fence line offset 100 ft from all plant tracks and buildings (A_n in Table 2). The "infield" area inside the track would be retained by the owner for agricultural purposes. Viaducts under the track at each end would provide

access to the property, and the property would be a large, open, unbroken expanse that would be attractive for large scale farming (about 6460 acres for Plant 44-60).

The learning curve effect on energy cost for a given plant can be seen by comparing one column of figures under a given land cost or by comparing Plant 49-60 with Plant 44-60. These data indicate that energy from Madaras plants is sensitive to learning curves. Madaras plants also are more economical as they are built larger, as shown dramatically in Figure 22, and to a much smaller extent on Table 2 (compare Plant 49-60 with Plant 44-60 energy costs).

Comparisons of the Madaras system with horizontal axis wind turbine generators (HA-WTG) were made to determine whether or not Madaras plants showed promise of producing electrical energy at a lower cost than HA-WTG's (the basic objective of this study). Comparisons were made with HA-WTG plants proposed by Mr. S.J. Hightower² of the Bureau of Reclamation, Department of Interior for installation at Medicine Bow, Wyoming. These two plants consisted of 49 and 98 MOD-1 WTG's, respectively, designed by the General Electric Company³. These plants were selected for the comparison because they utilized large, modern HA-WTG's, and because the study included all costs required to connect the HA-WTG array into a complete plant, just as this Madaras plant study has done.

Equitable bases for the comparison were developed, and these bases were coordinated with Hightower. The more important ground rules for the comparison were:

- 1978 dollars
- 5 year construction period
- Construction interest at 7%
- Plant Life of 30 years
- Financing:
 - Federal Annual Fixed Rate = 8.41%
 - Private Annual Fixed Rate = 15%

- Operation and Maintenance annual cost 2% of base plant cost
- Land purchased
 - Net area (A_n) in Table 2 for Madaras Plant
 - 1500 ft diameter per HA-WTG (specified by Hightower)
- Same learning curve equations and 85% learning curve for WTG and Madaras rotor

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

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

- Medicine Bow — air density ratio=0.81 (2131 m elevation)
 - Two plant sizes, each type: $\approx$ 98 MW, 196MW
 - Mean Wind speed = 9.7 m/s @ 9-m height
 - Federal financing
 - Land cost = \$200/acre
- Other Site — air density ratio = 1.0 - sea level
 - Same two plant sizes
 - Mean wind speed = 8.1 m/s @ 9-m height
 - Private financing
 - Land Cost = \$3000/acre

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

TABLE 3

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

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

	PLANT ID NO.	ROTOR OR WTG	TRACK	ELEC. CONN.	INSTALLED COST					TOTAL PLANT COST	COST kW	ANNUAL AND ENERGY COST			
					SITE AND FACILITIES	CONTINGENCIES (2)	MGMT. ENGR. OVERHEAD	LAND COST (3)	CONST. INTEREST			FIXED CHARGE (6)	O&M	TOTAL ANNUAL	ENERGY COST MILLS kW-hr
MEDICINE BOW PLANTS					10 ⁶ Dollars (1978)						\$kW	10 ⁶ Dollars (1978)			
	①	21.27	26.48	7.61	9.99	6.73	14.87	0.12	14.67	101.74	1026	8.56	1.74	10.30	25.0
	1a	55.52	N/A	6.85	9.35	(5)	10.70	0.56	14.42	97.40	994	8.19	0.99	9.18	22.4
	②	33.08	43.18	12.37	14.61	10.50	23.56	0.18	24.03	161.51	844	13.58	2.75	16.33	20.5
	2a	94.38	N/A	13.70	15.54	(5)	18.89	1.12	24.94	168.57	860	14.17	1.98	16.15	19.7
	③	37.38	49.44	14.15	16.35	11.90	26.78	0.21	27.25	183.48	806	15.43	3.17	18.55	19.6
PLANTS WHERE V = 8.1 m/s	④	←		SAME AS ①	①			1.84	Same as ①	103.45	1043	15.52	Same as ①	17.26	40.7
	4a	←		SAME AS 1a	1a		(5)	8.37	Same as 1a	100.21	1074	15.78	Same as 1a	16.77	46.2
	⑤	←		SAME AS ②	②			2.78	Same as ②	164.10	857	24.62	Same as ②	27.37	33.4
	5a	←		SAME AS 2a	2a			16.73	Same as 2a	184.18	940	27.63	Same as 2a	29.61	40.8
	⑥	←		SAME AS ③	③			3.15	Same as ③	186.42	818	27.96	Same as ③	31.08	31.9

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

Cost estimates of MOD-1 systems, used without modifications, were obtained from Hightower² and from General Electric³. Both the Madaras estimates and the MOD-1 estimates^{2,3} were based on engineering studies, not on manufactured hardware cost.

