SERI/STR-211-2277
UC Category: 60
DE84004512

Conceptual Design of an Electrofluid Dynamic Wind Energy System

A Subcontract Final Report

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Dayton, Ohio

May 1984

Prepared under Subcontract No. XE-1-1291-1

SERI Technical Monitor: R. Noun

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche A01
Printed Copy A03

PREFACE

The research described in this report was performed for the Midwest Research Institute, Solar Energy Research Institute (SERI) Division under Subcontract No. XE-1-1291-1 entitled "Conceptual Design of an Electrofluid Dynamic Wind Energy System" under Prime Contract No. EG-77-C-01-4042. This report summarizes all work performed under this one-year subcontract. The work was accomplished between 1 October 1981 and 1 October 1982. The Technical Monitor for SERI is Mr. Richard L. Mitchell.

The authors wish to acknowledge Dr. Frank L. Wattendorf for his able assistance and contributions to this program. Appreciation is also acknowledged to personnel of the University of Dayton Research Institute (UDRI) who assisted in this program: Mr. D. H. Whitford, Dr. Hans von Ohain, Mr. R. K. Newman, and Mr. M. J. Glaser. A special note of appreciation is due Ms. K. L. Fox for typing this report and for providing general assistance throughout the program.

SUMMARY

This report contains the conceptual design of the EFD wind driven generator, along with some of the performance estimates used to select the electrode spacing and other parameters. Various spacings and tube sizes in different wind fields were considered to assess the effects of the different parameters. As a result of the studies we chose a value of "a" of 3 and "b" = 1.656 (300 kV collector) for a tube diameter of 0.3048 m (1 foot). ("a" is the vertical spacing in tube diameters and "b" is the horizontal spacing.) Although a detailed stress analysis was not done, preliminary estimates indicate that the tower design will withstand head-on winds in excess of 100 mph (44 m/s) without damage.

A Rayleigh distribution was used for the mean wind velocity at 10 meter height with a 1/7th power law for the height variation to make our estimates of average power unit area (W/m^2). Drag losses were included as well as major losses involved in charge production and pumping. Although the design uses streamlined collector electrodes, cylinders were used in our drag calculations. We believe that this more than offsets the fact that we neglected the tower drag. Consequently, the estimates of power are probably conservative.

The major elements of the design are:

- Height: 65 m
- Length: 400 m
- Height of conversion section: 60 m
- Conversion section area: 24,000 m^2
- "a" = 3
- "b" = 1.656
- Collector voltage: 300 kV
- Attractor voltage: -30 kV
- Electrode diameter: 0.3048 m
- Average power in 6 m/s (at 10 m height) wind with 1/7th power law: 93.8 W/m^2
- Yearly energy: 19,700,000 kWh
- Drag pressure in 44 m/s (100 mph) wind: 262.6 N/m^2
- Supported by regularly spaced guyed towers; spacing 13.34 m

A capital cost estimate of the conceptual design was performed at the Solar Energy Research Institute. The total capital cost (not including land) from their calculations was:

Foundation	$ 56,000
Structual steel and rigging	8,750,000
Aluminum tubing-foils-plates	10,841,000
Insulator	288,000
Pumping and piping system/foggers	3,138,000
TOTAL CAPITAL COST	$ 23,073,000

This report is on the conceptual design while the SERI is responsible for the cost study which is presented in detail in Section 4.

Using these cost results, the SERI calculated the cost of energy (COE) using the standard Department of Energy equation for annualized cost of energy:

$$COE_{annual} = \frac{23,073,000 \times 0.18}{19,700,000} \quad .$$

Since no attempt was made to optimize the design, we feel that many opportunities exist for cutting the cost of an EFD wind driven generator.

Further, the maintenance and down time on the EFD wind driven generator should be less than for a conventional system with many units and having rotating parts. In addition the EFD wind driven generator does not require any additional power conditioning for long line power transmission.

However, a major effort is still required to develop an energy economic charging system. Once this problem is solved, we believe that it will be possible to produce EFD wind driven generators that will be cost competitive with other methods for producing high voltage dc power.

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NOMENCLATURE

D	diameter of electrodes
S_L	horizontal spacing of electrodes
S_T	vertical spacing of electrodes
a	dimensionless vertical spacing parameter (S_T/D)
b	dimensionless horizontal spacing parameter (S_L/D)
V	instantaneous wind velocity
$\overline{V}$	average wind velocity
V_{cutout}	peak wind speed at which generator ceases to produce power

SECTION 1.0

INTRODUCTION

An Electrofluid Dynamic (EFD) wind driven generator directly converts the kinetic energy of the wind into electrical energy. No moving parts are required for the operation of the EFD wind driven generator except possibly for turning it into the wind, and pumping a liquid in the colloid distribution system. Theory and experimental results have been reported in references 1 through 3. A schematic diagram of an EFD wind driven generator is shown in Figure 1-1.

In the EFD wind driven generator, charged particles of one polarity are seeded into the electrically neutral air. A viscous interaction between the wind and the charged particles drive them up an electrical potential hill, thereby producing power. Typically, the EFD generator uses high voltages and low current densities.

As seen in Figure 1-1 the generator consists of the following parts:

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

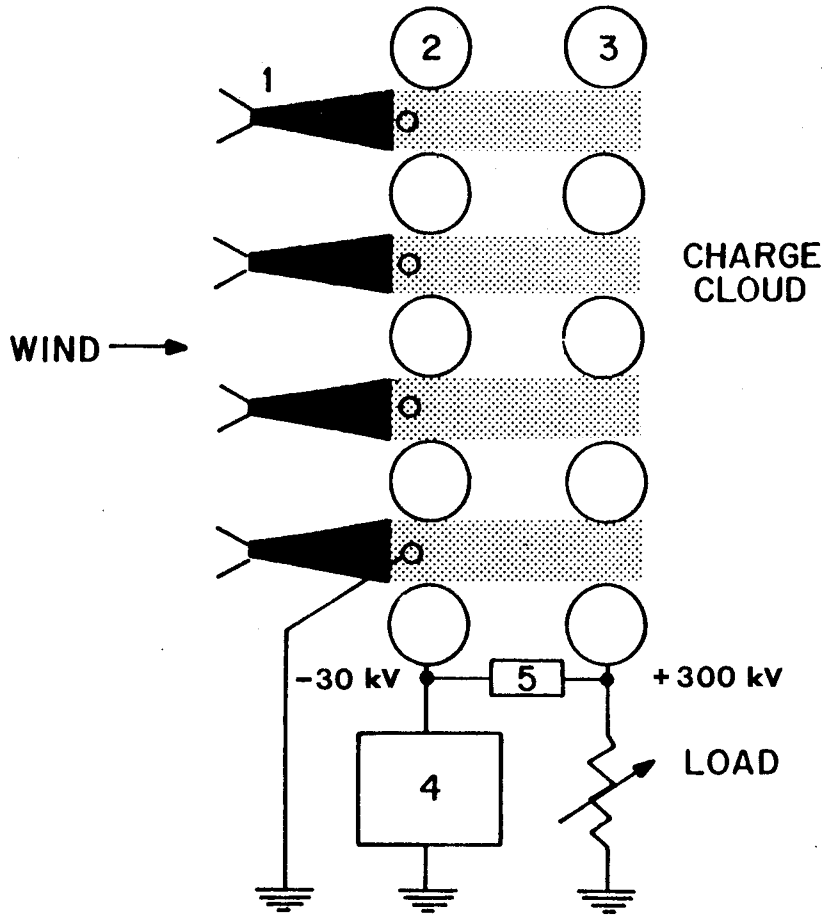
The feedback control system is used to regulate the current (i.e., charged particle production) in order to maintain a constant voltage at the collector electrode.

We have developed a theory of operation for the EFD wind driven generator [1-3] and have shown experimentally that the theory is valid [2]. The theory demonstrates that there is no fundamental reason that would prevent the application of the EFD wind driven generator concept. However, we still must develop an energy economic method of producing the charged particles.

The current laboratory techniques used for the production of charged particles require too much energy to be practical. Nonetheless, the theory indicates that the charged colloid-sized particles can be produced with only a small fraction of the output power being used.

The theory was far enough advanced that it seemed appropriate to make a somewhat detailed cost estimate of the EFD wind driven generator before proceeding with the required basic research. This report presents the results of that cost study.

