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PRELIMINARY TECHNICAL AND ECONOMIC EVALUATION OF VORTEX
EXTRACTION DEVICES

Final Report

By
T. R. Kornreich
R. J. Kottler, Jr.
D. M. Jennings

April 1980

Work Performed Under Contract No. AC02-77CH00178

JBK Scientific Corporation
Arlington, Virginia

U.S. Department of Energy

Solar Energy

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April 1980

JBF Scientific Corporation
Arlington, Virginia

prepared under

Subcontract No. AH-9-8003-6

for the

Solar Energy Research Institute
A Division of Midwest Research Institute
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Golden, Colorado 80401

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FOREWORD

The Solar Energy Research Institute (SERI) has been authorized by the U.S. Department of Energy to provide technical management services for the Wind Energy Innovative Systems (WEIS) program. The major focus of the WEIS program is to assess the technical and economic feasibility of innovative concepts and systems. Since a large number of these concepts may have potential merit, a critical examination of their technical and economic attributes will provide guidance and direction for future WEIS programmatic efforts.

This report contains a critical evaluation of two vortex extraction devices (the Tornado Wind Energy System and the Vortex Augmentor Concept) which are currently being funded by DOE. Emphasis is placed in this study on a comparison between these innovative concepts and comparable conventional horizontal axis wind turbines.

COMMENT

During FY79, studies were performed by subcontractors to assess the performance and cost potential of ongoing R&D efforts in the Wind Energy Innovative Systems program. To provide a baseline for the comparison of the different studies, specifications were provided for the calculation of the cost of energy, useful service life, wind environment and maximum design wind speed.

Innovative wind systems may have operating characteristics which are different from conventional wind systems. Optimum performance and minimum cost of energy may be sensitive to wind environment and wind loads. Future assessment studies will consider the effects of these conditions on the potential of the innovative system.

Irwin E. Vas

Manager

Wind Energy Innovative
Systems Projects

PREFACE

The technical staff personnel of the JBF Scientific Corporation who participated in this study were Dr. Theodore R. Kornreich (Principal Investigator), Richard J. Kottler, Jr., and Diana M. Jennings.

Dr. T.G. Toridis and Dr. K. Khozeimeh, Professors of Civil Engineering at the George Washington University, supported by Mr. S. Mehrkar, performed structural analyses of the Tornado Wind Energy System configurations. Dr. Daniel Schiff also served as a consultant on this project.

James T. Yen of the Grumman Aerospace Corporation and P.M. Sforza of the Polytechnic Institute of New York were very gracious in supplying information required for analyzing the Tornado Wind Energy System and the Vortex Augmentor Concept.

Dr. Irwin Vas and the Wind Energy Innovative Systems program staff have been both helpful and supportive of our efforts to complete this study.

In addition, many vendors and material suppliers (cited throughout the report) willingly supplied current price quotations so that the most up-to-date economic analysis could be carried out.

The JBF staff would like to express their sincere appreciation to all of these people whose outstanding cooperation enabled this study to be performed within the specified time period.

SUMMARY

PRELIMINARY TECHNICAL AND ECONOMIC EVALUATION OF VORTEX EXTRACTION DEVICES

Theodore R. Kornreich, Richard J. Kottler, Jr., and
Diana M. Jennings
JBF Scientific Corporation, Arlington, Virginia

ABSTRACT

Two innovative vortex extraction devices--the Tornado Wind Energy System (TWES) and the Vortex Augmentor Concept (VAC)--are critically evaluated to provide a preliminary assessment of their technical and economic viability as compared to conventional horizontal axis wind energy systems. This assessment was carried out over a wide range of power output levels and augmentation ratios appropriate to each of the concepts.

There are many technical uncertainties which still need to be resolved before the technical feasibility of the TWES can be assured. Present experimental work has dealt with very small-scale wind tunnel tests so that available data cannot be used with any degree of confidence to resolve these uncertainties and estimate full-scale system performance. However, even if all of the technical uncertainties are favorably resolved for the TWES, its "mature product" energy cost would be considerably greater than the mature product energy cost of conventional wind systems patterned after machines currently in use and under development (such as the MOD-0A and the MOD 2). The major cost driver for the TWES is the large, fixed vane reinforced concrete tower that is required. For example, the tower needs to be 103 meters high and have a 52 meter outer diameter to produce 1 MW of rated power at the best augmentation ratio that can be substantiated with data presently available.

The VAC is not subject to as many technical uncertainties as the TWES but still presents certain problems (such as vortex breakdown) which need to be experimentally evaluated. Field test data were not made available for this analysis. However, even under the most favorable VAC performance claims, its energy cost is considerably greater than the energy cost of comparable conventional horizontal axis wind systems. The major cost driver for the VAC are the delta surface (which acts as the wind augmentation device) and the transmission subsystem.

In both the TWES and VAC designs, rotor costs have been greatly reduced compared to conventional systems. However, that cost saving has been more than offset by the large costs associated with the augmentors.

Therefore, it appears that neither the TWES nor the VAC can be economically competitive with conventional wind systems even under the most favorable performance conditions claimed for these vortex extraction devices. If only performance data that has been experimentally validated is used in the analysis, the TWES energy cost is estimated to be at least 2 to 5 times the energy cost of conventional systems across the range of sizes considered (200 kW to 4 MW) while the VAC energy cost is estimated to be 1.5 to 3 times the energy cost of conventional systems across a power output of 40 kW to 1 MW.

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SECTION 1.0

INTRODUCTION AND APPROACH

1.1 INTRODUCTION

There are a number of advanced concepts being investigated under the sponsorship of the U.S. Department of Energy as part of the Wind Energy Innovative Systems (WEIS) program. This study, one of a series of technical analyses, provides a critical evaluation of the technical aspects, performance characteristics, and prospective costs of two vortex extraction devices--the Tornado Wind Energy System (TWES) and the Vortex Augmentor Concept (VAC)--in order to help guide future R&D efforts in the WEIS program.

The natural wind resource available throughout the United States is at a relatively low power density level. The hardware costs of utilizing this diffuse energy source is one reason why the utilization of wind power has not become widely established. However, through the use of an "augmentor", a mechanism for concentrating low power density levels, a system providing increased energy intensity may be developed. The "augmentor" effectively enables the extraction device to capture more energy than it could from an unaugmented natural wind force. If the cost effectiveness of a system which utilizes this concept could be demonstrated, a much broader application of wind turbine systems throughout the nation might be realized. The objective of this study is to determine whether vortex augmentation concepts have the potential for becoming cost-effective as compared to conventional horizontal-axis wind systems.

Section 1.2 presents an overview of the analytical approach used in the study. Section 2 contains the detailed technical and economic evaluation of the Tornado Wind Energy concept, including:

- o Establishment of a baseline case and a spectrum of alternative cases for evaluation;
- o Discussion of the major technical uncertainties which need to be resolved;
- o Capital cost and energy cost estimates for a "mature product" TWES and a comparison with conventional wind systems.

The corresponding evaluation of the Vortex Augmentor Concept is contained in Section 3.

Results of this study are preliminary because system configurations for the two vortex extraction concepts are not yet well-defined. This evaluation is based on the best data available, including information supplied by the principal investigators, but nevertheless contains many assumptions. These assumptions are clearly identified in the report. Despite the preliminary nature of results, the findings presented offer a basis for first approximations as to the future economic potential of these two systems.

1.1 ANALYTICAL APPROACH

A comparison of the energy cost levels attainable by mature product versions of the two vortex extraction devices and comparable horizontal axis wind systems was conducted in accordance with the approach outlined in Figure 1-1. At the start of the project, a meeting was held with each principal investigator* to obtain current technical data on each device.

After reviewing this data, principal subsystems were identified and a baseline case established. These baseline cases included selection of a representative rated power level and an anticipated augmentation ratio defensible in terms of experimental data and other supporting evidence. Required subsystem sizes were determined using published information wherever possible. Since each device is at a relatively early stage in its development, firm data on system configuration, size and materials were not available. A number of design assumptions were thus required in order to perform the analysis. These assumptions are clearly indicated in the report and the sources of information used are identified in every case.

In addition to the baseline cases, other cases were considered for each device to allow for analysis of a range of power output levels and "optimistic" augmentation ratios. The set of cases considered was the basis for establishing prospective economic viability for the two concepts over a wide range which included the most optimistic claims as to system performance and power output.

Mature product hardware costs for the TWES and VAC were obtained either through vendor price quotations or by computing the materials and fabrication costs for a particular subsystem. The sum of all subsystem costs yields the total mature product hardware cost. Non-hardware cost (site preparation, system assembly, installation and checkout, transportation, general and administrative expenses, contractors' fees, etc.) was estimated to be a fixed percentage** of hardware cost (1). The sum of hardware and non-hardware cost is the total installed cost.

*James T. Yen (Grumman Aerospace Corporation) for the Tornado Wind Energy System (TWES) and P.M. Sforza (polytechnic Institute of New York) for the Vortex Augmentor Concept (VAC).

**Forty percent based on MOD-2 estimates.

Figure 1-1 Economic Analysis Approach

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SECTION 2.0

THE TORNADO WIND ENERGY SYSTEM (TWES)

2.1 SYSTEM DESCRIPTION AND PRELIMINARY DESIGN

The TWES concept involves the creation of a confined, tornado-like vortex within a stationary tower (see Figure 2-1) through the injection of ambient wind flow. A tornado created in a natural environment will exhibit both a strong suction force and a very low pressure area within the core*. This combination produces the wind augmentation attributed to the system concept.

Grumman Aerospace Corporation, developer of the TWES concept, initially thought the tower design would consist of adjustable vanes oriented in the direction of the wind. More recent efforts indicate a fixed vane, omni-directional design may be more cost-effective.

The fixed-vane tornado tower has no moving parts and will admit wind flow from any direction. The tower is expected to incorporate a duct structure which diverges from the rotor downward to the ground plane. This structure houses several major subsystems including rotor, transmission and generator.

Based on rated power levels, a series of power output vs. wind speed curves was developed for each vortex extraction device. In terms of cut-in and rated wind speed, and characteristic shape, they were similar to conventional horizontal-axis systems. The combination of the power output profile and the wind duration profile specified by SERI for use in this study enabled the total annual energy output to be calculated. A 90% availability factor was used to determine total usable energy output. The energy cost was then determined using the standard equation for computing the busbar cost of electricity.

Energy costs for the TWES and VAC were compared to the energy costs of comparable-sized conventional horizontal axis systems in the same wind regime**. This comparison enabled conclusions to be drawn concerning the potential economic viability of the TWES and the VAC across a range of sizes and performance levels.

The rotor is positioned vertically at the mouth of the diverging base and directly beneath the core of the vortex, thus permitting maximum utilization of the vortex strength. The increased mass flow and convergence of the base towards the rotor, creates a plenum chamber effect which further enhances pressure drop across the turbine.

*Analytical and experimental investigations have not yet indicated which of these factors is responsible for the greatest portion of the augmentation effect.

**A mature product version of the MOD-OA (200 kW); a mature Product MOD-2 (2.5 MW); a mature product version of one of 40 kW systems currently under development by DOE.

Figure 2-1

Conceptual View of Tornado Wind Turbine (first concept)

Augmented power output is not the only advantage of the TWES concept. The vortex created within the tower acts as a buffer and effectively smooths wind flow, thus eliminating the need for a pitch control mechanism and intricately designed rotor blades. This buffering effect suggests that a constant chord, fixed pitch blade could be used in lieu of more expensive designs. The specific output of a TWES will depend on a design optimization process which links tower height and diameter with ambient wind speed.

Although the fixed vane tower geometry is an integral part of current TWES design concepts, no firm vane design has yet been established. In this analysis we have considered two alternative vane designs. In our original discussions with the Grumman Aerospace Corporation, limitations in information available on the tower design led us to select for evaluation the design illustrated in Figure 2-2. As this assessment progressed, a second candidate vane design emerged (see Figure 2-3) and was aimed at providing improved aerodynamic characteristics. The analysis of the TWES presented here considers both of these vane design concepts.

2.1.1 First Design Concept

The tower design shown in Figure 2-2 is based on a 1 MW baseline TWES*. The required tower dimensions are 112.7 m (370 ft) in height (including supports) and 51.8 m (170 ft) in diameter. Discussion with the principal investigator indicated that the TWES tower would likely be constructed of reinforced concrete and that the tower might have anywhere from 8 to 16 vanes.

The conceptual tower design for evaluation has 12 vanes with a ratio of vane cross-sectional area to air space between vanes of 2 to 1. The inner and outer walls of the tower were assumed to be circular while each vane was assumed to have both inward and outward parabolic curvature at its respective edges. A structural analysis** indicated that for this design each vane must be 10 feet thick with a cross-sectional area of 27.0 m^2 (294 ft^2).