The major observations drawn from the data in Table 3 are:

- Plant cost is about equal for both systems.
- Annual energy output and hence plant factor is higher for the Madaras plants than for the HA-WTG plants at the 8.1 m/s mean wind speed region. MOD-1 performance data for this other site were obtained from General Electric.¹
- Madaras plants use considerably less gross land area than HA-WTG units spaced 15 rotor diameters apart (915 m); less net area needs to be purchased for Madaras plants; and the remaining land area in the "infield" of a Madaras plant can be used more efficiently for agriculture or industry than the broken up tracts of land scattered among arrays of HA-WTG plants.
- Annual operation and maintenance costs of Madaras plants are greater because of their added complexity.
- Energy cost of Madaras plants at Medicine Bow varies from 4 percent to 12 percent higher than that for comparable HA-WTG plants; and at the other site, Madaras plant energy cost is from 13.5 percent to 22.2 percent less than HA-WTG cost.
- Madaras plant energy cost relative to HA-WTG energy cost is unaffected by the magnitude of the annual fixed cost rate, but land affects the relative cost position of HA-WTG plants because HA-WTG plants use considerably more land area than Madaras plants.

6. CONCLUSIONS

This conceptual design study of the Madaras Rotor Power Plant included an analysis of all major components of the Madaras system. The study has successfully addressed each of the unanswered questions outlined in Paragraph 1, and has fulfilled the basic study objective. It is believed that a reasonably efficient conceptual design for the Madaras system has been developed, and that this design fulfills all criteria initially established.

¹Korneich, T.R., Proceedings of the Third Biennial Conference and Workshop on Wind Energy Conversion Systems, Volume 1, September 19 to 21, 1977, Sponsored by the United States Department of Energy.

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

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

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

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

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

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

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

7. The potential problem areas and disadvantages of Madaras plants relative to HA-WTG plants are:

- The Madaras system is more complex, has higher losses, and will require higher operation and maintenance costs than a horizontal axis wind turbine system.
- The use of a racetrack plant configuration is necessary for optimum Madaras plant performance (at this time). Thus, Madaras plants will be limited to regions having nearly unidirectional winds or to those regions in which off-axis winds have an angular variation of less than $\pm 45^\circ$ and which occur only a small portion of a total year.

8. The advantages of the Madaras plant over a comparably-sized HA-WTG plant are:

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

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

10. Although more efficient HA-WTG systems (MOD-2) are being developed, it is believed that more efficient Madaras systems also can be developed given the opportunity to conduct the necessary design studies.

11. At this stage of the investigation, it is not possible to state conclusively whether or not the Madaras system will significantly out-perform a similarly-sized horizontal axis wind turbine system. However, the results of the present study, which are thought to be conservative, are sufficiently encouraging to warrant further investigation. Areas requiring further study include:

- Definition of mutual interference for racetrack plants and for circular track plants having track end diameters greater than 8000 ft (2439 m)
- Development of optimal spin schedules which include modulating rotor speed at all points along the track such that the propulsive force is optimized at all times
- Further consideration of different types of electrical equipment, transmissions, and braking techniques
- Analyses of different end plate designs which promise to reduce viscous friction and inertia loads, and hence reduce spin power, without a proportionate decrease in aerodynamic performance
- Reduction of rotor weight and inertia by optimized design and use of new materials and construction techniques that are cost effective. Included in this analysis should be the consideration of larger rotors, and filament winding techniques.
- In-depth studies of power collection and distribution as well as system control
- A thorough study of manufacturing techniques to develop the most cost-effective methods for producing Madaras plants, and the determination of detailed costs of mass-produced units
- A life cycle cost study to include system reliability as well as maintenance, operation, and depreciation costs of the system

REFERENCES

1. Brulle, R.V., Feasibility Investigation of the Giromill for Generation of Electric Power, Midterm Report, April-November 1975, Energy Research and Development Administration, November 1975.
2. Hightower, Stanley J., "A Proposed Plan for Integration of Wind Turbine Generators with a Hydroelectric System," Presented at the Annual Meeting of the Missouri Basin Systems Group, Sioux Falls, S.D., March 9, 1977.
3. Korneich, T.R., Proceedings of the Third Biennial Conference and Workshop on Wind Energy Conversion Systems, Volume 1, September 19 to 21, 1977, Sponsored by the United States Department of Energy. Paper by R.J. Barchet of the General Electric Co., Volume I, page 76.