SCHEMATIC OF AN EFD WIND GENERATOR



1 COLLOID CHARGING SYSTEM
2 INLET/ATTRACTOR ELECTRODE
3 COLLECTOR ELECTRODE
4 HIGH VOLTAGE POWER SUPPLY
5 FEEDBACK CONTROL SYSTEM

Figure 1-1. Schematic of an EFD Wind Generator.

SECTION 2.0

PERFORMANCE ESTIMATES

In order to arrive at a conceptual design that could be costed, it was first necessary to develop performance estimates of an EFD wind driven generator in various assumed wind fields. At this stage of the development of an EFD wind driven generator, it would be unrealistic to attempt to optimize a design. Nonetheless, major trade-offs could be studied that would enable us to choose a conceptual design that would be realistic in its major aspects and for which we could expect reasonable performance.

For this parametric study we used a Rayleigh distribution for the wind as suggested by Cliff [4]. Further, we assumed a 1/7th power law for the height variation (from the reference 10 meter height) to study the effects of the EFD wind driven generator as a function of height. A specific site was not selected for this study and the effect of wind direction variation from the dominant wind energy direction was not considered.

The following parameters were investigated or included in the model:

- Reynolds number effects related to electrode diameter
- Electrical field anchoring effects as a function of electrode spacing
- Parasitic drag as a function of electrode spacing in the vertical direction
- The effects of drag as a function of electrode spacing in the wind direction
- Water pumping requirements for the colloid particles
- Charging requirements for the colloid particles
- Surface tension requirements for producing the colloid-sized particles
- The effects of collector voltage on performance.

The spacing in the vertical direction is indicated by a parameter "a" which is the center-to-center spacing of the electrodes divided by the tube diameter. The spacing in the wind direction is indicated by a parameter "b" which is the center-to-center spacing in the wind direction divided by the tube diameter. This notation is shown on Figure 2-1.

The overall drag is a function of the number of rows (N = 2 in Figure 2-1) and all of our calculations have been restricted to the two row case (N = 2).

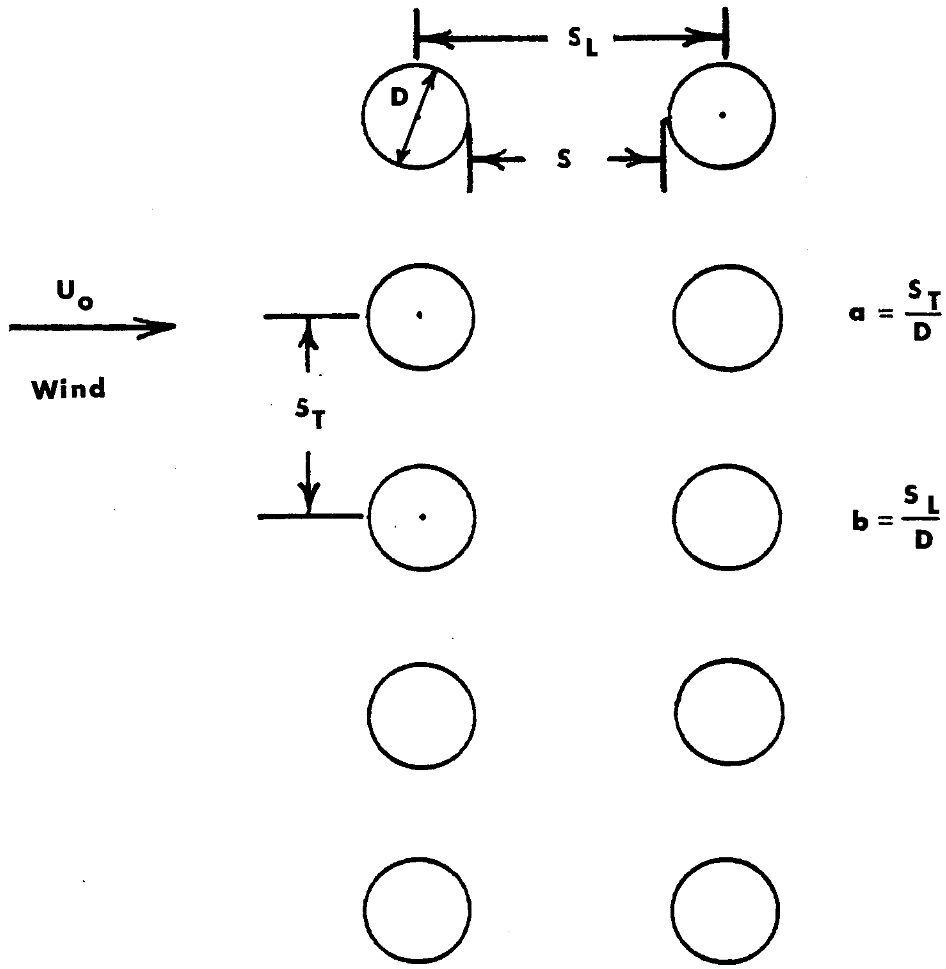


Figure 2-1. Spacing Notation for EFD Wind Driven Generator.

Using the theory presented in reference 1, we can construct curves of power per unit area versus velocity for an EFD wind driven generator. Figure 2-2 presents curves of this type where "a" is a parameter (vertical spacing in number of tube diameters). All of the curves are for a value of "b" of 1.5 (horizontal spacing in number of tube diameters) and a tube diameter of 0.3048 m (1 foot). With the larger values of "a" we have a wide spacing with low drag and low electric forces due to the limited ability to anchor the field lines. The generator limits performance except at low velocities where the relative performance is good. At the high velocities the configurations with wide spacing have relatively poor performance.

With small values of the parameter "a" we have narrow spacing with high drag and high electric forces possible. In this case the generator does not limit performance until the velocity is quite high. However, the output is low because of the high drag until the velocity is very high.

From Figure 2-2 we can see that an optimum value of "a" can be found for a given wind field. This is shown in Figure 2-3 which was obtained from a computer program using a Rayleigh distribution for the wind velocity and equations of performance like those used to construct Figure 2-2. The mean wind speed is the curve parameter of Figure 2-3. A cutout velocity of 30 m/s was assumed in calculating the performance shown on Figure 2-3, but in a high wind the electric forces are so low compared to the drag forces that there may be no need to shut the generator down in these high winds. The effect of using a higher cutout velocity (50 m/s) was negligible at average wind speeds less than 10 m/s. Therefore, a cutout velocity of 30 m/s was used in all subsequent calculations since it saved on computer time.

We see from Figure 2-3 that the peak power per unit area occurs at lower values of "a" for the higher velocities. At an average wind speed of 6 m/s the peak power per unit area occurs at a value of "a" of 2.2.

The velocities of interest lie between 4 m/s and 10 m/s and the peak region is blown up for these velocities on Figure 2-4 where several values of the parameter "b" were used for each velocity. Here we see that the performance increases for lower values of "b" since the drag is reduced. However, as the spacing is reduced, the collector voltage must also be reduced. In reference 2 it is shown that the losses associated with current production increase at lower voltages since higher currents are required for a given power. Thus, not all of the increased power is available for useful power production. This point is covered quantitatively later in the study.

Figure 2-5 shows the effect of tube diameter (and indirectly Reynolds number) on performance. In Figure 2-5 the peak is shown to be higher for the larger diameter tubes. This is a result of the lower drag associated with the higher Reynolds number which