The converging duct was assumed to have a conical geometry with sheet steel construction and right angle triangular bracing for support. The rotor was assumed to have two constant chord, fixed pitch blades***. The gear box assumed is a speed increaser system which converts 1000 rpm rotor output to the 1800 rpm input required for an "off-the-shelf" generator. The entire system will likely be placed on a concrete foundation, the dimensions (and cost) of which are strongly site-dependent.

*See Section 2.3 for detailed discussion of baseline system.

**See Appendix A for details.

***Grumman has recently redesigned the rotor as a "multi-bladed gas turbine-like system"; this redesigned system is expected to be much more costly than the one used in our analysis.

Figure 2-2
TORNADO WIND ENERGY SYSTEM
Base Line Design – First Concept ^a

2.1.2 Second Concept

All TWES components for the second design concept with the exception of the tower will be the same as in the first. The second tower design makes use of "wing-like" vanes to enhance aerodynamic efficiency, which differ the support dimensions and column orientation and size from the first concept. An illustration of this concept is given in Figure 2-3.

2.2 TECHNICAL UNCERTAINTIES

A review of the technical literature concerning anticipated TWES operation indicates there are a number of potential problems which need to be resolved. The basis for resolving these problems can only be the gathering of experimental data not yet available. Experimental work done to date has primarily been wind tunnel testing of small tower section models about one percent of the baseline TWES height discussed here. Therefore, available data is of limited use in projecting full-scale system performance. TWES flow characteristics are insufficiently understood to allow performance projections with the degree of confidence required for estimating energy costs to the satisfaction of prospective users. The difficulties encountered in evaluating flow considerations make it difficult to optimize system design or predict power output without the benefits of extensive wind tunnel testing.

Aside from flow problems, a full-scale TWES could present other difficulties associated with turbine design and power conditioning. For example, introduction of waste heat at the bottom of the TWES tower seems attractive as a performance enhancement device, but practical engineering problems must be resolved before energy utilization and associated costs of this feature can be determined.

While it appears that construction of a baseline TWES would be within the present state of technology, such a project would require customized construction. On-site tower fabrication would be required for the mW-scale TWES envisioned. The pumping of concrete to heights of 370 feet is not a standard industrial construction technique. For smaller systems it is possible that factory-produced modules could be delivered to the TWES site for assembly, but there would be high transportation costs associated with this fabrication strategy.

In summary, there are major technical concerns associated with certain aspects of system design optimization and performance which require resolution prior to demonstration of TWES commercial readiness. The balance of this section explores the major technical problems in greater depth.

Figure 2-3

TORNADO WIND ENERGY SYSTEM Base Line Design—Second Concept^a

^aDimensions in ft

2.2.1 Major Flow Problems

"It has become apparent that there are at least four major unresolved flow problems that must be understood in order to predict the TWES output. In addition to these key unsolved problems, there are many other problems of a secondary effect that must be solved. Despite a very large amount of definitive advice from a wide variety of sources, it is not clear to us how any of the aforementioned problems can be avoided if performance calculations are to be made. Unfortunately, neither is it yet clear how any of those same problems can be solved" (2).

Obviously, in order to have some degree of confidence in TWES performance estimates these problems must be satisfactorily resolved. At present, modeling the TWES flow for computational purposes and scaling TWES performance to full-size systems cannot be accomplished with any degree of assurance*. One alternative, perhaps the only presently available, is to test substantially larger TWES models in the field in order to develop realistic data supporting anticipated power production.

Five major flow problems of concern are discussed below.

2.2.1.1 Mechanism of Vortex Formation

A model has not yet been developed which describes the physical phenomena leading to the action of tower surfaces in forming the tower vortex. Kelvin's theorem indicates that a change in circulation along a closed fluid line in a frictionless, homogeneous fluid cannot occur. This theorem indicates that core vorticity could be prevented from forming from an irrotational free wind if there were no surfaces and if the air was inviscid. However, it is the tower surfaces which create the vortex; the circulation around the wall surfaces must add up to be equal and opposite to the circulation around the vortex core, making proper allowance for the convection of core vorticity in the axial direction. The tower surfaces (i.e., the tower inlet vanes) act as lifting surfaces which shed their trailing vorticity at the tip to form the inlet flow into a vortex. This process must be better understood in order to properly design inlet vanes and tower geometry and to reliably predict system performance.

2.2.1.2 Dependence of Vortex Core Diameter on Tower Reynolds Number

One of the major areas of uncertainty in the performance of a full-scale TWES is the way in which terms on either side of equation (2-1) depend on tower Reynolds number (Re).

*An excellent survey of the difficulties encountered in attempting to solve turbulent flow problems has been presented by Hans Liepmann in Elements of Gasdynamics, Galcit Aeronautical Series, 1957, John Wiley & Sons, Inc., New York.

$$D/D_c = R/r_c \quad (2-1)$$

where: D = tower diameter
 R = tower radius
 D_c = vortex core diameter
 r_c = vortex core radius.

The tower Reynolds* number is given by:

$$Re = V_0 D / \nu \quad (2-2)$$

where: V_0 = wind speed at the tower wall (assumed to be equal to free stream wind speed, V_∞)
 ν = kinematic viscosity of the air.

The ratio of tower radius to vortex core radius is a function of Re ,

$$R/r_c = K (Re)^m \quad (0 \leq m \leq 1) \quad (2-3)$$

where: K = a constant.

There is some disagreement as to the value of m that might be expected from the TWES. Some feel that the vortex structure (including the core) will scale uniformly with increases in tower size (i.e., $m = 0$). Others feel that m will be greater than zero, although not necessarily close to unity. There is no experimental data to support the selection of any specific value for m . However, its importance is shown in the analysis below.

One study (3) has shown that the TWES power output is given by:

$$P = K' \Gamma_\infty^3 / r_c \quad (2-4)$$

where: Γ_∞ = the vortex circulation
 K' = a constant.

For a given wind speed and tower size, the TWES power output may be expressed as:

$$P = K'' (Re)^m \quad (2-5)$$

where: $\Gamma_\infty = 2\pi V_0 R$ is the circulation in the potential vortex outside the vortex core

K'' = a constant.

*Reynolds number is a dimensionless grouping of flow variables for a specific stream, and is given by the product of stream velocity and stream diameter divided by kinematic viscosity. Depending on the Reynolds number, a flow situation may be laminar, transitional, or turbulent.

Since

$$\begin{aligned} (\Gamma\infty)^3/r_c &= \text{constant} (R^2) (R/r_c) = \text{constant} (R^2) (Re)^m \\ &= \text{constant} (R^2) (V_0 D/\nu)^m, \end{aligned} \quad (2-6)$$

another way of expressing the power output is:

$$P = K'' (R)^{2+m}, \quad (0 \leq m \leq 1). \quad (2-7)$$

Thus, if TWES tower dimensions are doubled, the power output for a fixed wind speed would increase between four and eight-fold depending on the appropriate value of m . Since this range of uncertainty has important implications for the economic viability of the TWES concept, it is convenient to express the scaling uncertainty in TWES power output from tower radius R_1 to tower radius R_2 as:

$$\Delta P = (R_2/R_1)^{\Delta m}. \quad (2-8)$$

Thus, if the value of m were known with any degree of certainty this would enable a reasonable estimate of power increase as a function of tower dimensions to be developed.

It has also been proposed that the vortex core radius changes as a function of height along the vertical axis of the tower (1). It is important to understand and predict this effect in order to design tower shape in a manner optimal to increased system power and decreased energy cost. The high velocity near the vortex core causes a reduction in centerline air density which superimposes a buoyancy effect on the pumping action observed. This effect, also a function of tower height, is important to design optimization. This topic represents another area where a quantitative understanding of the physical phenomena is still lacking.

2.2.1.3 Interaction of Vortex Wake with the Atmosphere

The vortex exits from the tower at less than atmospheric pressure and interacts with incident air flow above the tower. This interaction will apparently result in a sharp downstream curvature of the coherent vortex (from vertical to horizontal), followed by an apparent vortex breakdown as the vortex axis becomes parallel with free stream wind velocity. It is claimed that this strong interaction between the vortex and the incident wind transfers a significant amount of energy from the wind to the vortex, as the pressure in the vortex wake is restored to atmospheric pressure (1,4).

This process can be viewed as a means of extracting energy from wind streams above the tower without any additional mechanical subsystems. The magnitude of this secondary effect cannot be ascertained since no theory or quantitative data exists for establishing the interaction. An understanding of these wake processes is necessary for system design optimization and system power prediction.

2.2.1.4 Turbine, Axial Flow, and Vortex Stability

The original analysis of vortex and system performance assumed that the exhaust flow from the turbine contained negligible angular momentum (5,6). It was also recognized that if the turbine exhaust was directed at the proper exit angle, the angular and axial components of the turbine exhaust momentum could lead to an efficient and stable turbine-vortex interaction. Attainment of this flow geometry could reinforce the vortex core and thus have a beneficial effect on overall system performance.

It has since been concluded by Yen (2,4) that the flow regime surrounding the turbine exhaust "plays a very significant and mysterious role in inducing tower axial flow", and that the turbine exhaust layer inflow interaction creates a "pumping effect" which is a central part of the overall TWES process.

Most of the theoretical work on the TWES project up to now has been devoted to the study of the flow process described above. Until these interactions can be completely understood, it will be difficult to properly design and confidently predict the performance of a large TWES.

2.2.2 Other Problem Areas

There are several other problem areas discussed below which, while not directly related to the solution of flow problems, are of importance in the assessment of TWES technical feasibility.

2.2.2.1 Multiple Rotor Configurations

For a commercial scale TWES, the vortex core cross-section will probably be much larger than the area that can be covered by a single rotor of the type proposed. Therefore, it has been proposed that a number of smaller rotor assemblies rather than a single large one be used to extract energy in the vortex (4). The baseline 1 MW TWES would have a vortex core diameter of 20.7 m (68 ft). If 3 m (10 ft) diameter rotors were used it would take approximately 35 - 40 of these to cover the vortex core. Even if the diameter were increased to 6 m (20 ft), nine would still be required. This multiple rotor approach introduces several problems, two of which are discussed below.

The interaction between turbine exhaust and vortex stability may affect axial flow along the tower. It is not known at present how multiple rotor impacts on vortex behavior can be quantitatively assessed.

A second concern is the design aspects of combining multiple mechanical inputs into a single, conditioned electrical power output. This problem may be approached in a number of different ways, but it is likely that costs will be greater and efficiency lower than if a single turbine were used.

Since it is anticipated that all rotors in this configuration will operate at constant speed, three candidate approaches exist:

- o Parallel operation of each individual rotor/generator as a complete turbogenerator set.
- o Connection of all rotor assemblies to a mechanical system which powers a single generator.
- o Connection of a partial group of rotor assemblies through a mechanical system to a single generator, followed by the combination of the electrical output from all the partial group generators.

A set of problems common to all these options is the support structure design detail for the rotors which, in conjunction with the shafts, may interfere with the air stream entering the duct. The space between rotors represents about 22% of the total area covered by the rotors. If this space is not blocked off, a power loss may be experienced; if the space is blocked off, the aerodynamic balance between turbine exhausts and tower vortex core may be adversely affected.

Another potential problem involves the effects of multiple exhausts on the axial and angular velocity component requirements of the vortex core. It appears that structural support requirements and the multiple exhaust stream dynamics pose some difficult flow problems which must be addressed in the TWES design process.

Irrespective of the multirotor design approach, a loss in power extraction efficiency compared to the extractive efficiency of a single large blade is almost certain to be encountered. If each rotor is connected to its own generator, and electrical outputs are combined, a transmission, generator and power conditioner for each unit will be required. It is very likely that a number of transmission-generator-power conditioner sets (rated at P_0 kW each) will cost more than one transmission-generator-power conditioner set with the same total rating.

If the rotor assemblies are connected to a mechanical system which powers a single generator, the cost of the transmission-generator-power conditioner set and the electrical wiring should be reduced. However, the cost of the mechanical coupling of all of the individual assemblies to a single shaft output may more than offset savings. Also, the mechanical design may be complicated (with an attendant cost increase) by potentially unequal power outputs of different rotors. Such mechanical coupling equipment does not appear to be commercially available, and would likely be costly to develop. If a partial group of rotor assemblies were connected to a mechanical system which powers a single generator and the electrical output from all the generators were combined, it is likely that this hybrid approach would combine the problems of both the single-generator and the multi-generator approaches.

There is insufficient information available to determine which of the above options would be most cost-effective in a commercial, mass production situation. A more detailed examination of this system design aspect and its attendant cost considerations is required.

2.2.2.2 Waste Heat Utilization

It has been suggested that the addition of waste heat at the bottom of the TWES tower could serve to enhance the power output of the system. While this idea may improve TWES performance, there are a number of limitations on its potential use.

Combustion air from in-situ burning in coal mines has been suggested as a heat source for the TWES (7). This in-situ technology has not been demonstrated, and any waste heat generated from this process must not only meet environmental control requirements but may also present additional materials requirements (i.e., resistance to sulfuric acid corrosion) on the TWES components.

Use of cooling water from other power production processes presents other problems. The warm water could not directly heat the inlet air at the tower base because evaporation would reduce the heat input to the air and lead to condensation in the tower. Thus, a water-to-air heat exchanger loop would be required. Because of the small temperature gradient, large heat transfer areas would be required, thus leading to significant additional costs.

A more fundamental difficulty in the use of waste heat stems from the fact that in order to convert the available heat into mechanical work, the air stream near the tower base must be hotter and less dense than the air stream leaving the top of the tower. This thermally-induced density gradient is exactly opposite to that required to promote vortex stability and an axial pumping motion. Therefore, the use of waste heat as a "performance booster" for the TWES appears to introduce fundamental and serious problems which would likely prevent any performance benefit that might be obtained.

2.2.2.3 Tower Vanes

At present, the tower design incorporates fixed vanes which represent a significant capital and operating cost saving compared to an adjustable vane design. However, the use of fixed vanes will possibly degrade the performance that might be obtained as compared to the adjustable vane configuration.

Irrespective of the use of either fixed or adjustable vanes, these vanes are designed to maximize lifting force, thus creating the trailing vortices that are shed to create radial flow into the tower vortex. These vanes will be subjected to wind forces

designed to be maximized rather than minimized as in most structural applications. This intentional vortex shedding effect may produce an oscillatory or "strumming" effect with a frequency directly proportional to wind speed. Because of the great variation in wind speeds to be encountered during TWES operation, a considerable frequency range may be encountered which may include some of the natural mechanical vibration modes of the vanes. If such a situation occurs, internal fatigue and structural degradation could result. This operational aspect must be carefully considered in the TWES tower and vane design.

2.2.2.4 Foundation Requirements and Siting

A subject not addressed in the technical literature on the TWES is the foundation required for the structure. The extremely large weight of the TWES tower (see Sections 2.3 and 2.4) limits the sites where it might be erected. If the TWES were constructed anywhere but on bedrock, the foundation could conceivably cost more than the entire system.

Severe restrictions on TWES siting limit its utility. For example, the Grumman suggestion of placing tornado systems in coastal areas does not appear reasonable because of the generally poor soil conditions in these areas and the attendant need for a massive foundation.

2.3 BASELINE TWES EVALUATION

In order to facilitate comparison of the TWES and a conventional horizontal axis system, a MW-scale unit has been chosen to represent the baseline configuration. In the analysis, a TWES with a rated power output of 1 MW is compared with a conventional wind turbine similar to the current MOD-2 design. As indicated in Section 2-1, two different tower design concepts will be evaluated.

2.3.1 Design Concept #1

2.3.1.1 Tower Configuration

The most recent analysis by Grumman (4) was used for developing tower dimensions of the baseline system. Using a power coefficient of 0.1 as the baseline value* the tower height required to produce a 1 MW rated output is 103.6 m (340 ft). The required outer tower diameter is 51.8 m (170 ft). The tower base is supported 9.1 m (30 ft) above ground level**.

*This is the highest value obtained in small-scale model tests; impact of higher values of C_p on TWES costs are examined in Section 2.4.

**Based on discussions with J. Yen who indicated that current plans envision a height to outer diameter ratio of 2.

Tower construction is of reinforced concrete and consists of 12 vanes*. The vane design was developed based on structural considerations. A detailed structural analysis of a tower (see Appendix A) which would need to withstand 53.6 m/sec (120 mph) winds led to the following results:

- o Number of Vanes 12
- o Length of Vanes 103.6 (340 ft)
- o Vane Cross Sectional Area 37.3 m^2 (294 ft^2)
- o Reinforced Concrete per Vane 2831 m^3 ($1 \times 10^5 \text{ ft}^3$)
- o Weight of Each Vane $6.8 \cdot 10^6 \text{ kg}$ ($15 \times 10^6 \text{ lb}$)
- o Vane Supports: 12 columns each of which is 9.1 m (30 ft) high has a cross-sectional area of 13.9 m^2 (150 ft^2), requiring 127 m^3 (4500 ft^3) of reinforced concrete and weighing $306,800 \text{ kg}$ ($675,000 \text{ lb}$).
- o Wall Thickness 3 m (10 ft)
- o Inner Tower Diameter 45.7 m (150 ft)

The vanes would be joined at the top and bottom of the structure by two reinforced concrete rings, each of which has a surface area of about 464 m^2 ($5,000 \text{ ft}^2$) and is 3 m (10 ft) in depth. Each ring therefore requires about 1416 m^3 ($50,000 \text{ ft}^3$) of concrete and weighs $3.4 \times 10^6 \text{ kg}$ ($7.5 \times 10^6 \text{ lb}$).

The 3 m (10 ft) wall thickness is more than sufficient to withstand required wind loading. However, the maximum winds that might be applied to the TWES (53.6 m/sec) would cause a horizontal deflection of almost 0.6 m (2 ft) at the upper reaches of the tower. Deflections any larger than this could cause the concrete to crack thereby reducing the torsional stiffness of the tower and leading to potential structural impairment. Internal structural stress on the tower attributable to the internal vortex were not considered.

On-site construction would be required to fabricate a tower of this size. The use of modular construction was not considered feasible for a project of this size since:

- o Present-day construction techniques for projects of this kind could only use on-site techniques with movable forms;
- o Modules of the size needed to construct the TWES tower could present significant transportation problems.

The cost of construction of the baseline TWES tower was determined as follows. Reinforced concrete costs typical of present-day office building construction were determined (8) to be as follows:

- o $\$42.37/\text{m}^3$ ($\$1.20/\text{ft}^3$) - materials
- o $\$19.43\text{m}^3$ - $\$33.25/\text{m}^3$ ($\$0.55/\text{ft}^3$ - $0.95/\text{ft}^3$) - construction.

*Strategies are discussed in Section 2.7.

The lower value of construction costs applies to the construction of a thin wall while the maximum refers to construction of non-conventional shapes. The complexity of the TWES vanes and ring supports would undoubtedly lead to costs at the upper end of the range. Columns which are of a simpler design were assumed to include labor (construction) costs of $\$26.49/\text{m}^3$ ($\$0.75/\text{ft}^3$).

Table 2-1 summarizes the cost estimates associated with construction of a baseline 1 MW TWES tower for this first design concept. The total estimated cost is \$2.9 million, with the vanes accounting for almost 90% of the cost. The total tower weight is approximately 91×10^6 kg (200×10^6 lb).

The actual cost if the baseline tower were built would probably be greater than the \$2.9 million figure based on "standard office building" construction. Factors contributing to the additional cost include additional equipment and manpower required for simultaneous vane construction*; additional structural framing needed for the vanes until the top reinforcing ring can be poured and cured; and the internal shield needed to obstruct wind flow until the tower is completed and operational.

2.3.1.2 Generator

The 1 MW generator needed for the baseline design would be a standard item weighing 3,090 kg (6800 lb) with a present cost of \$25,000 (9).

2.3.1.3 Rotor and Hub

Initial Grumman TWES designs call for constant chord, fixed pitch rotor blades. An analysis is currently underway to determine the performance enhancement obtained by using twisted blade designs. Present thinking is that nine curved blades with an approximate 2 to 1 ratio of hub diameter to blade length is appropriate. Since the cost-effectiveness of this new rotor design is unclear, we have estimated the rotor and hub costs based on the original constant chord, fixed pitch concept**.

Based on data supplied by Grumman (10), the rotor diameter is expected to be 20% of the height of the tower. Assuming that the hub diameter is about 10% of rotor diameter***, the characteristics of the rotor and hub were estimated and are shown in Table 2-2. The total cost of rotor/hub fabrication is estimated to be about \$10,000 for the baseline 1 MW configuration.

*Recommended by structural engineers to alleviate the support problems that would be encountered if individual vane construction were used.

**The new curved blade approach would introduce significant additional cost over that presented here.

***This is based on conventional wind turbine dimensions for large scale systems.

Table 2-1

ESTIMATED COST OF 1 MW BASELINE TWES
TOWER (DESIGN CONCEPT #1)

<u>Number</u>		<u>Required Reinforced Concrete, 10³ kg (10³ Cubic feet)</u>		<u>Cost to Build \$/m³ (4/ft³)</u>	<u>Total Cost (1979 Dollars x 10⁶)</u>
Vanes	12	34	(1200)	75.92 (2.15)	2.58
Columns	12	1.53	(54)	68.86 (1.95)	0.10
Rings	2	2.8	(100)	75.92 (2.15)	0.22
<hr/>					
Total	---	38.3	(1354)	---	2.90

Table 2-2

BLADE/HUB CHARACTERISTICS
FOR BASELINE 1 MW TWES
(DESIGN CONCEPT #1)

Rotor Diameter	20.7 m	(68 ft)
Hub Diameter	2.13 m	(7 ft)
Blade Length	9.3 m	(30.5 ft)
Blade Chord	1.2 m	(4 ft)
Total Blade Surface Area	45.3 m ²	(488 ft ²)
Total Weight of Blade Skin ^a	11.1 kg	(2488 lb)

Total Blade Cost (Materials Only) ^b	\$	375
Hub Cost (Materials Only) ^{b,c}		4250
Total Materials Cost ^b	\$	4625

Total Cost of Fabrication ^{b,d} (Hub and Blades)	≈	\$10,000
--	---	----------

^aUsing .32 cm (1/8 in) steel sheet 24.9 kg/m²; cost \$0.33/kg; inner supports not considered.

^bAll costs are in 1979 Dollars.

^cBased on weight 1930 kg (4250 lb) extrapolated from Kaman Aerospace Corporation (1977); cost of \$2.20/kg supplied by Edgcomb Metals Inc.

^dMultiplier of about 2 for materials cost to total cost supplied by Grumman Aerospace Corporation.

2.3.1.4 Duct

The duct is a converging, conical component linking the tower base and rotor (see Figure 2-4). It is 9.1 m (30 ft) in height with the larger and smaller radii being 22.0 m (75 ft) and 10.7 m (35 ft) respectively.

Figure 2-4: TWES Duct Configuration^a

^aDimensions in ft

Total duct surface area is about 2880 m² (31,000 ft²) with a weight of 71,400 kg (157,000 lb) and a materials cost of about \$24,000 (11), assuming .3 cm (1/8 in) steel sheet is used.

The duct also requires 11 support braces, spaced at 6 m (20 ft) intervals, which weigh about 8636 kg (19,000 lb) and have a total materials cost of about \$4,000. Assuming that labor costs in fabricating the duct are equal to the materials cost, the total cost of duct (and bracing) fabrication is \$56,000.

2.3.1.5 Transmission

The transmission is a gear speed increaser which takes the 1000 rpm rotor output and raises it to the 1800 rpm needed for generator operation. The rated torque for a 1 MW system is 7000 ft-lb and since peak torque is estimated to be three times rated torque (12), 28,455 J (21,000 ft-lb) represents the peak design torque. A transmission to meet these requirements would cost about \$39,000 and would weigh approximately 6363 kg (14,000 lb) (13).

2.3.1.6 Non-Hardware Costs

The costs associated with site preparation, system assembly and installation, transportation of subsystems to the site, general and administrative expenses, and contractors' fees are usually expressed as a fixed percentage of total hardware cost. This study will use a fixed percentage of 40%, which represents the latest estimate for a mature product MOD-2 wind turbine system (1)*.

*Land acquisition costs have not been included.

2.3.1.7 Total System Cost

Table 2-3 presents a summary of the total cost associated with the installation of a mature product 1 MW baseline TWES. Total installed system cost is estimated to be \$4,240,000 compared to \$800,000 to \$1,000,000 for a 1 MW mature product system patterned after the MOD-2. Almost all of the entire TWES hardware cost is associated with the tower, while non-hardware costs constitute the remaining significant portion of total system cost.

This TWES cost estimate is believed to be significantly understated because a number of items (especially the foundation) were not included. Section 2.6 presents the rationale that has led us to this conclusion.

2.3.2 Design Concept #2

A cost estimate for the second design concept (wing-like vanes) was also developed. The wing vane design concept is identical to the first baseline design with the exception of vane configuration details.

A structural analysis of this configuration indicates that the absolute minimum width of the vanes that would be required to withstand 53.6 m/sec (120 mph) winds would be 1.2 m (4 ft). This was based on the minimum usage of reinforcing rods allowed by American Concrete Institute (ACI) specifications. In the case of a four foot vane width, the maximum deflection encountered at the tower top in 53.6 m/sec (120 mph) winds would be 2.3 feet.