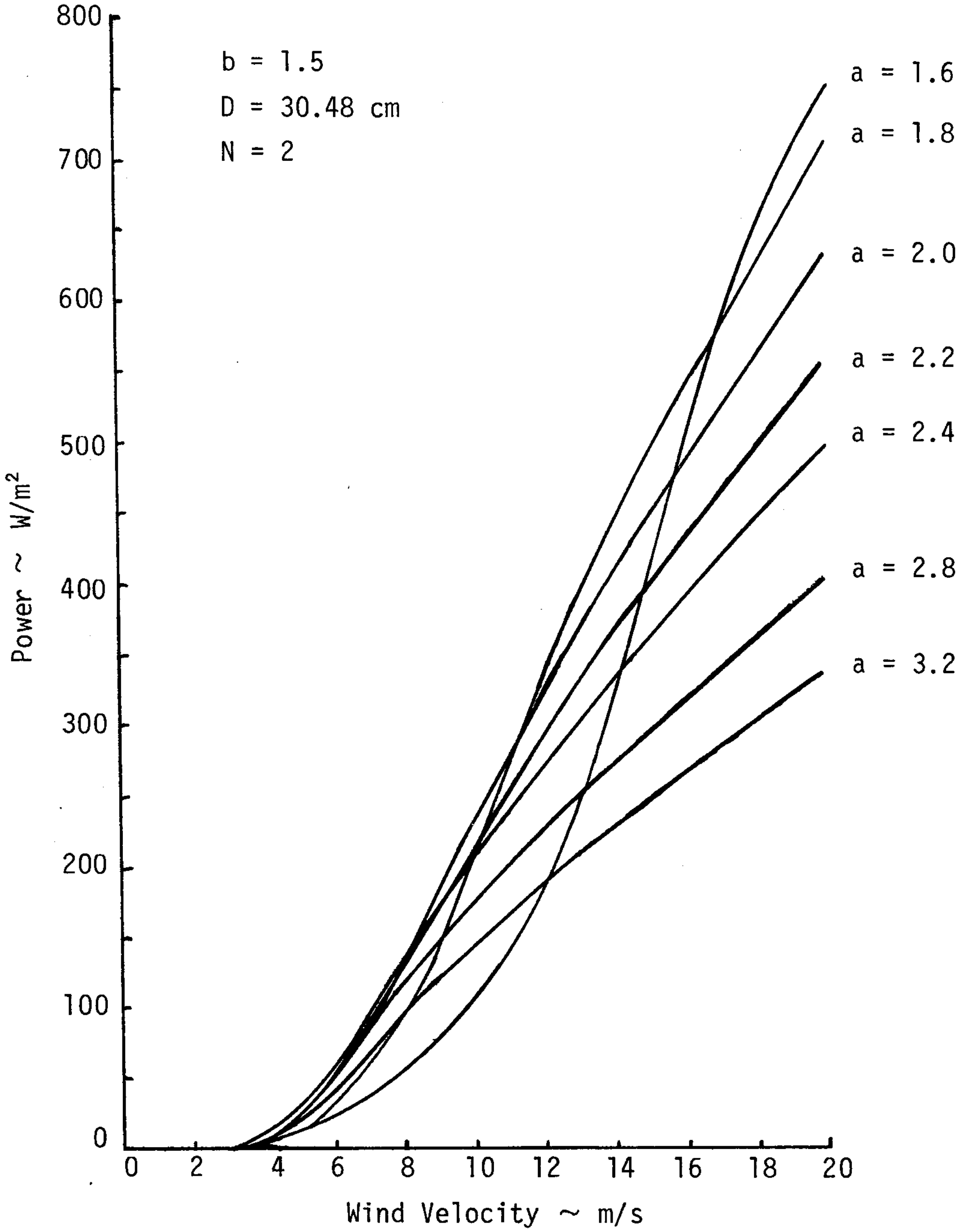


Figure 2-2. Typical Power/m^2 Versus Instantaneous Wind Velocity for Various Spacing.

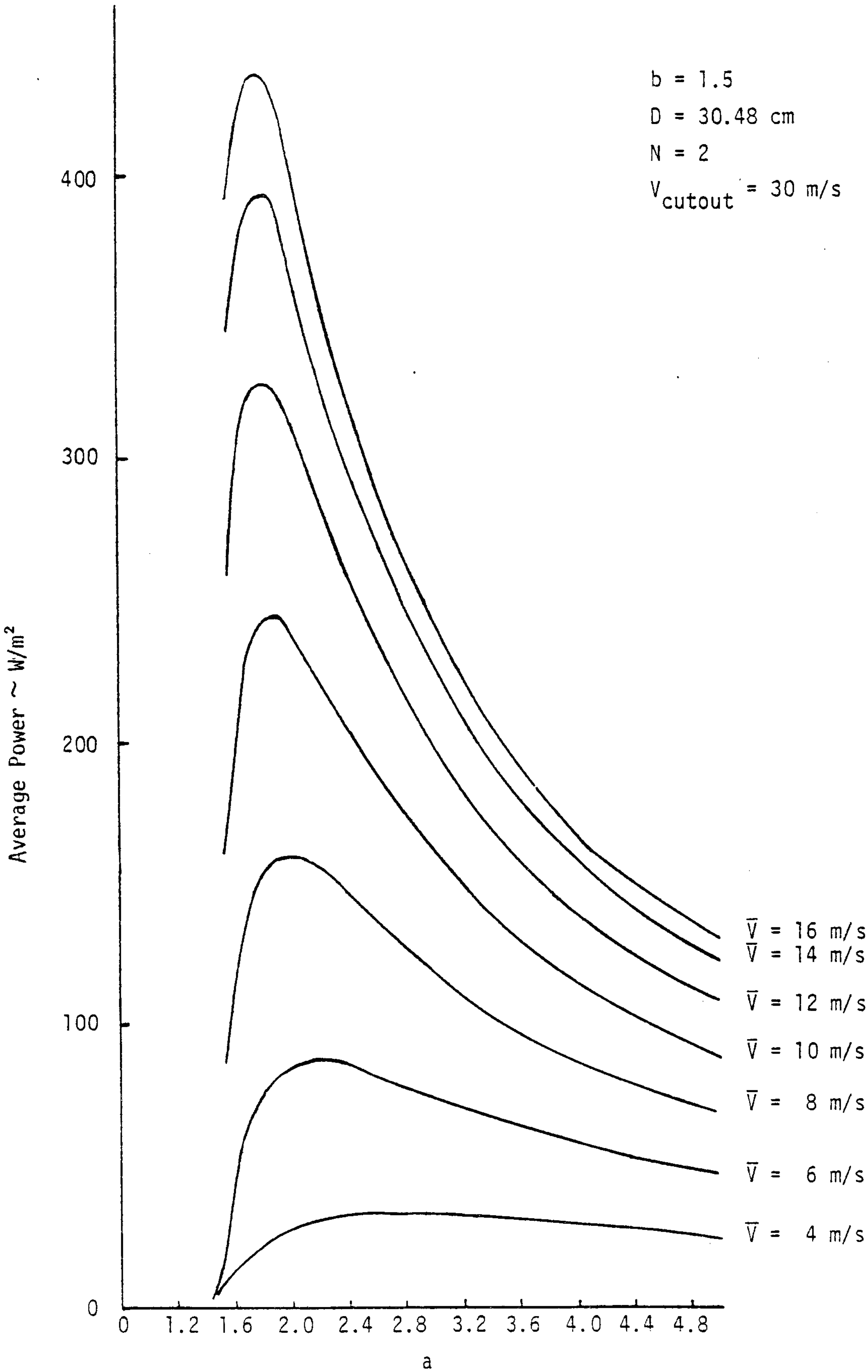


Figure 2-3. Average Power Versus "a" for Various Mean Wind Speeds, V_{cutout} = 30 m/s.