It is believed that good construction practice and the incorporation of required safety factors would necessitate a vane width of at least 1.8 m (6 ft) if this TWES design modification were used*. In 53.6 m/sec (120 mph) winds, the maximum deflection encountered with 1.8 m (6 ft) vanes would be about 0.3 m (1.0 ft).

Based on the use of a wing-like vane, maximum vane width is reached at a point equal to 30% of the chord length. Assuming a 15° angle of attack for the vane and the use of 12 vanes and a 9.1 m (30 ft) wide support ring, the total chord length is about 28.3 m (92.7 ft) (see Figure 2-5).

Structural analysis of the TWES tower indicates that support rings should cover the entire tower cylinder; these rings should be 1.5 m (5 ft) deep for the 1.8 m (6 ft) vane width and 0.9 m (3 ft) deep for the 1.2 m (4 ft) vanes.

*See Appendix A for detailed structural analysis.

Table 2-3

ESTIMATED COST OF
1 MW BASELINE TORNADO WIND ENERGY SYSTEM
(DESIGN CONCEPT #1)

	<u>Weight - kg (lb)</u>	<u>Cost (1979 Dollars)</u>
Tower	91.8X10 ⁶ (202X10 ⁶)	2,900,000
Generator	3,091 (6,800)	25,000
Rotor and Hub	3,045 (6,700)	10,000
Duct	80,000 (176,000)	56,000
Transmission	6,363 (14,000)	39,000
<hr/>		
Total Hardware	91.9X10 ⁶ (202.2X10 ⁶)	3,030,000
Non Hardware Costs (40% of Hardware Cost)		1,210,000
<hr/>		
Total	91.9X10 ⁶ (202.2X10 ⁶)	4,240,000

Figure 2-5: Wing Vane Design Configuration^a

^a Dimensions in ft

Based on input from Grumman, a 9.1 m (30 ft) support column height was used. Structural analysis indicates columns would need to be 9.1 m (30 ft) long to properly distribute both support ring and tower weight. A 3m (10 ft) width would be needed to support the dead weight of the tower and the bending forces attributable to 53.6 m/sec (120 mph) winds. Column orientation was taken to be collinear with the axis of the vanes.

The structural characteristics for the two vane cases are given in Table 2-4. The cost of a 1 MW TWES using these wing-like vanes was established using the same costing procedures reported for the first design concept. The results are summarized in Table 2-5. The tower with 1.2 m (4 ft) vanes is significantly less expensive than the first concept while the 1.8 m (6 ft) vane configuration is more costly. At the baseline size the installed TWES cost is estimated to be no less than \$3,180,000; however, as in the first case a number of significant cost items were not considered. It appears that a mature product, baseline TWES installation would be at least 3 to 4 times as costly as a conventional horizontal axis wind system with the same rated power level.

2.3.3 TWES Performance

A given value for conduct of this study was an annual mean wind speed of 5.4 m/sec (12 mph). However, the wind resource varies considerably with different locations and heights and is sensitive to terrain conditions. Wind velocity also varies on a diurnal and seasonal basis. These variations must be reconstructed from the given value for annual mean wind speed in order to facilitate performance analysis. The first important parameter is the wind speed at the vertical elevation of the wind turbine rotor. This velocity governs the power output and the annual energy output of the system.

Table 2-4

STRUCTURAL CHARACTERISTICS OF BASELINE
TWES TOWER (DESIGN CONCEPT #2)

VANES

	<u>Case A</u>	<u>Case B</u>
Height - m (ft)	103.6 (340)	103.6 (340)
Width - m (ft)	1.2 (4)	1.8 (6)
Number	12	12
Cross-Sectional Area - m ² (ft ²)	19.3 (208)	28.8 (310)
Weight per Vane - kg (lb)	4.8X10 ⁶ (10.6X10 ⁶)	7.2X10 ⁶ (15.8X10 ⁶)

Support Columns

Dimensions - m (ft)	9.1 x 9.1 x 3 (30 x 30 x 10)	9.1 x 9.1 x 3 (30 x 30 x 10)
Number	12	12
Volume per column - m ³ (ft ³)	255 (9000)	255 (9000)
Weight per column - kg (lb)	0.63X10 ⁶ (1.4X10 ⁶)	0.63X10 ⁶ (1.4X10 ⁶)

Support Rings

Number	2	2
Dimensions - m (ft)	9.1 x 9.1 x 0.91 (30 x 30 x 3)	9.1 x 11.5 x 1.5 (30 x 38 x 5)
Surface Area - m ² (ft ²)	743.2 (8000)	743.2 (8000)
Volume per column - m ³ (ft ³)	679.4 (24,000)	1132 (40000)
Weight per column - kg (lb)	1.63X10 ⁶ (3.6X10 ⁶)	2.7X10 ⁶ (6X10 ⁶)

Table 2-5

COST ESTIMATE FOR 1 MW BASELINE TWES
(DESIGN CONCEPT #2)

	<u>Case A - Four Foot Vanes</u>		<u>Case B - Six Foot Vanes</u>	
	<u>Weight - kg (lb)</u>	<u>Cost (1979 \$)</u>	<u>Weight - kg (lb)</u>	<u>Cost (1979 \$)</u>
Tower	68.6X10 ⁶ (151X10 ⁶)	2,140,000	99X10 ⁶ (218X10 ⁶)	3,100,000
Generator	3090 (6,800)	25,000	3090 (6,800)	25,000
Rotor and Hub	3044 (6,700)	10,000	3044 (6,700)	10,000
Duct	80,000 (176,000)	56,000	80,000 (176,000)	56,000
Transmission	<u>6362 (14,000)</u>	<u>39,000</u>	<u>6362 (14,000)</u>	<u>39,000</u>
Total Hardware	68.7X10 ⁶ (151.2X10 ⁶)	2,270,000	99.2X10 ⁶ (218.2X10 ⁶)	3,230,000
Non-Hardware Cost (40% of Hardware Cost)	-----	<u>910,000</u>	-----	<u>1,290,000</u>
Total	-----	3,180,000	-----	4,520,000

A steady-state wind profile estimate for engineering applications is given by:

$$V_z = V_r \frac{\ln (Z/Z_o)}{\ln (Z^r/Z_o)} \quad , \quad (2-9)$$

where

V_z = mean wind speed at elevation Z

V_r = mean wind speed at a reference elevation above ground level (Z_r)

Z_o = surface roughness length (0.17 ft being characteristic of moderate terrain)

To develop annual energy output estimates for the TWES and comparable conventional systems, it is necessary to calculate power output over the range of wind speeds from cut-in to cut-out speeds. The power output vs. wind speed curve for the TWES is expected to be similar to that of a conventional system (10), and is shown in Figure 2-6.

The wind speed duration profile used was based on the equation*

$$H_z = 8766 \exp \frac{-\pi}{4.06} \frac{V}{V_z}^{2.27} \quad , \quad (2-10)$$

where

V = wind speed (m/s)

H_z = time (hours) that the wind speed equals or exceeds V

Z = elevation above ground level (m)

This equation is plotted in Figure 2-7. By combining the power output profile and the wind speed duration curve an estimate of annual energy output is 3,130,000 kWh, assuming 100% availability of the TWES. Making the usual assumption of 90% availability (to account for planned and forced outages), the expected annual energy output of the 1 MW TWES at an annual mean wind speed of 5.4 m/sec (12 mph) is 2,820,000 kWh, corresponding to a capacity factor of 0.33.

*This profile provided by SERI.

Figure 2-6 Baseline TWES Power Curve

2.3.4 TWES Energy Cost

For electrical generation, the cost of energy (COE) is calculated from:

$$\text{COE} = \frac{(\text{IC})(\text{FCR}) + (\text{AOM})}{(\text{AKWH})} \quad (2-11)$$

where

IC = initial installed cost
FCR = fixed annual charge rate = 0.18 yr^{-1}
AOM = uniform annual operation and maintenance (O&M) cost
AKWH = total annual kWh produced including planned outages

The energy cost for the baseline TWES (1 MW) ranges from 24 - 34 cents/kWh, if annual O&M costs are taken as 3% of installed system cost*. The capital and energy costs for the baseline TWES are shown below.

	<u>First Concept</u>	<u>Second Concept</u>	
		<u>4 Foot Vanes</u>	<u>6 Foot Vanes</u>
Installed Capital Cost (\$ million)	4.24	3.18	4.51
Annual Energy Output (Million kWh)	2.82	2.82	2.82
Energy Cost (cents/kWh)	32	24	34

2.4 RANGE OF TWES SIZES AND COSTS

In addition to the baseline TWES configuration, the costs for TWES variations covering a broad range of sizes and augmentation ratios were examined. The largest size considered was by a 183 m (600 ft) tower height limitation (10), while the smallest size considered was a 200 kW system comparable in rated output to the MOD-OA system currently in use. The two augmentation ratios used were 4.5 (baseline) and 13.5 (optimistic)**. The system sizes/power output combinations that were evaluated are shown in Table 2-6. The rated power output of the largest TWES varies from 4 MW (4.5 augmentation) to 12 MW (13.5 augmentation) ratio.

*For conventional large-scale systems, annual O&M estimates are estimated to be 3% of initial system cost; TWES O&M costs were considered to be the same (as a first approximation).

**Developed from Yew (ref. 4) referred to a conventional wind system with a power coefficient normalized to a value of 0.35.

Figure 2-7 Wind Speed Duration Curve

Table 2-6

CHARACTERISTICS OF TWES SYSTEMS EVALUATED^a

	Augmentation Ratio = 4.5 (Baseline)			Augmentation Ratio = 13.5 (Optimistic)		
Rated Power ^a (mW)	0.2	1.0	4.0	0.6	3.0	12.0
Tower Height - m (ft)	51.8 (170)	103.6 (340)	182.9 (600)	51.8 (170)	103.6 (340)	182.9 (600)
Tower Diameter - m (ft)	25.9 (85)	51.8 (170)	91.4 (300)	25.9 (85)	51.8 (170)	91.4 (300)
Rotor Diameter - m (ft)	10.4 (34)	20.8 (68)	36.6 (120)	10.4 (34)	20.8 (68)	36.6 (120)

^a $C_p = 0.1$ for all cases.

2.4.1 Baseline Augmentation

Using the same approach followed in sizing and estimating the costs of the baseline TWES design, estimates for the 200 kW and 4 MW systems (with baseline augmentation ratios) were developed for each vane design concept and are presented in Tables 2-7 and 2-8. The total installed cost for a 200 kW TWES is estimated to range between \$920,000 and \$1,280,000. This compares to a mature product cost estimate of about \$230,000 for an advanced 200 kW conventional horizontal axis system similar to the MOD-OA.

Mature product cost for a 4 MW TWES ranges from \$8 million - \$14.4 million, depending on the case considered. A 4 MW conventional horizontal axis system patterned after the MOD-2 has a projected mature product cost of about \$3.2 million (14). Assuming that the baseline TWES augmentation ratio of 4.5 is attainable and incorporating the cost estimate of the 1 MW TWES (see Section 2.3), the tornado wind energy system has installed capital costs that are:

- o about 4 - 5.5 times as great as conventional systems at the 200 kW size;
- o about 3.2 - 5.5 times as great as conventional systems at the 1 MW size; and
- o about 2.5 - 4.5 times as great as conventional systems at the 4 MW size.

2.4.2 Optimistic Augmentation

If the 13.5 augmentation ratio is used, the TWES costs already reported for the 200 kW, 1 MW and 4 MW systems would apply to the 600 kW, 3 MW and 12 MW systems except for the small additional costs incurred for the larger-sized generators.

The total installed capital costs (in millions of 1979 dollars) for these higher output Tornado Wind Energy Systems are:

<u>First Concept</u>		<u>Second Concept</u>	
		<u>4 foot Vanes</u>	<u>6 foot Vanes</u>
600 kW	1.1	0.94	1.30
3 MW	4.74	3.68	5.01
12 MW	8.25	10.1	14.6

Therefore, the estimated total installed TWES costs are:

- o about 1.5 - 2 times as great as conventional systems at the 600 kW size and the 3 MW size; and
- o slightly lower to about 1.5 times as great as conventional systems at the 12 MW size.

Table 2-7

ESTIMATED COSTS OF 200 kW TWES:
BASELINE AUGMENTATION

COST (1979 DOLLARS)

	First Concept ^a	Second Concept ^a	
		<u>4 ft. Vanes</u>	<u>6 ft. Vanes</u>
Tower	750,000	610,000	870,000
Rotor	5,000	5,000	5,000
Duct	18,000	18,000	18,000
Generator	8,000	8,000	8,000
Transmission	<u>12,000</u>	<u>12,000</u>	<u>12,000</u>
Total Hardware	793,000	653,000	913,000
Non-Hardware Costs	<u>317,000</u>	<u>267,000</u>	<u>367,000</u>
Total ^b	1,110,000	920,000	1,280,000

^aAugmentation Ratio = 4.5.

^bFoundation and other special costs not included.

Table 2-8
ESTIMATED COSTS OF 4 MW TWES:
BASELINE AUGMENTATION

	COST (1979 DOLLARS)		
	First Concept ^a	Second Concept ^a	
		<u>4 ft. Vanes</u>	<u>6 ft. Vanes</u>
Tower	5,400,000	6,700,000	9,900,000
Rotor	15,000	15,000	15,000
Duct	190,000	190,000	190,000
Generator	70,000	70,000	70,000
Transmission	<u>92,000</u>	<u>92,000</u>	<u>92,000</u>
Total Hardware	5,767,000	7,067,000	10,267,000
Non-Hardware Costs	<u>2,303,000</u>	<u>2,823,000</u>	<u>4,103,000</u>
Total ^b	8,070,000	9,890,000	14,370,000

^aAugmentation Ratio = 4.5.

^bFoundation and other special costs not included.

There is no evidence available at the present time to substantiate the optimistic augmentation assumption. Also, TWES costs have been understated because of the factors discussed in Section 2.6. It is thus unlikely that even under these "optimistic" assumptions, TWES capital costs could be competitive with conventional systems at any point across the spectrum of performance and size considered.

2.5 TWES VS. CONVENTIONAL SYSTEM ENERGY COST COMPARISON

Based on the data presented in Sections 2.3 and 2.4, an energy cost comparison can be made for the range of TWES sizes and their conventional counterparts. There are no conventional wind systems optimized for operation at annual mean wind speeds as low as 5.4 m/sec (12 mph). We have used performance and cost data for conventional systems designed to operate at annual mean wind speeds of 6.3 - 8 m/sec (14 -18 mph). Therefore, the energy cost for the conventional systems for wind speeds of 5.4 m/sec (12 mph) is likely to be overstated in relation to the achievable mature product energy cost obtainable for an optimally designed system.

The annual energy outputs for the tornado wind systems over the range of sizes considered is shown in Table 2-9. TWES capacity factors average about 0.35 at 90 percent availability for the systems shown.

The energy cost developed using the equation presented in Section 2.3 for the TWES and conventional systems is shown in Table 2-10. Only in one case (the 12 MW "optimistic" augmentation situation) is the TWES energy cost comparable to the conventional system energy cost (5-8 cents/kwh vs. 7 cents/kwh). However, even if experimental data could be obtained to support the 13.5 augmentation ratio claimed, the additional cost of a foundation alone to support the 172.7×10^6 kg (380×10^6 lbs) weight of the lowest cost (first concept) TWES would be greater than the system cost reported earlier. Given the conditions and assumptions discussed in this analysis the several TWES designs evaluated do not appear to be economically competitive with conventional horizontal axis systems.

2.6 ITEMS EXCLUDED IN TWES COST ESTIMATES

The cost estimates presented for all of the TWES design concepts in Sections 2.3 and 2.4 are substantially lower than the values expected if a mature product TWES were manufactured. This underestimate is due to two factors: first, the costs of a number of system components were not included; and second, the costs of other aspects of the TWES installation were understated because the unique nature of the TWES did not permit reasonable estimates to be made at this time.

Table 2-9

ANNUAL ENERGY OUTPUTS FOR TWES vs. RATED POWER

<u>TWES Rated Power</u>	<u>Annual Energy Output (Million kWh)^{a,b}</u>
200 kW	0.53
600 kW	1.6
1 MW	2.8
3 MW	8.4
4 MW	13.3
12 MW	40.0

^aAt 90% availability.

^bFor annual mean wind speed of 5.4 m/sec (12 mph).

Table 2-10
TWES vs. CONVENTIONAL SYSTEM
ENERGY COST COMPARISON

<u>Energy Cost, Cents/kWh^a</u>			
<u>Rated Output</u>	<u>Conventional^b System</u>	<u>TWES: Baseline Augmentation</u>	<u>TWES: Optimistic Augmentation</u>
200 kW	8	39 - 51	
1 MW	8	24 - 34	
4 MW	7	13 - 23	
<hr/>			
400 kW	8		14 - 18
3 MW	7		10 - 13
12 MW	7		5 - 8

^aIn 1979 Dollars.

^bNot optimized.

The TWES costs presented thus far have not included costs for the rotor shaft, site excavation, power conditioning equipment and the tower foundation. In addition, the rotor cost estimates were based on the use of less expensive fixed pitch, constant chord blades while Grumman's present intention is to employ curved, twisted blades to enhance the aerodynamic efficiency of the TWES. Also, the rotor cost used included only that of the metallic skin; internal support costs were not considered.

Tower construction costs, which represent the overwhelming fraction of total TWES cost, also have been substantially underestimated because they were based on the use of current "office building" reinforced concrete technology (\$2.15 per cubic foot installed) and therefore did not include the additional costs associated with the customized nature of the TWES design. Structural engineers (8, 15) feel that construction of the tower vanes would have to occur simultaneously and not individually. Therefore, additional equipment and manpower would be needed for the TWES installation than for an office building.

Interim support for the vanes will be necessary until the top ring has been completed and the concrete has cured. Furthermore, an internal shield will be necessary to obstruct the wind flow (during tower construction) until the tower has been completed. All of these considerations will increase the cost of the reinforced concrete TWES tower well beyond the \$75.92/m³ (\$2.15/ft³) used. There is no way to estimate the additional cost these factors represent because of the unique configuration of the TWES and the unfamiliarity of the construction industry with the concept. An additional cost for concrete pumping was not included because, again, good estimates for TWES construction could not be made at the present time. However, this concrete pumping cost would be more than the nominal \$7.00/m³ (\$0.20/ft³) which represents current costs for standard reinforced concrete construction*.

2.7 EVALUATION OF TOWER DESIGN ALTERNATIVES

The tower is the major cost driver in all TWES designs. In an attempt to reduce the tower cost, Grumman has suggested several alternative design approaches. These alternatives are discussed here together with our rationale for not including them in the TWES design concepts which were evaluated.

2.7.1 Foam-filled Vanes

To reduce the extremely high tower weight, Grumman suggested that the tower vanes be filled with a polyurethane foam instead of reinforced concrete. A structural analysis of

*If \$0.20/cu ft is used, TWES costs would increase by 10 percent over costs already presented.

the TWES tower* showed this approach to be infeasible, not only for foam but for other materials (such as laminated plastics), since the tower would be subject to relatively large deflections leading to greatly reduced torsional vane strength and a greatly increased risk of structural failure.

In order to insure that the vanes can withstand the drag forces, the dead weight of the tower structure, and the bending forces attributable to the wind, the structural analysis indicates that reinforced concrete is the only realistic choice for vane construction.

2.7.2 Use of Guy Wires

Grumman has suggested that guy wires be attached to the 1 MW-scale single vane TWES tower to handle wind stresses in lieu of "beefing up" the tower. However, guy wires are not generally incorporated in reinforced concrete construction because of difficulties in assuring the integrity of the cable attachments. Also, the use of guy wires could significantly increase the land area required for the TWES installation. In order to reduce the impact of the land use problem, Grumman has proposed attaching the guy wires at several points along the tower as shown in Figure 2-8.

Elevation View

Plan View

Figure 2-8 Use of Guy Wires as an Alternative Tower Support Strategy

However, this approach does nothing to address potential attachment problems and introduces additional problems due to a need for an "extra-strength" superstructure and cable. This would not only add substantial cost but would possibly disrupt wind flow. For these reasons, the use of guy wires is not considered a realistic design alternative.

*See Appendix A.

2.7.3 Plastic Vanes

Grumman has suggested the possible use of plastic vanes in place of reinforced concrete. While it might be possible to obtain plastic materials with sufficient strength to withstand the large forces on the TWES tower, their cost would likely prove to be greater than reinforced concrete. Therefore, plastic vanes were not considered to be a practical alternative at this time.

2.7.4 Vane Thickness

Grumman feels that 20 cm (8 in) thick TWES tower vanes should be satisfactory for the baseline 1 MW system. The structural analysis presented here indicates that 20 cm (8 in) vanes would buckle due to the wind stresses and the tower weight. If the stresses due to tower weight were relieved by placing support columns between the support rings, these columns (which would be relatively large) might obstruct the wind flow, thereby degrading TWES performance. To assure the structural integrity of the tower, we feel that vanes at least 1.2 m (4 ft) thick are required and, even in this case, good construction practice* has not been followed; 1.8 m (6 ft) thick vanes are needed to incorporate the necessary safety factors.

*The American Concrete Institute, the Uniform Building Codes, The American Society for Testing and Materials, and the HUD Minimum Property Standards all provide guidelines for good construction practice in concrete structures.

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SECTION 3.0

THE VORTEX AUGMENTOR CONCEPT

3.1 SYSTEM DESCRIPTION

The VAC utilizes aerodynamic design techniques, similar to those used in supersonic aircraft design, to concentrate the natural winds. The "augmentor" of the VAC is a triangular (or delta) aerodynamic surface configuration as shown in Figure 3-1. This surface has a sharp leading edge which, when directed into the wind at an appropriate angle, causes the oncoming natural wind flow to separate from the surface. This flow separation leads to the production of vortices.

The concentrated wind flows exhibit an increased axial velocity over a smaller area than the natural wind flow. However, the effective operation of the VAC not only depends on the production of the vortices, but also on the manner in which they are produced; that is, the vortices need to be consistent, reproducible and controllable. In order for maximum energy extraction to be realized, the rotor must also be sized and placed for optimal utilization of the oncoming vortex.

The vortex augmentor system represents a complex aerodynamic design in terms of wind flow interactions but the structural design is relatively simple. The major subsystems in the VAC include:

- o Delta Augmentor Surface
- o Rotor and Hub
- o Deflecting Flap
- o Generator
- o Transmission
- o Vertical Fin
- o Augmentor Support Structure

Available power output is determined by the strength and stability of the vortex produced. The vortex velocity and stability are directly dependent upon the ambient wind velocity and the angle of attack of the "delta" surface.

It has been suggested that through the addition of a flap, deflected approximately 15 degrees downward behind the original trailing edge, a further increase in the available power is possible. This "deflecting flap" on the trailing edge provides an additional control surface for maintaining an optimal "delta" surface angle of attack. By serving as a pitch control mechanism, the flap reorients angle of attack to respond to ambient wind flow variations, and increases available power by maintaining an optimal angle of attack. Investigations in this area are currently being conducted on the Polytechnic Institute of New York prototype VAC device. Present estimates of overall VAC power

Figure 3-1
Conceptual View of a
Vortex Augmented Wind Turbine

Figure 3-2

VAC Wind Flow Interactions

augmentation indicate that a ten-fold (or greater) increase in available power could be obtained as compared to an equivalent conventional system in the same wind regime. However, there is no experimental evidence available to support these claims.

The VAC system incorporates two rotors because the delta surface produces two identical vortices rotating axially in opposite directions along each edge, as shown in Figure 3-2.

The vortices effectively process the wind to smooth out any non-uniformities in the flow before they reach the blades. This enables the system to incorporate low cost (constant chord) blades and eliminates the need for any pitch control mechanism.

Another advantage of this vortex/rotor interaction is the pre-rotation of the wind before it reaches the rotor. Due to this pre-rotation, the rotor diameter may be reduced in comparison to a conventional system of equivalent output thereby offering the potential for increased rotational speeds (>40 rpm) and reducing the requirements placed on the step-up transmission.

3.2 TECHNICAL UNCERTAINTIES

There are technical uncertainties which might require modifications in the basic VAC design or contribute to reductions in anticipated performance levels. These uncertainties are discussed here, but any quantitative attempt to assess their impact on VAC performance or cost is beyond the scope of this analysis. The only satisfactory approach in quantifying these impacts is to gather field test data on VAC operation. A preliminary field test program is currently underway at the Polytechnic Institute of New York, but no data as yet are available.

Major uncertainties discussed here involve the effect of blade design on potential starting problems, and vortex breakdown.

3.2.1 Blade Design and Starting Problems

The VAC blades are of the constant chord, fixed pitch type. Normally a fixed pitch blade is characterized by a twist which aids the rotors in initial starting. Use of a constant chord blade may present a starting problem. If the wind is perpendicular to the rotor plane, a stall condition will prevail which means there will be no lift or torque. One approach in alleviating this problem involves close control over the angle of attack so that the augmentor surface can be brought into the wind according to schedule. This close control may not always be feasible in a "real-world" environment. Another option involves the addition of a starting motor to the VAC which would lead to additional cost. Although the wind tunnel tests conducted to date have not presented any VAC starting problems (16), firm conclusions cannot be drawn until field test data are available.