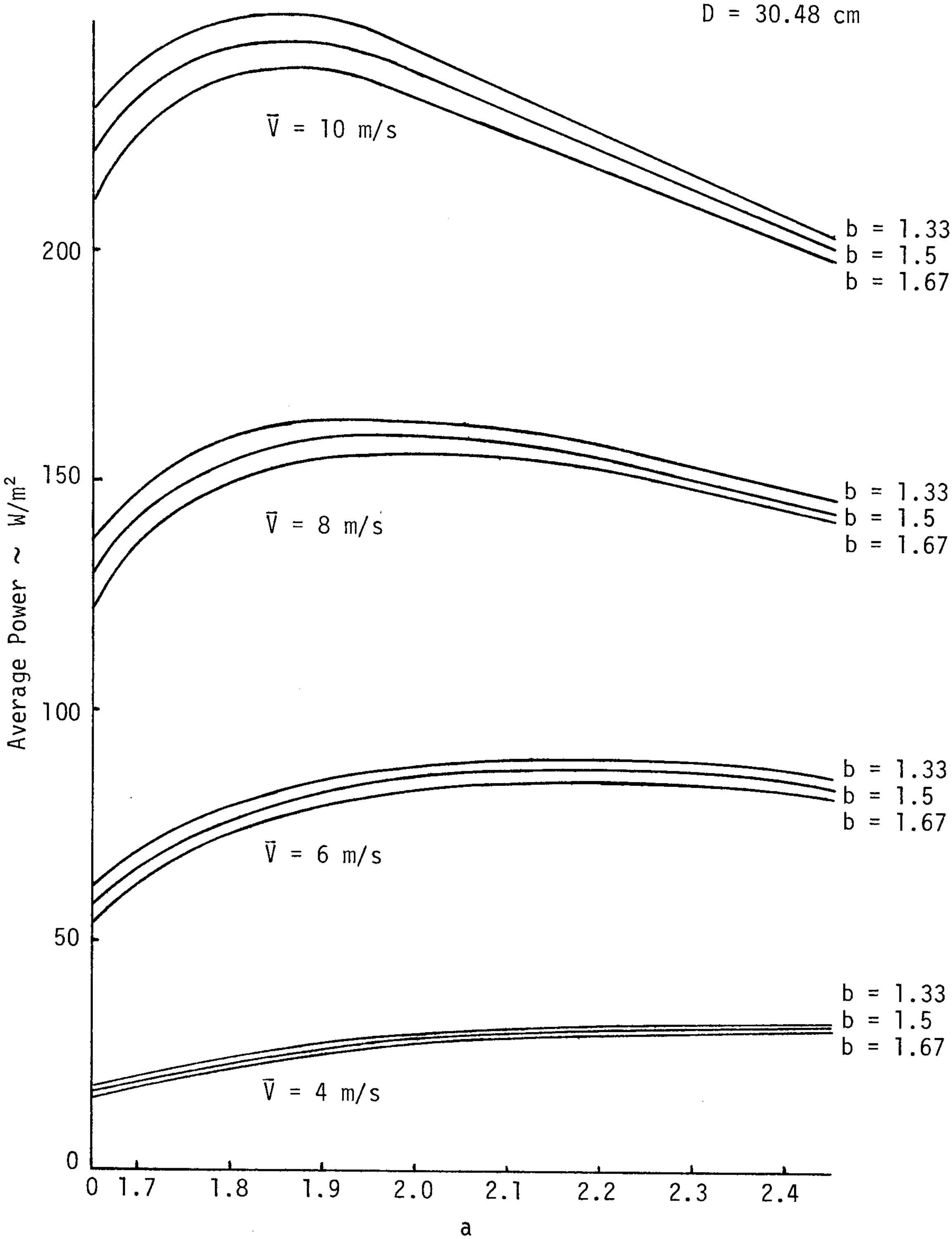


Figure 2-4. Average Power Versus "a" as a Function of Wind Speed and Horizontal Spacing, "b".

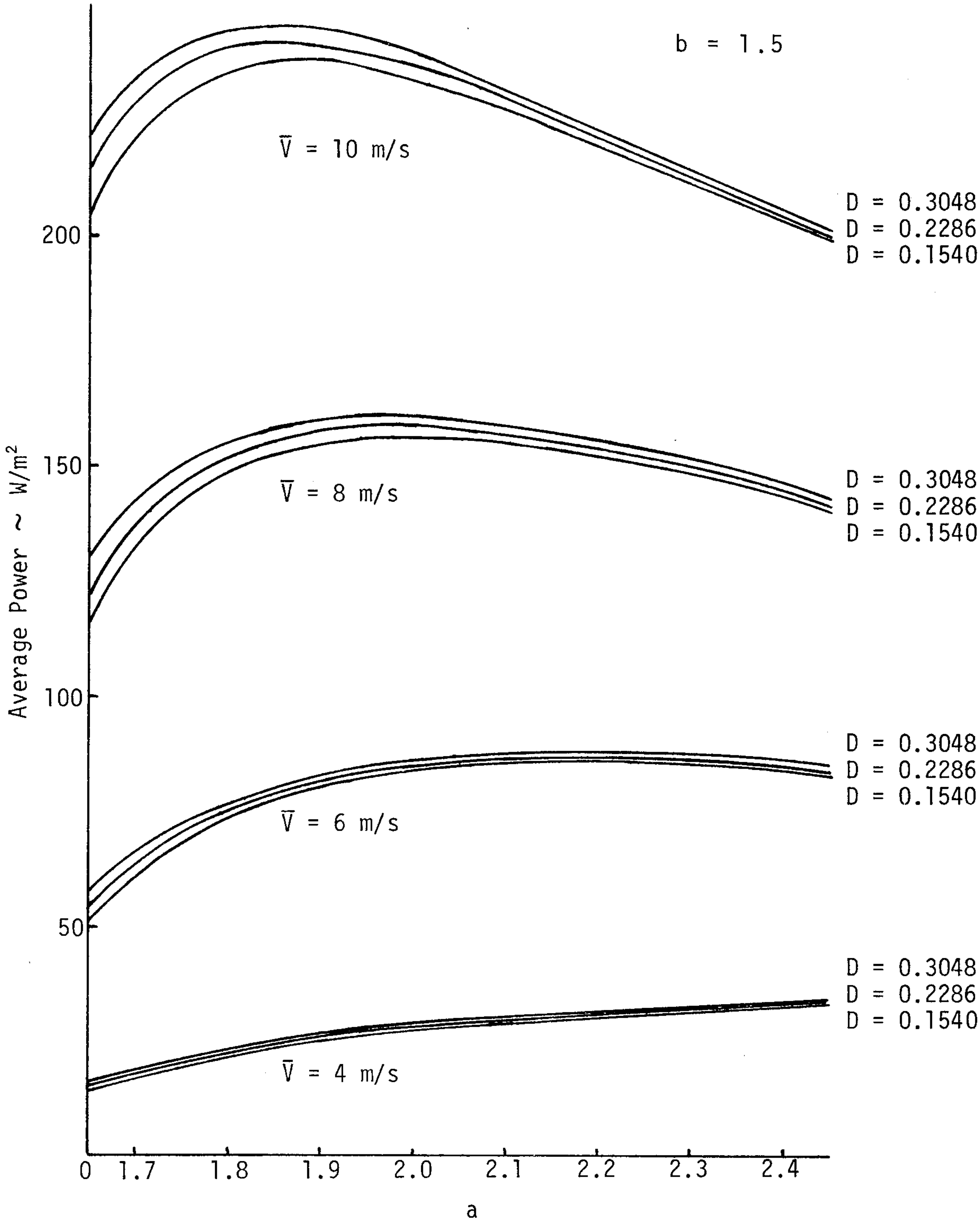


Figure 2-5. Average Power Versus "a" as a Function of Wind Speed and Electrode Diameter.

results from the larger diameters. Ease of handling for construction and other considerations led us to select a tube diameter of 0.3048 m (1 foot) for our design and all subsequent calculations.

Figure 2-6 was developed from Figure 2-3, and it displays the average power per kilogram of electrode material. The tube is assumed to have a 1/8 inch wall of aluminum. The peaks of the curves have shifted to higher values of "a". The cost of the rig would be a fixed cost plus a factor times the weight per unit area of the collector array. If the fixed costs are small, Figure 2-6 would be similar to a plot of power per unit cost versus "a". Higher fixed costs would make the peaks shift further to the left (lower values of "a") toward the more favorable performance. The wind region of interest is from 6 to 8 m/s. Since the cost factors are not known, we have chosen a value of 3 for "a". In addition, the higher values of "a" significantly reduce the drag forces in a high wind and these forces drive the tower design.

Figure 2-7 presents a study of rig height for the selected value of "a" and a 1 foot (0.3048 m) tube diameter. This figure is based on a 6 m/s wind at a height of 10 m with a 1/7th power law variation with altitude. We have included water pumping requirements in this calculation. Thus, a peak with altitude can occur. The curve parameter is the collector voltage which affects both drag (through the horizontal spacing) and the losses (lower voltages require higher currents for a given power, and therefore, more water per unit area).

Figure 2-8 is a blow-up of Figure 2-7 and indicates that in the altitudes of interest a 300 kV collector voltage is nearly an optimum. The great advantage in performance of going to taller rigs is apparent. However, at this time we do not yet know the variation of costs with rig height and arbitrarily chose a height of 60 m for the first design iteration.