3.2.2. Vortex Breakdown

The vortex breakdown phenomenon is associated with a major change in the structure of the vortex. If vortex breakdown does occur, projected system performance will be degraded to the extent of the breakdown encountered.

There are two primary locations where vortex breakdown can occur. The most severe breakdown would likely occur along the trailing edge of the delta. The delta surface is in a sense a structural boundary between a high and low pressure field. High pressure is located underneath the surface; low pressure is found above the delta. The creation of the vortex can be attributed somewhat to the movement of air from a high to low pressure area. Because the delta has three sides, three vortices are created. The one originating at the trailing edge, if large enough, can contribute to a breakdown of the two side vortices. However, it is believed that the deflecting flap of the VAC (which occupies the back width of the delta), may be long enough (14.3 m) and mobile enough so that the trailing edge vortex created would not affect the side vortices. The resolution of this issue awaits experimental validation.

Another area of vortex breakdown may occur near the rotors. One condition necessary for vortex breakdown is an adverse pressure gradient in the axial direction. The VAC rotors create a high pressure area in front of the blades which, together with the low pressure on the delta surface, could create an adverse pressure gradient with a potential for vortex breakdown.

3.2.3. Structural Considerations

There are three primary structural considerations which require attention in VAC design and analysis. These include: stresses due to gravity forces, stresses due to aerodynamic forces, and tower requirements.

3.2.3.1 Stresses Due to Gravity Forces

The aerodynamic surfaces of the VAC include a delta platform, trailing edge flaps and a vertical tail. The vertical tail has an area 20% - 25% of the platform area and is rigidly mounted to the wing. Two rotors and their attendant trans missions and generators must also be rigidly mounted to the wing, since the entire system rotates 360 degrees about a vertical axis and approximately 30 degrees about a horizontal axis (to adjust the angle of attack). The delta wing includes flaps with a controllable angle of deflection, and a control mechanism which must be included in the wing structure. The total dead load to be supported includes the weights of the delta wing, wing flaps and control mechanism, vertical tail, and the two rotors with their ancillary equipment.

This entire structural load must be supported at the center of gravity, in contrast to an aircraft wing which is supported along its entire maximum chord length. The single point support requirements result in greater maximum stresses in the wing structure compared to the situation when the wing is supported along a chord. This effect may be ameliorated by proper design, but care must be taken not to interfere with aerodynamic performance; it should also be recognized that this type of wing support approach has received little design analysis in the past.

For the VAC field test prototype (3 m x 5.5 m delta wing) made of 0.64 cm (1/4-inch) thick steel plate and supported at the center of gravity, the maximum stress reaches 241,290 pa (35,000 psi) for a flat plate but may be reduced by more than 50% when a transverse radius of curvature of 25.3 m (83 ft) is provided. Stress may be reduced still further when smaller radii of curvature is used (17). The VAC field test prototype has a power output which would correspond to a small-scale wind turbine with rated power on the order of 10 kW. The stresses in larger VAC wings are expected to be substantially greater, and may limit the practical size of the VAC system to smaller power ratings than can be achieved with conventional wind turbines.

3.2.3.2 Stresses Due to Aerodynamic Forces

Aerodynamic forces will generally act in a direction opposite to gravity forces, and thus tend to counteract them. If the aerodynamic forces exceed the gravity forces, the stress in the wing structure will be reversed in sign, and if the aerodynamic forces are more than twice as great as the gravity forces, the resultant stresses may be greater than those due to gravity forces alone. Such situations may occur in high winds prior to system "shutdown".

In excessively high winds, the VAC will have to be "shutdown" to avoid potential damage. This will require orienting the VAC so that both the delta wing and the vertical tail are parallel to the wind direction. However, gusts can create rapid changes in wind direction as well as rapid increases in wind speed. The angular moment of inertia of the wing system combined with the large surface areas of the wing and tail may make them more vulnerable to damage in gusty winds than a conventional wind turbine in the "shutdown" condition.

3.2.3.3 Tower Requirements

As will be seen later in Section 4, the VAC will weigh considerably more than a conventional wind turbine of the same power rating. The aerodynamic surface areas of the VAC delta wing

and tail would be many times the blade area of a conventional wind turbine. A conventional wind turbine such as the MOD-OA has a rotor solidity of .03, (i.e., the blade area represents 3% of total "swept" area). In contrast, a VAC device rated at 200 kW has an equivalent "aerodynamic solidity" of 178% based on the same convention. Accordingly, the weight per unit of equivalent swept area for the VAC wing and tail would be much greater than the weight per unit swept area of the rotor blade. The two VAC transmissions, although requiring a smaller step-up ratio than conventional transmissions, would, together with the two VAC rotors, weigh more than a conventional wind turbine transmission. Altogether, the VAC system would represent a significantly greater weight on top of the tower than a conventional wind turbine system of the same power rating. This will require a stronger tower in order to support the load.

3.2.3.4 Other Considerations

A flutter problem may develop with the augmentor surface because of its flat-plate design. It has been suggested that a bow-like delta design (with greatest depth near the support tower) might help alleviate this problem. Irrespective of the delta surface design finally selected, heavy reinforcement is required, otherwise an aeroelasticity problem may result.

Angular positioning of the augmentor surface could lead to a drag problem. As the angle of attack changes, air loading on the delta surface could increase drag levels such that VAC performance might be degraded. Experimental data is necessary to confidently evaluate these technical uncertainties.

3.3 BASELINE VAC SYSTEM

A 200 kW baseline size has been selected to make the required comparisons between the VAC and a conventional horizontal axis system. In the analysis, a VAC is compared with a conventional, unaugmented wind turbine (similar to the MOD-OA system), which also has a nominal 200 kW power rating. In using the MOD-OA as the basis of comparison, it is important to realize that its 38.1 m (125 ft) diameter rotor could actually supply about 400 kW of rated power but is constrained to 200 kW of maximum power output in its present operational configuration.

In terms of system performance, the conventional counterpart to the 200 kW VAC will resemble the MOD-OA system already installed at Clayton, New Mexico and Culebra, Puerto Rico and slated for installation at Block Island, Rhode Island and Kaena Point, Hawaii in 1979 - 1980.

3.3.1 VAC Hardware Requirements and Associated Costs

Figure 3-3 illustrates the proposed operational VAC configuration with the major subsystems identified. Our analysis considers the size and weight requirements for each major subsystem of

Figure 3-3
**CONCEPTUAL VORTEX AUGMENTED
WIND ENERGY SYSTEM**

Base Case Design

top view

^aDimensions in ft

- Key:**
- A: Delta Surface
 - B: Rotor Blade
 - C: Hub
 - D: Rotor Shaft
 - E: Nacelle
 - F: Nacelle Support
 - G: Fairing
 - H: Generator
 - I: Gear Speed Increaser
 - J: Deflecting Flap
 - K: Vertical Tail
 - L: Bedplate
 - M: Springs
 - N: Vertical Right Angle Gearbox
 - O: Hinge
 - P: Tower

side view

a prototypical 200 kW VAC, and provides cost estimates for each fabricated subsystem. Some VAC subsystems can be obtained as "off-the-shelf" items; vendor price quotations have been obtained whenever possible. For other subsystems we have estimated total material requirements and have projected labor costs required for manufacture in order to obtain total fabricated subsystem cost.

Where vendor price quotations were not available, estimated labor costs were assumed equal to the material cost. In many cases, this could lead to an understatement of cost since factors of 2.5 to 3 are commonly applied to materials costs to obtain total costs for this type of production process (1,18). The subsystems for which cost underestimates may be significant include the rotor, augmentor surface, vertical tail assembly, deflecting flap, and fairing.

Minimum costs were used for the tower which was assumed to be made of reinforced concrete. A steel truss tower, as envisioned in the original VAC design, would be much more costly. Furthermore, the 4.3 m (14 ft) diameter tower used in the 200 kW baseline VAC configuration is probably insufficient to support the large augmentor surface required. A more detailed analysis must be conducted to obtain the increase in required tower size and this increase will undoubtedly add to the VAC cost. The support foundation for the entire system is included in the installed VAC cost. However, the value used was based on the absolute minimum foundation envisioned*. The actual foundation weight requirement (a site-dependent variable) would likely be much larger, thereby significantly increasing cost as presented here.

Total hardware cost represents the present cost (F.O.B. factory) of fabricating all system components. To this total hardware cost must be added foundation costs as well as site preparation costs, system assembly and installation costs, transportation to the VAC site, general and administrative expenses, and contractors' fees**.

The rationale for determining size and cost of major VAC subsystems is presented below.

3.3.1.1 Rotor Subsystem

The VAC employs two rotors with a total of four blades. Based on an augmentation ratio of six, the best current estimate of VAC performance level, the VAC blade radius would be approximately 40% of the radius of an equivalent conventional machine, which yields a baseline VAC blade radius of 6.0 m (20 ft). It

*Foundation weight assumed equal to total system weight.

**Site acquisition costs are excluded from this estimate.

is expected that the VAC blades will be of the constant chord fixed pitch type. As a first approximation it is assumed that each VAC blade will have a 0.6 m (2 ft) chord length; therefore, the total blade surface area is 59.5 m² (640 ft²). If fabricated from .32 cm (1/8 in) steel sheet with foam core and internal supports the total blade weight for the system would be about 1,590 kg (3,500 lb) with a total fabrication cost of approximately \$5,000 (19,20).

The other major rotor subsystem component is the hub which secures the blades to the connecting shaft. The VAC has an estimated 6 to 1 ratio between blade and hub diameter (17). Based on a 12.2 m (40 ft) diameter blade, the baseline hub diameter would be approximately 2.1 m (7 ft). Extrapolating data on hub sizes for wind turbines in the 500 kW to 1,500 kW size range, the weight of each hub would be approximately 1,908 kg (4,200 lb) with a corresponding fabrication cost of approximately \$17,000 (21). Total rotor cost for the baseline 200 kW VAC is \$22,000.

3.3.1.2 Augmentor Surface

The rotor subsystem is attached to the augmentor (delta) surface. Sizing of the delta surface for a full-scale VAC requires a trade-off between achievable augmentation ratio and the materials and fabrication requirements of the augmentor surface. In sizing the delta surface for a baseline VAC, we have considered three sizing guidelines that have been proposed in the literature (17,16,22).

The first sizing guideline requires the augmentor surface area to be "generally 2/3" of the swept area for a conventional rotor system of equivalent power. An additional guideline gives the ratio between delta surface length and VAC rotor diameter as approximately 6 to 1. A final guideline states the length of the delta surface as equivalent to the blade diameter for a conventional system of equivalent power. Application of each of these three guidelines, unfortunately, leads to widely varying size requirements for the augmentor surface. In sizing the delta surface for the baseline case design, the vertical dimension was governed by the width needed for rotor clearance. Based on the design of the current small-size VAC prototype, the rotors are located 80% of horizontal distance between the apex of the delta surface and the trailing edge (see Figure 3-3). Since each blade has a 12.2 m (40 ft) diameter and requires some additional clearance, a minimum delta width at the rotor location would be 30.5 m (100 ft), which leads to a maximum delta width of about 38.1 m (125 ft) at the trailing edge.

The current VAC field test prototype has a delta length of about 5.8 m (19 ft) and width of 3.0 m (10 ft). If this prototype is scaled up to the baseline VAC system, the delta length required would be 71.6 m (235 ft), close to the 73.1 m (240 ft) estimate obtained by using the "6 times rotor diameter" guideline.

We have used the 71.6 m (235 ft) delta length in the baseline case with the realization that, in order to determine the optimum delta size, a detailed performance/economic tradeoff analysis must be conducted. These tradeoff analyses are beyond the scope of this study; however, smaller delta surfaces associated with higher augmentation ratios will be considered later in the analysis.

The augmentor surface construction is similar to that of an aircraft wing although the fabrication requirements are not as stringent. In order to construct this surface, two delta-shaped flat plates of 0.64 m (1/4 in) steel plate will be used (23). The two plates will be bonded together by 10 cm (4 in) wide flanges similar to "I" beams in appearance.

Based on these dimensions, total weight will be about 136,300 kg (300,000 lb); the structural support flanges are estimated to weigh 31,800 kg (70,000 lb) based on the given spacing. Overall material costs for the augmentor surface (and associated flange supports) are estimated at \$65,000 with a total fabrication cost approximating \$130,000 (19).

3.3.1.3 Deflecting Flap

The kinetic energy flux in the vortex field is larger than that in the undisturbed flow by a factor which represents the augmentation effect of the delta surface. By changing the angle of attack of this surface, a velocity change within the vortex will result. A downward deflection strengthens the vortex and brings it closer to the surface, while upward flap deflection weakens the vortex without substantially altering its position. Operation at high angles of attack can provide power under relatively low wind conditions, while under high wind conditions the power load may be reduced by decreasing the angle of attack of the augmentor surface.