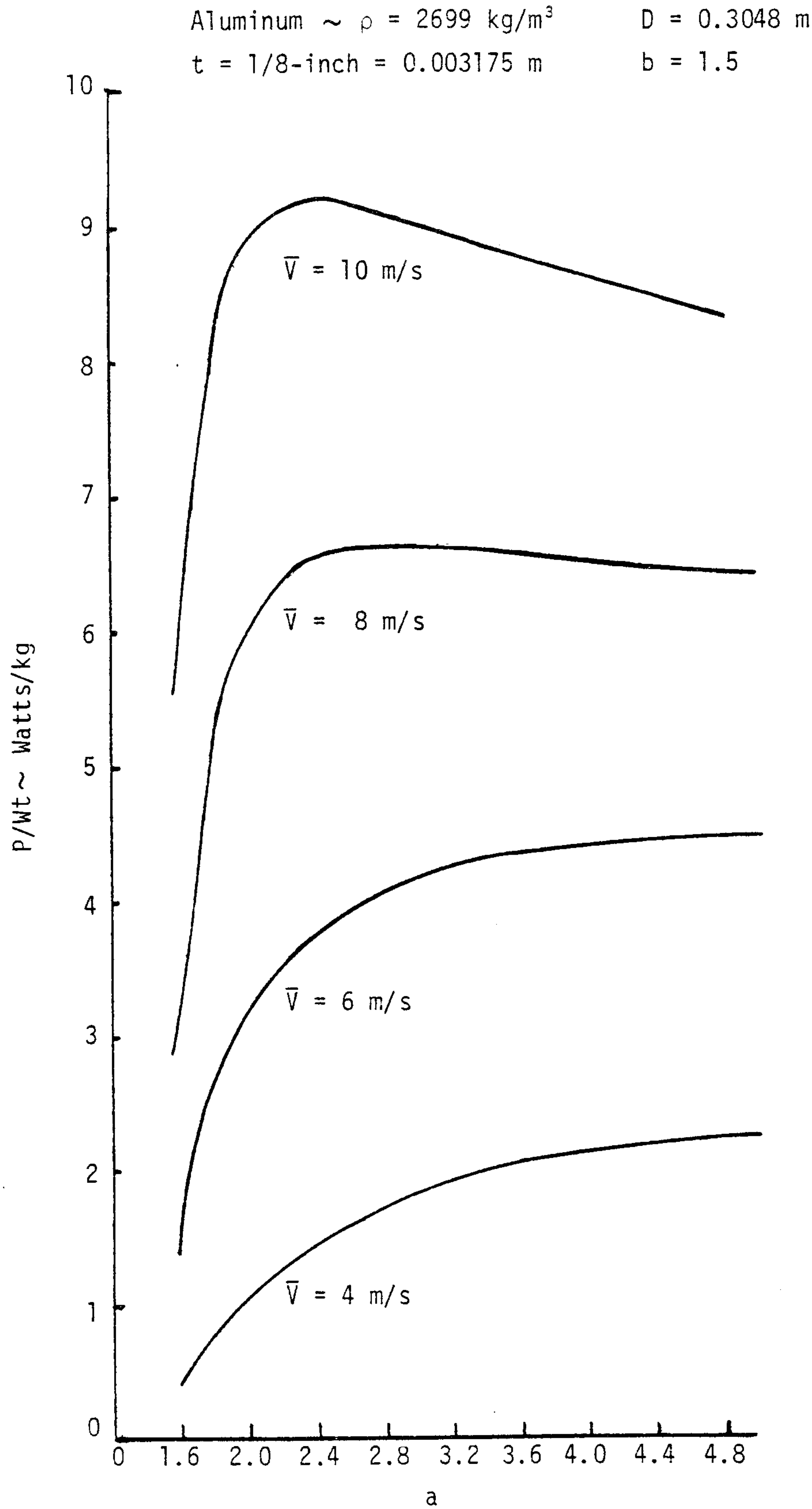


Figure 2-6. Average Power/kg of Electrode Weight (1/8 inch aluminum, 1 foot diameter) Versus "a" for Various Wind Speeds.

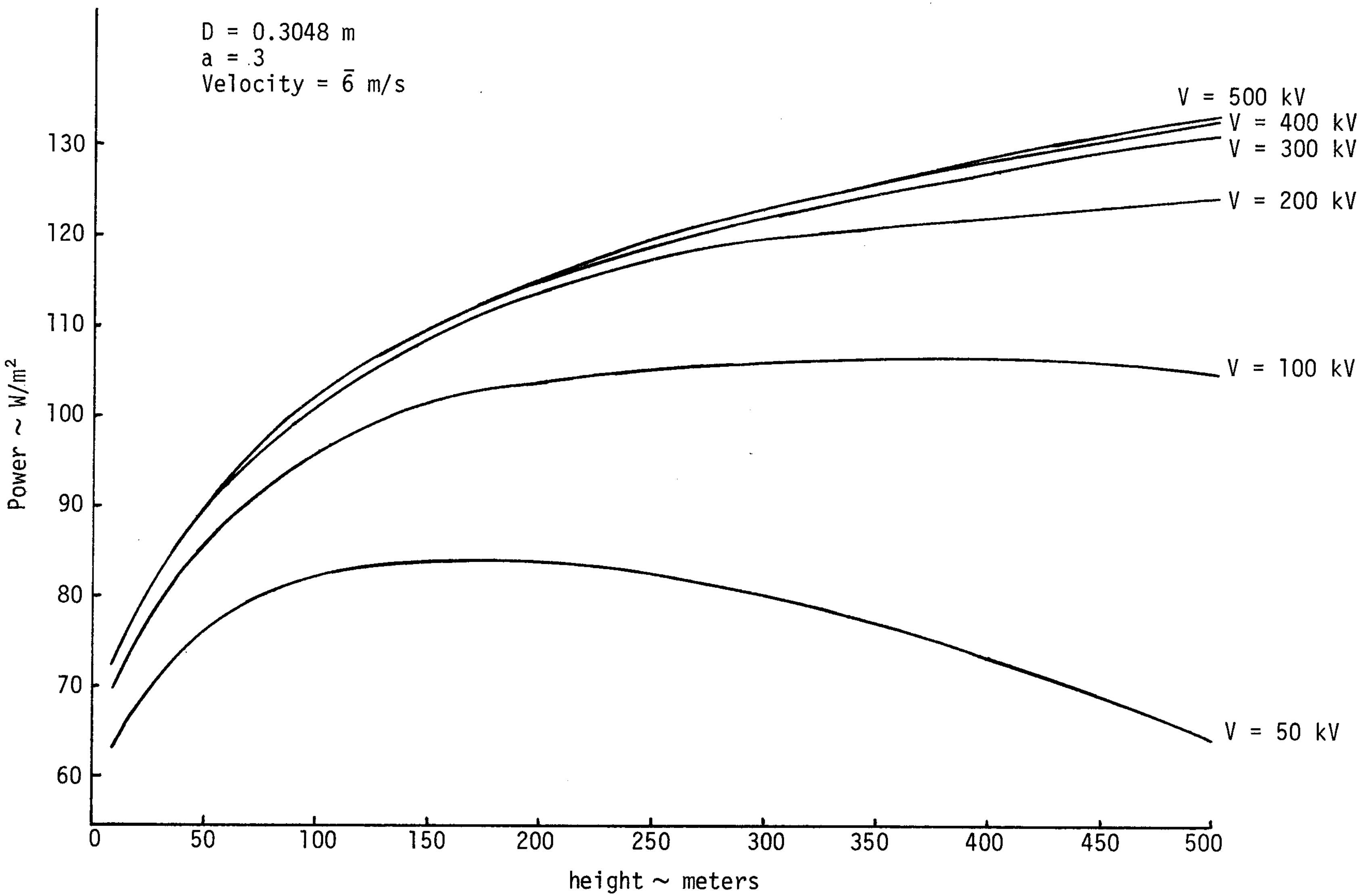


Figure 2-7. Average Power Versus Height of Rig in a 6 m/s Average Wind at 10 m for "a" of 3 and 1 foot Diameter Rods. A 1/7th Power Law Was Assumed.

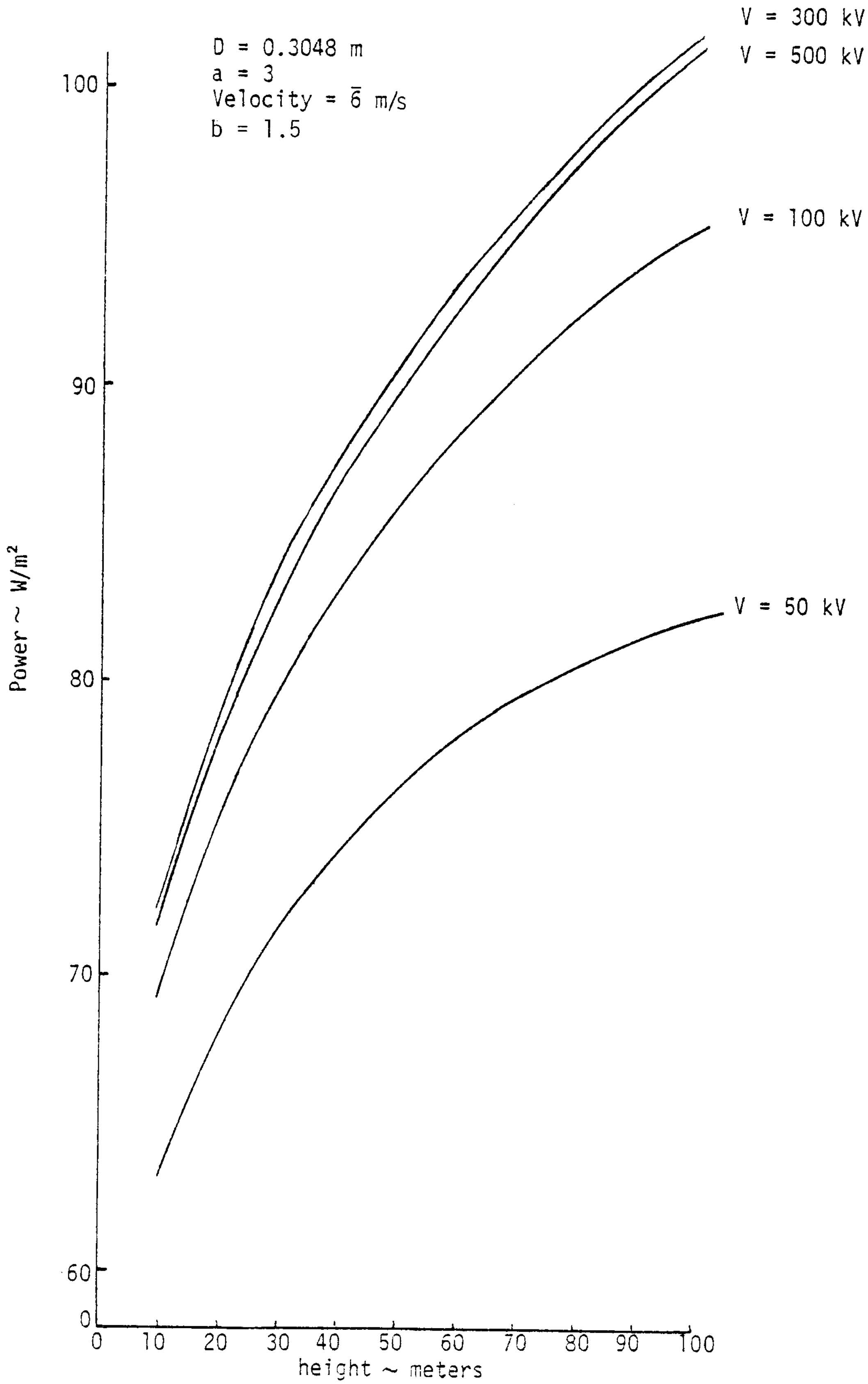


Figure 2-8. Average Power Versus Height of Rig Up to 100 m.

SECTION 3

CONCEPTUAL DESIGN

During the course of the performance study a number of design variables were chosen for the conceptual design. We have set the following design variables which resulted from that study along with other arbitrary decisions:

- A one stage conversion section (N = 2) using two electrodes
- A tube diameter of 0.3048 m (1 foot)
- A value of "a" of 3 (center-to-center spacing shown in Figure 2-1)
- A value of voltage of 300 kV
- Attractor voltage - 30 kV
- A value of "b" of 1.656
- Conversion section height 60 m
- Total height above ground 65 m
- Length 400 m
- Area of conversion section: 24,000 m^2
- Supported by regularly spaced guyed towers: spacing 13.34 m.

For a design based on the above parameters, we obtained the following estimates:

- Average power in 6 m/s (10 meter reference height) wind with 1/7 power law: 93.8 W/m^2
- Yearly energy 19,700,000 kWh at 100 percent availability
- Drag pressure in 44 m/s (100 mph) wind: 262.6 N/m^2.

Figure 3-1 shows a schematic front view of the full size rig. The conversion section starts at 5 m above the ground and is supported by guyed towers spaced at 13.34 m. The towers are supported on insulators that are, in turn, supported by concrete piers. The overall width of the conversion section is 400 m.

The ends of the EFD wind driven generator are also guyed to support side loads.

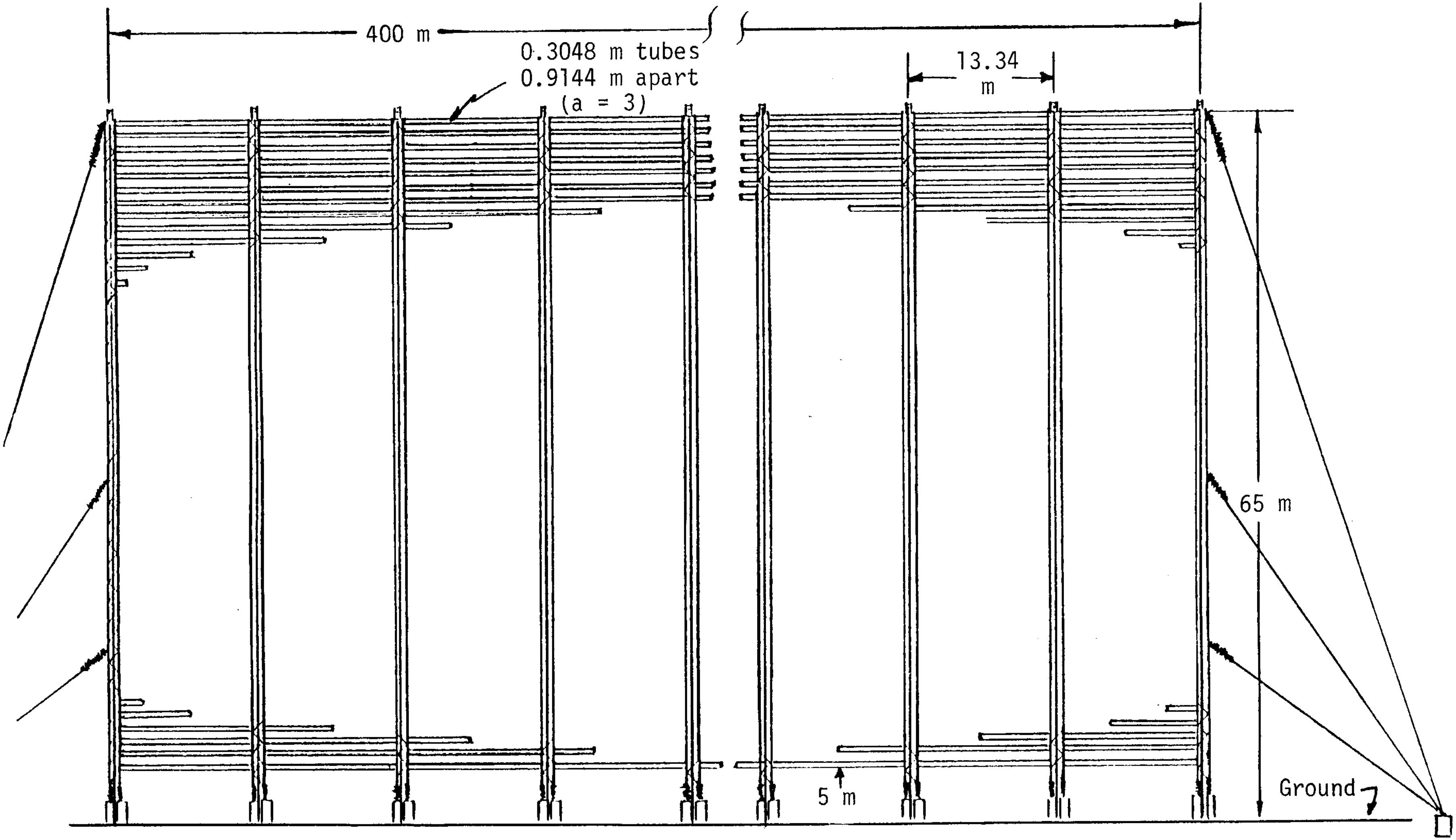


Figure 3-1. Front View of Rig. Area = 60 × 400 = 24,000 m^2 (258,000 ft^2).
Each tower supports 13.34 × 60 = 800 m^2 (8,600 ft^2).

Figure 3-2 shows a side view of the towers along with details of the guy wires which are anchored into concrete. The guy wires are separated from the towers by insulators of epoxy-fiberglass rod (e.g., Ohio Brass Company Hi-Lite insulator). These insulators are strong and light. For example, a 500 kV insulator only weighs 40 pounds and can have maximum design tension ratings of up to 80,000 pounds [5].