The deflecting flap, attached to the back width of the delta, is responsible for changing the angle of attack of the delta surface. This flap is 20% of the overall length of the delta and occupies two-thirds of the back width. For the 200 kW VAC, the length of the flap is 14.3 m (47 ft), while the width is made up of two 12.8 m (42 ft) sections. Total surface area of back and front of the flaps combined is 724 m^2 (7,900 ft^2).

Construction of the deflecting flap is expected to be similar to that of the delta. Two plates are structurally supported by flanges. The flat plates weigh about 8,200 kg (40,000 lb) and are supported by flanges weighing about 2,725 kg (6,000 lb). The total cost of materials for the deflecting flap and supports is estimated to be about \$7,000 (19); total fabrication costs are estimated to be about \$14,000.

3.3.1.4 Vertical Tail

Yaw control of the VAC is accomplished aerodynamically. A vertical tail positioned near the back edge of the delta along the centerline responds to changes in wind direction and provides a characteristic time response of less than 30 seconds*.

In terms of size, the vertical tail area is about 20% of the wing planform area (17) and is equivalent to an area of about 306 m^2 ($3,300 \text{ ft}^2$) for the baseline VAC system. If the tail is made of 0.3 cm (1/8 in) steel plate, its approximate weight is 15,000 kg (33,000 lb) with an additional 2,726 kg (6,000 lb) for flanges spaced three feet apart vertically and diagonally. The cost of materials for the vertical tail and flanges is about \$6,000 (19); total fabrication cost is estimated to be about \$12,000.

3.3.1.5 Transmission

Two configurations for the transmission subsystem were considered (13). One approach (see Figure 3-4A) uses two vertical right angle gear boxes connected to the rotor by a drive shaft and a gear speed increaser. For each rotor, one of the gear boxes (located in the nacelle) would be used for changing the directions of the shaft and would transfer the energy required to accommodate the peak torque created during periods of wind gust.

For the 200 kW VAC, the maximum torque, three times rated torque (24)**, is about 40,650 J (30,000 ft-lb). The two right angle gear boxes required for the two VAC rotors each would weigh about 2,045 kg (4,500 lb) and cost about \$40,000 each in order to meet these specifications. The two remaining gear boxes (one per rotor) would be located in the fairing, which also houses the two gear speed increasers for the twin rotor VAC. The gear speed increasers would be used to advance the horizontal shaft transmission.

The input to the gear speed increasers corresponds to the rotational speed of the VAC rotors, which is 3.5 times as great as that of a conventional system of equivalent power (approximately 140 rpm) (17). This 140 rpm input is increased to 1,800 rpm through the horizontal shaft transmission. The two gear boxes in the fairing would be identical to those on the nacelle and would cost \$40,000 each. The two gear speed increasers would each cost \$30,000 and weigh 2,045 kg (4,500 lb) (13). The total transmission subsystem cost, including four gear boxes and two gear speed increasers, would be \$222,000 plus the costs for the required drive and connecting shafts.

*For the field test prototype; no credible time response estimate has yet been made for the baseline size VAC.

**Rated torque is defined to be rated power output of VAC divided by rotational speed of the blades.

Since the cost of this transmission configuration would be prohibitive for the 200 kW VAC, an alternative was investigated which would require a modification to the design currently proposed by Sforza. This alternative would replace the rotor shaft, nacelle, upper right angle gear box, drive shaft, lower right angle gear box and gear speed increasers with connecting shafts and gear drives (see Figure 3-4B).

In this configuration, the rotor would be mounted on a 8.5 m (28 ft) connecting shaft attached to a gear drive at the delta surface. This unit would convert vertical shaft work to horizontal shaft output and step up the speed from the 140 rpm rotor output to the 1,800 rpm required by the generator. The cost of this configuration is estimated to be about \$28,000 for each gear drive (13); two of these gear drives would be required, for the two rotors. Two connecting shafts (rotor to transmission) and two transmission shafts (transmission to generator) would also be required. Scaling the size and cost requirements for these shafts from mature product estimates for the MOD-2 leads to a total fabricated cost for the four shafts of about \$87,000. Total weight of the four shafts is about 8,630 kg (19,000 lb). The total transmission cost for this alternative approach is \$143,000, significantly less expensive than the original approach.

3.3.1.6 Fairing

The fairing is a cylindrical compartment located above the centerline of the delta surface. For the 200 kW VAC, the length of the cylindrical fairing would be about 8.8 m (29 ft) and its diameter 5.2 m (17 ft), giving a total surface area of about 186 m² (2,000 ft²)*. If the unit is constructed out of 0.32 cm (1/8 in) steel sheet, its total weight will be about 4,544 kg (10,000 lb) with a total materials cost of about \$1,500 (19). Total fabricated cost of the fairing is estimated at \$3,000.

3.3.1.7. Generators

A two generator system (located in the fairing) is recommended for the VAC to facilitate the two rotors rotating at different speeds. Each of the 100 kW generators weights about 570 kg (1,250 lb) and costs about \$4800 (25). If an exact match of rotor speeds could be assured, the use of one 200 kW generator in place of two 100 kW generators would save \$1,000, an insignificant cost savings.

3.3.1.8 Other Tower-mounted Components

The total baseline system weight thus far totals approximately 229 500 kg (505,000 lb), of which the augmentor surface is the dominant item. The system rests on nine industrial grand springs which allow the unit to vary its angle of attack. These springs represent the primary component of the attitude control system (16).

*This size is consistent with designs of comparable conventional wind systems.

Figure 3-4 VAC Transmission Subsystem Options

(A)

Two Right Angle Gear Boxes and One Gear Speed Increaser per Rotor

(B)

One Connecting Shaft/Gear Drive per Rotor

These straight compression industrial springs are in a free standing mode, 91.4 cm (36 in) in height and 46 cm (18 in) in diameter. Each spring has a total of 8-1/2 turns and is rated up to 27,270 kg (60,000 lb). The bar from which the spring is manufactured is 7.6 cm (3 in) thick; weight of each spring is 364 kg (800 lb), and the cost of each is \$570 (26).

The nine springs are attached to a bedplate which serves as a base for the VAC. The bedplate for the 200 kW baseline was assumed to be similar to that used for the MOD-1 system, since overall weights of the two systems are comparable. Estimated bedplate weight is thus about 6,800 kg (15,000 lb), with a total cost of \$6,000.

3.3.1.9. Tower

Summing all the major subsystem weights, the total system weight above the tower is 239,810 kg (527,700 lb). The estimated height of the tower for the 200 kW baseline VAC would be about 22.0 m (75 ft) (17).

Based on current intermediate and large conventional wind turbine designs (MOD-OA and MOD-1), the open truss tower weight is typically comparable to the weight supported on top of the tower. If this assumption is made for the VAC, the total tower weight could be approximately equal to the tower-mounted system weight, that is, 239,800 kg (527,700 lb) with a total cost of about \$475,000*.

If a prestressed, reinforced concrete tower is used in place of the open truss type, a large reduction in tower cost may be obtained. One study suggests that the proportion of tower weight to tower-mounted system weight for a concrete tower design would be about 3 to 1. This estimate would lead to a total tower weight of almost 450,000 kg (1.6×10^6 lb). This represents a total reinforced concrete volume of slightly less than 300 m³ (10,700 ft³) with a total cost of about \$21,400 (8). It must be emphasized that a sized concrete tower has been used in our cost analysis; a detailed structural analysis is necessary to determine if this minimum value is adequate to support the 71.6 m (235 ft) augmentor surface.

3.3.1.10 Foundation

The total baseline VAC weight (including tower) is 958,000 kg (2.1×10^6 lb). The foundation weight required to support this weight would likely be several times that value, but could only be determined through a detailed structural analysis. As a conservative estimate of foundation weight, it is assumed that the foundation weight would equal the total VAC weight. Present concrete foundation costs are \$0.11/kg (\$0.05/lb) (1), giving a foundation estimate of \$105,500.

*Mature product cost for an open truss tower is \$2.00/kg (90 cents/lb).

3.3.1.11 Non-Hardware Costs

There are certain non-hardware costs (site preparation, VAC erection, checkout and installation, transportation of subsystem to the site, general and administrative expenses, etc.) associated with the readying of a wind turbine installation. For a mature product wind system, these costs represent about 40% of the total hardware cost (1). Since total hardware cost for the 200 kW VAC baseline system is \$366,000, total non-hardware costs for this installation are estimated to be about \$145,000.

3.3.2 Total Installed System Costs

A summary of the cost breakdown for the 200 kW VAC baseline system is presented in Table 3-1. The total installed cost for the 200 kW baseline "mature product" VAC system is estimated to be \$617,000, which is about 2.7 times the estimated cost of a mature 200 kW conventional horizontal axis design patterned after the MOD-OA (14). The transmission and the augmentor surface are about equal in cost and together constitute about 80 percent of the total baseline VAC hardware cost.

3.4 VAC SYSTEM PERFORMANCE

The ground rules for this analysis required that the wind turbines be assumed to operate in a regime where the annual mean wind speed is 5.4 m/sec (12 mph). As indicated in Section 2, the wind resource varies considerably at different locations and heights and is sensitive to terrain conditions. An important parameter in system performance is the wind speed at the wind turbine elevation with respect to the ground. This velocity governs the power output and the annual energy output of the system. A reasonable representation of the steady-state wind profile for engineering applications was used in the Tornado Wind Energy System analysis (see Equation 2-9) and will be used again here.

To develop annual energy output estimates for the VAC and a comparable conventional system, it is necessary to calculate the power output of each system over a range of wind speeds from cut-in to cut-out. It is assumed in this analysis that the rated power levels, the cut-in wind speed, rated wind speed and cut-out wind speed are the same for each system (23). The wind speed duration profile used in the TWES analysis has been adjusted for different hub heights and will be used again for the VAC performance analysis.

Both the MOD-OA and the VAC baseline system have a 30.5 m (100 ft) hub height. Therefore, the mean wind speed at hub height for both systems will be the same (6.6 m/sec). Since the cut-in, rated, and cut-out wind speed are also the same, the power output for each system as a function of wind speed will be identical (see Figure 3-5).

Table 3-1

WEIGHT AND COST ESTIMATE FOR PROTOTYPICAL
200 kW VORTEX AUGMENTOR SYSTEM (BASELINE CASE)

Major Component	Weight - kg (lb)		Total Fabrication Cost (1979 Dollars)
Rotor (4 blades, 2 hubs)	5450	(12,000)	22,000
Augmentor Surface (Flat Plates, Flanges)	167,230	(368,000)	130,000
Deflecting Flap (Including Supports)	20,904	(46,000)	14,000
Vertical Tail (Including Supports)	17,723	(39,000)	12,000
Fairing	4,545	(10,000)	3,000
Transmission (2 Gear Drives and 4 Shafts)	12,724	(28,000)	143,000
Generators (2 @100 kW)	1,136	(2,500)	9,500
Industrial Springs (9)	3,272	(7,200)	5,100
Bedplate	<u>6,816</u>	<u>(15,000)</u>	<u>6,000</u>
TOTAL ON TOP OF TOWER	239,810	(527,700)	344,600
Tower (Reinforced Concrete)	<u>719,000</u>	<u>(1,582,300)</u>	<u>240,000</u>
TOTAL HARDWARE	958,900	(2,110,000)	584,600
Foundation ^a	958,900	(2,110,000)	105,500
Non-Hardware Costs ^b (0.40 x hardware costs)	---	---	<u>233,900</u>
TOTAL	1,917,800	(4,220,000)	924,000

^a Foundation cost is \$0.11/kg (\$0.05/lb); actual foundation weight would likely be several times total hardware weight. Estimated weight given is the minimum that could be envisioned under any circumstances.

Source: Boeing.

^b Site acquisition costs not included.

Figure 3-5

Easeline VAC Power Curve

Combining the power output profile and wind speed duration curve leads to an estimated annual energy output of 686,00 kWh* for each system. Applying a 90% availability factor to take account of planned and forced outages, the expected annual energy output of both VAC and conventional systems is 618,000 kWh, which corresponds to a capacity factor of 0.35.

3.5 BASELINE VAC ENERGY COST

For electrical generation, the cost of energy (COE) can be calculated from Equation 2-11. Energy cost for the VAC and conventional system were developed using a 12 mph wind regime. However, the conventional system will be less efficient in the wind regime due to its design mean wind speed of 18 mph. This decrease in efficiency corresponds to a greater energy cost than would be expected if optimal design conditions existed. For the baseline 200 kW VAC, the energy cost is about 21 cents/kWh which compares to an estimate of about 8 cents/kWh for a next generation mature product version of the MOD-OA.