Figures 3-3 and 3-4 show detail of the tower design including the electrodes and bubble delivery tubes. Although the details of the charging system are not known at this time, we feel that the pumping and delivery system shown would allow a representative cost estimate of the system. The collector electrodes are shown as strut shaped since this would result in significantly lower drag than circular shaped electrodes. Since the electric field lines are anchored, for the most part, on the upstream electrodes, they were left circular in cross-section.

In the calculations presented in Section 2, both electrodes were assumed to be circular. The substantial increased drag resulting from this assumption is partially offset by the fact that we neglected the tower drag and the variation in wind direction.

The conceptual design was submitted to the Solar Energy Research Institute (SERI) for costing of the design and their estimate is given in the next section.

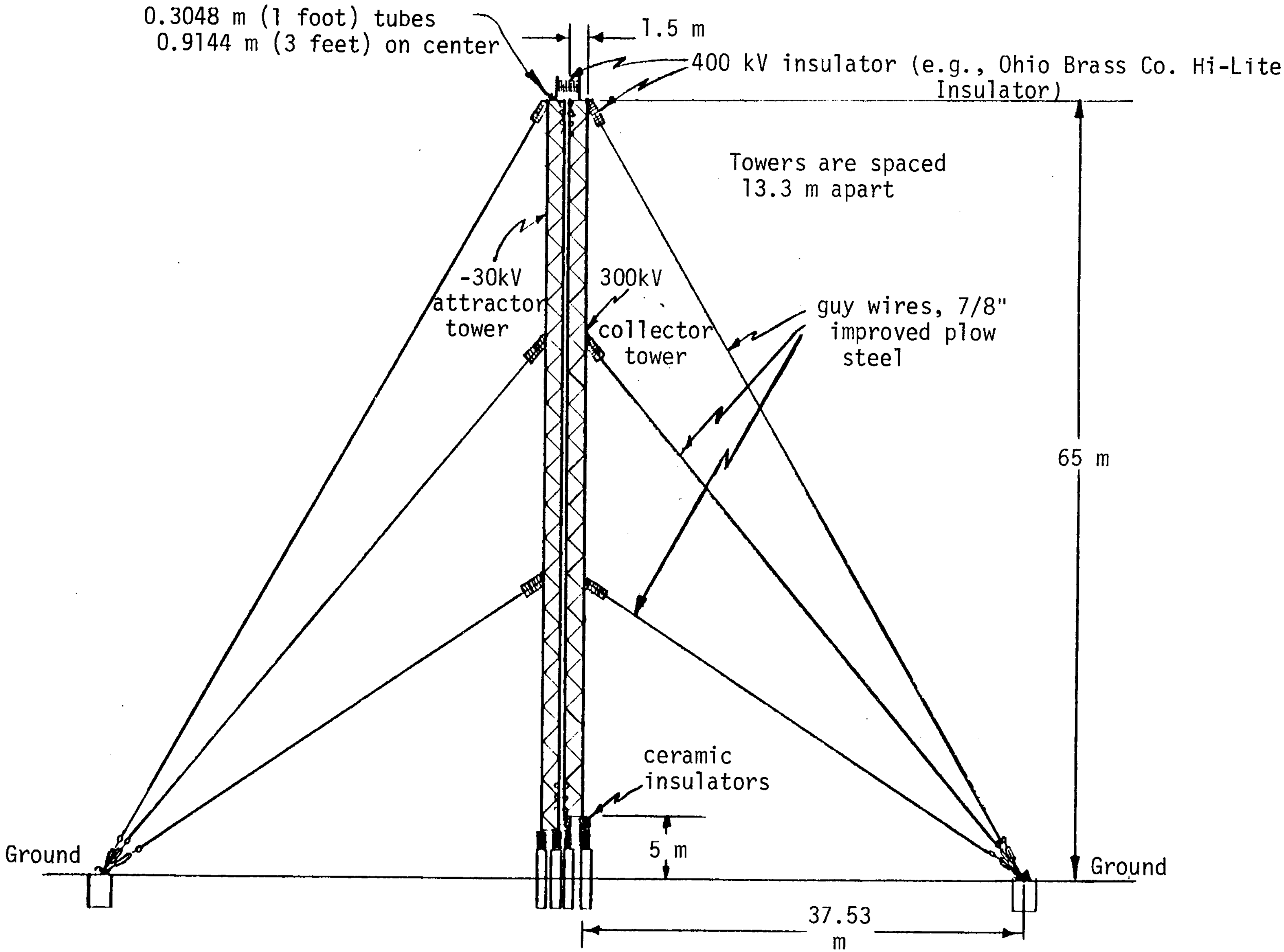


Figure 3-2. Side View of Tower.

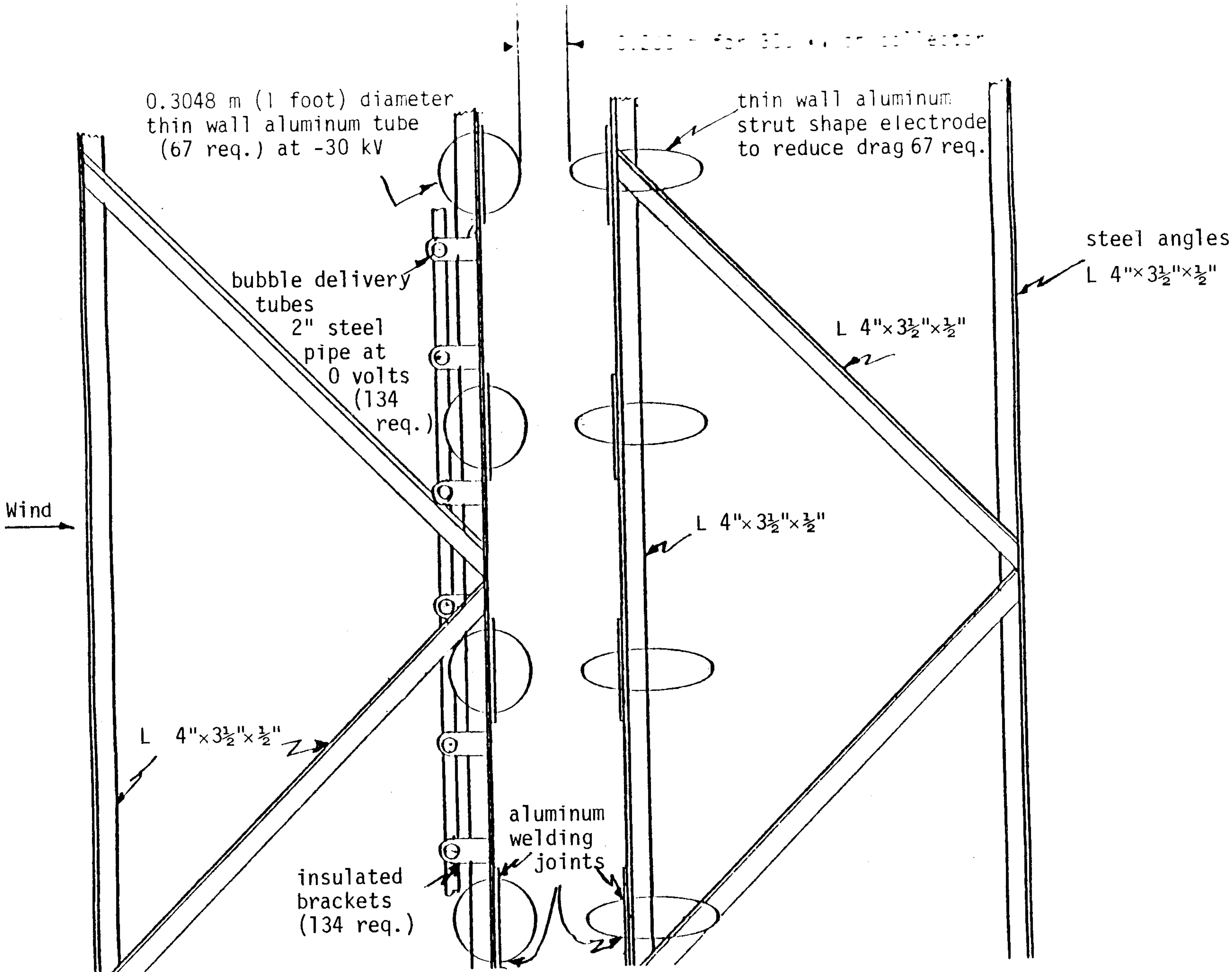


Figure 3-3. Detail of Towers and Rods: Side View.

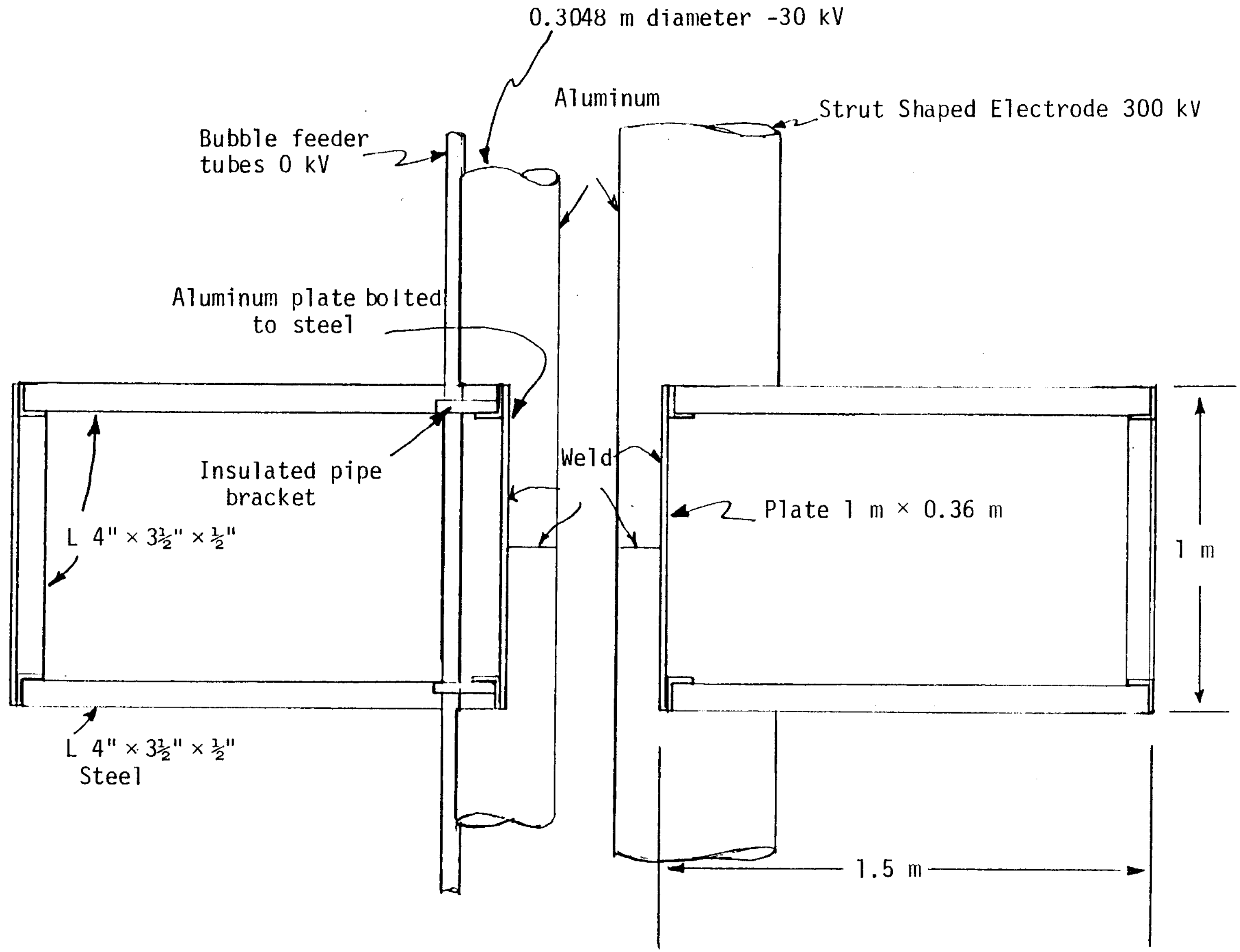


Figure 3-4. Detail of Tower: Top View.

SECTION 4

SERI PREPARED COST ESTIMATE

The following capital cost estimate of the electrofluid dynamic wind generator as presented by Dr. John E. Minardi and Mr. Maurice O. Lawson of the University of Dayton Research Institute, was developed by Ms. Connie Vineyard and Mr. Dave Lasier of SERI [6]. This cost estimate was developed through the use of the "Richardson Process Plant Construction Estimating Standards" and other manufacturers of specialized equipment.

Capital Cost (not including land)

Foundations	$ 56,000
Structural Steel & Rigging	8,750,000
Aluminum Tubing - Foils - Plants	10,841,000
Insulators	288,000
Pumping & Piping System/Foggers	3,138,000
TOTAL CAPTIAL COST	$ 23,073,000

Capital Detail Break Down

Foundation	$ 56,057
Structural Steel	8,598,745
Guy Wires	124,102
Aluminum Plate	735,694
Aluminum Tube	4,661,368
Aluminum Strut (Foil)	5,444,310
Insulators - (Guy)	191,065
Insulators - Barrier	96,695
Water Piping System	1,850,178
Steel Plates	26,621
Pumping Systems	155,444
Spray Nozzles (Foggers)	1,132,434
	$ 23,072,713

SECTION 5

CONCLUSIONS

The total capital cost (not including land) as given in the previous section for the first build is:

Foundation	$ 56,000
Structural steel and rigging	8,750,000
Aluminum tubing-foils-plates	10,841,000
Insulators	288,000
Pumping and piping system/foggers	3,138,000
TOTAL CAPTIAL COST	$ 23,073,000

The cost of energy (COE) using the standard Department of Energy (DOE) equation for annualized cost of energy is:

$$COE_{annual} = \frac{23,073,000 \times 0.18}{19,700,000} .$$

Since no attempt was made to fully optimize the design, it is felt that many opportunities exist for cutting the cost of an EFD wind driven generator. Although this particular design was for a length of 400 m, a configuration many times longer could easily be constructed. Thus, large amounts of energy could be extracted from favorable wind sites since extremely large conversion sections are possible.

Further, the maintenance and down time on the EFD wind driven generator should be less than for a conventional system with many smaller units with rotating parts. In addition the EFD wind driven generator does not require any additional power conditioning for long line power transmission.

However, a major effort is still required to develop an energy economic charging system. Once this problem is solved, we believe that it will be possible to produce EFD wind driven generators that will be cost competitive with other methods for producing high voltage dc power.

SECTION 6.0

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6. Richard L. Mitchell to John E. Minardi, 23 August 1982, correspondence.

Document Control Page	1. SERI Report No. SERI/STR-211-2277	2. NTIS Accession No.	3. Recipient's Accession No.

4. Title and Subtitle Conceptual Design of an Electrofluid Dynamic Wind Energy System	5. Publication Date March 1984 6.
7. Author(s) J. E. Minardi, M. O. Lawson	8. Performing Organization Rept. No.
9. Performing Organization Name and Address University of Dayton Research Institute Dayton, Ohio	10. Project/Task/Work Unit No. 4801.10 11. Contract (C) or Grant (G) No. (C) XE-1-1291-1 (G)
12. Sponsoring Organization Name and Address Solar Energy Research Institute 1617 Cole Boulevard Golden, Colorado 80401	13. Type of Report & Period Covered Technical Report 14.

15. Supplementary Notes

Technical Monitor: Bob Noun

16. Abstract (Limit: 200 words) This report contains a conceptual design of the electrofluid dynamic (EFD) wind-driven generator and performance estimates used to select the electrode spacing and other parameters. Various spacings and tube sizes in different wind fields were considered to assess the effects of different parameters. Although a detailed stress analysis was not done, preliminary estimates indicate that the tower design will withstand head-on winds in excess of 100 mph (44 m/s) without damage. Many opportunities appear to exist to cut the cost of an EFD wind-driven generator. Maintenance and downtime on this wind-driven generator should be less than for a conventional system with many units having rotating parts. The EFD wind-driven generator also does not require additional power conditioning for long-line power transmission. It should be possible to produce EFD wind driven-generators that are cost competitive with other methods of producing high-voltage dc power, once a charging system is developed.

17. Document Analysis

a. Descriptors Charged Particles ; Colloids ; Design ; Drag ; EFD Wind Generators ; Electric Generators ; Velocity ; Wind Turbines

b. Identifiers/Open-Ended Terms

c. UC Categories

60

18. Availability Statement National Technical Information Service U. S. Department of Commerce 5285 Port Royal Road Springfield, Virginia 22161	19. No. of Pages 34 20. Price A03

Form No. 0069 (3-25-82)