3.6 RANGE OF POTENTIAL VAC SIZES

In addition to the baseline VAC configuration, the costs of mature product VAC systems from 40 kW to 1 MW were also examined. A baseline augmentation ratio as well as an optimistic augmentation ratio** were used to cover the spectrum of size and performance expectations for the VAC.

3.6.1 Baseline Augmentation-Analysis of Size Sensitivity

Using the same approach followed in sizing and estimating the costs of the baseline system, cost estimates for 40 kW and 1 MW VAC systems were performed and are presented in Table 3-2)***. The total installed cost for a 40 kW VAC system is estimated to be slightly over \$157,000, which compares to about \$50,000 for a mature product 40 kW horizontal axis system currently under development by the U.S. Department of Energy (28). The initial capital cost of a mature 40 kW VAC system is more than four times that of a comparable horizontal-axis system.

At the 1 MW size, the total installed VAC cost is estimated to be \$1,574,000, as opposed to the present mature product cost estimate of \$800,000 to \$1,000,000 for a comparably-sized horizontal axis system (12). Therefore, at the baseline augmentation ratio of 6, the 1 MW VAC would be 1.5 - 2 times the cost of the conventional counterpart.

*Assuming 100% availability.

**The optimistic augmentation ratio of 16.0 is the maximum value indicated in Sforza (17) when compared to a conventional wind system with a power coefficient of 0.36; the baseline augmentation ratio is 6 on the same basis.

***The 1 MW size limitation was suggested by P.M. Sforza (23).

Table 3-2

WEIGHT AND COST ESTIMATES FOR 40 kW
AND 1 MW VAC SYSTEMS: BASELINE AUGMENTATION

	<u>40 kW^a</u>			<u>1 MW^a</u>		
	Weight	kg (lb)	Cost (1979 \$)	Weight - kg (lb)		Cost (1979 \$)
Rotor	1,045	(2,300)	\$ 5,200	10,900	(24,000)	\$ 44,000
Augmentor Surface	30,360	(66,800)	23,500	377,600	(831,000)	300,000
Deflecting Flap	3,720	(8,300)	2,600	47,760	(104,000)	34,000
Vertical Tail	3,227	(7,100)	2,300	40,900	(90,000)	29,000
Fairing	863	(1,900)	600	9,090	(20,000)	6,000
Transmission	5,907	(13,000)	54,300	58,620	(129,000)	430,000
Generators	409	(900)	2,400	3,180	(7,000)	26,000
Industrial Springs	727	(1,600)	1,100	6,816	(15,000)	11,000
Bedplate	1,227	(2,700)	1,100	12,720	(28,000)	12,000
TOTAL ON TOP OF TOWER	47,530	(104,600)	93,100	567,000	(1.25X10 ⁶)	892,000
Tower (Reinforced Concrete)	142,600	(313,800)	46,900	1.7X10 ⁶	(3.74X10 ⁶)	561,000
Total Hardware	190,000	(418,400)	140,000	2.8X10 ⁶	(4.9X10 ⁶)	1,453,000
Foundation ^b	190,000	(418,400)	21,000	2.8X10 ⁶	(4.9X10 ⁶)	250,000
Non-Hardware Costs	---	---	56,000	---	---	581,000
Total	380,000	(836,800)	\$217,000	5.6X10 ⁶	(9.8X10 ⁶)	\$2,284,000

^a Augmentation Ratio = 6.

^b Foundation weight and cost are the minimum that could be envisioned under any circumstances and is therefore understated.

3.6.2 "Optimistic" Augmentation

Assuming that the most optimistic augmentation ratio of 16 could be obtained, the corresponding weights and mature product costs for 40 kW, 200 kW and 1 MW VAC systems were calculated (see Tables 3-3, 3-4, and 3-5). Reductions in installed VAC costs at optimistic augmentation levels are about 20 percent each for the 40 kW and 200 kW systems, and 33 percent for the 1 MW system. In all cases, however, even at this high augmentation level the total VAC costs are still greater than for comparable conventional wind systems.

Under optimistic augmentation assumptions, the VAC installed capital costs are:

1.7 - 2.5 times that for conventional systems at the 40 kW, 200 kW and 1 MW sizes.

3.7 ENERGY COST COMPARISON

The key economic criterion in this analysis is a comparison of VAC energy cost and the energy cost for a comparable conventional wind system. These energy costs are developed for mature product versions of the systems being evaluated. At present there are no conventional wind systems optimized for annual mean wind speeds as low as 5.4 m/sec (12 mph). Therefore, we have used conventional system cost estimates for systems optimized to operate at $\bar{V} = 6.26 - 8.0$ m/sec (14 - 18 mph). The energy cost for the conventional systems at $\bar{V} = 5.4$ m/sec (12 mph) is thus likely to be over-estimated in relation to the achievable mature product energy cost for an optimally designed system.

The annual energy outputs and the capacity factors for the VAC systems evaluated are as follows:

<u>Rated Output</u>	<u>Capacity Factor*</u>	<u>Annual Energy Output (kWh)*</u>
40 kW	0.30	101,000
200 kW	0.34	618,000
1 MW	0.36	3,200,000

There is an improvement in the capacity factor with increasing system size because the hub height increases from 16.8 m (55 ft) at the 40 kW size to 38.1 m (125 ft) at the 1 MW level. The energy cost comparison for VAC and conventional systems over the 40 kW to 1 MW rated power range is shown in Table 3-6 for the baseline and optimistic augmentation cases.

At both the 40 kW and 200 kW rated power levels, the VAC energy cost is several times that of conventional systems despite the fact that the conventional energy cost does not refer to an

*At 90% availability.

Table 3-3

ESTIMATED WEIGHT AND INSTALLED TURN-KEY COST
FOR 40 kW VAC: OPTIMISTIC AUGMENTATION OF 16.0

	<u>Weight - kg (lb)</u>		<u>Cost (1979 \$)</u>
Rotor	909	(2,000)	\$ 4,200
Augmentor Surface	15,450	(34,000)	12,000
Deflecting Flap	1,950	(4,300)	1,300
Vertical Tail	1,636	(3,600)	1,100
Fairing	836	(1,900)	600
Transmission	5,900	(13,000)	54,300
Generators	409	(900)	2,400
Industrial Springs	364	(2,700)	1,100
<hr/>			
TOTAL ON TOP OF TOWER	28,720	(63,200)	77,600
Tower (Reinforced Concrete)	86,100	(189,600)	2,600
Total Hardware	114,900	(252,800)	80,200
Foundation ^a	114,900	(252,800)	12,600
Non-Hardware Costs	---	---	32,000
<hr/>			
Total	229,800	(505,600)	\$124,800

^aFoundation weight and cost are the minimum that could be envisioned under any circumstances and is therefore understated.

Table 3-4.

ESTIMATED WEIGHT AND INSTALLED TURN-KEY COST
FOR 200 kW VAC: OPTIMISTIC AUGMENTATION OF 16.0

	<u>Weight - kg (lb)</u>		<u>Cost (1979 Dollars)</u>
Rotor	4,544	(10,000)	\$ 18,000
Augmentor Surface	68,620	(151,000)	53,000
Deflecting Flap	8,634	(19,000)	6,000
Vertical Tail	7,271	(16,000)	5,000
Fairing	4,544	(10,000)	3,000
Transmission	12,720	(28,000)	143,000
Generators	1,136	(2,500)	9,500
Industrial Springs (4)	1,454	(3,200)	2,200
Bedplate	6,816	(15,000)	6,000
<hr/>			
TOTAL ON TOP OF TOWER	115,430	(254,700)	245,700
Tower (Reinforced Concrete)	347,200	(764,000)	10,500
Total Hardware	454,000	(1.0X10 ⁶)	256,200
Foundation ^a	454,000	(1.0X10 ⁶)	50,800
Non-Hardware Costs	---	---	102,000
<hr/>			
Total	908,000	(2.0X10 ⁶)	\$408,000

^aFoundation weight is minimum that could be envisioned under any circumstances and is therefore understated.

Table 3-5

ESTIMATED WEIGHT AND INSTALLED TURN-KEY COST
FOR 1 MW VAC: OPTIMISTIC AUGMENTATION OF 16.0

	<u>Weight - kg (lb)</u>		<u>Cost (1979 Dollars)</u>
Rotor	10,000	(22,000)	\$ 40,000
Augmentor Surface	103,160	(227,000)	80,000
Deflecting Flap	32,720	(72,000)	22,000
Vertical Tail	10,900	(24,000)	8,000
Fairing	9,090	(20,000)	6,000
Transmission		(129,000)	430,000
Generators	3,180	(7,000)	26,000
Industrial Springs	2,900	(6,400)	4,500
Bedplate	12,724	(28,000)	12,000
<hr/>			
TOTAL ON TOP OF TOWER	243,310	(535,400)	628,500
Tower (Reinforced Concrete)	729,800	(1.6X10 ⁶)	23,000
Total Hardware	972,900	(2.14X10 ⁶)	651,500
Foundation ^a	972,900	(2.14X10 ⁶)	107,000
Non-Hardware Costs	---	---	260,500
<hr/>			
Total	1.95X10 ⁶	(4.28X10 ⁶)	\$1,029,000

^aFoundation weight and cost are the minimum that could be envisioned under any circumstances and is therefore understated.

Table 3-6

VAC ENERGY COSTS (¢/kWh)

Rated Power	Conventional ^a	VAC - Baseline Augmentation Ratio	VAC - Optimistic Augmentation Ratio
40 kW	10	44	34
200 kW	8	31	19
1 MW	7	14	9

^aNot for optimized system.

optimal design for a $\bar{V} = 12$ mph site. At the 1 MW scale, the VAC energy cost is 1.3 times the conventional system energy cost at the optimistic augmentation ratio and for the baseline case, the VAC energy cost of 14 cents/kWh is about twice that of the conventional counterpart. Therefore, the VAC does not appear to be economically competitive with comparably-sized conventional horizontal axis wind energy systems.

Section 4.0

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APPENDIX A

STRUCTURAL ANALYSIS OF THE TORNADO WIND ENERGY SYSTEM

At the outset of this project, only limited and preliminary information was available from the Grumman Aerospace Corporation on the TWES tower design. Therefore, it was necessary for the study team to fill in the gaps by making reasonable assumptions concerning the design. One of the principal assumptions made involved definition of a conceptual vane design. The first concept focused on satisfying the structural requirements of the tower rather than optimizing its aerodynamic performance.

Midway through the study, Grumman indicated that their design team was leaning toward the use of "wing-like" tower vanes which were aimed at enhancing the aerodynamic performance of the system. Grumman did not supply design details for this new concept but merely indicated the general nature of the vane shape. Again the JBF study team established a baseline case vane design (concept #2) to be analyzed.

An analysis of each vane design was conducted to establish the baseline tower configuration needed to withstand the maximum design wind of 53.6 m/s at 9.1 m (120 mph at 30 ft) above ground*. A summary of this analysis follows:

1. First Vane Concept

Data received from Grumman indicated for a 1 MW baseline case, the TWES tower would have the following characteristics:

- o Height 103.6 m (340 ft)
- o Outer Diameter 51.8 m (170 ft)
- o Number of Vanes 8 to 16
- o Bottom of tower is at 9.1 m (30 ft) above ground level
- o Material of Construction - Reinforced concrete

The vane shape assumed by JBF is illustrated in Figure A-1.

The design assumptions and data base used in the analysis is shown in Table A-1. The wind loading pressures at the 120 mph design wind speed are**:

Height Above Ground m (ft)	Wind Loading Pressure kg/m ² (lb/ft ²) for 53.6 mps (120 mph) winds
< 9.1 (< 30)	190.4 (39)
9.1 (30)	234.3 (48)
106.7 (350)	405.2 (83)
121.0 (400)	419.8 (86)

*A zero gust factor was assumed.

**Source: U.S. Department of Housing and Urban Development,
"Design and Construction of Large Panel Concrete Structures,"
HUD-H-2131 R, April 1975

Table A-1

Design Assumptions and Data Base:
Concept #1

- o Number of Tower Vanes = 12 (Mean of Grumman value)
- o Ratio of open to closed tower surface area = 2:1
- o Tower located in flat, open area
- o Linear variation of pressure with heights more than 30 ft above ground
- o Concrete strength: $f_c = 4 \text{ Ksi or } 281.2 \text{ kg/cm}^2$
- o Steel strength: $f_y = 60 \text{ Ksi or } 4218 \text{ kg/cm}^2$
- o In the absence of information concerning internal pressure and pressure distribution from the air flow over the vanes, it was assumed that the windward side would be subject to a positive pressure and the leeward side to a suction force with no relief attributable to the open area between the vanes.
- o The Neutral Axis is 1.22 m (4 ft) from the outer surface and perpendicular to the radial line to the centroid.
- o The tower supported on columns with center lines collinear with the axis of the vanes.

FIGURE A-1
FIRST VANE CONCEPT

The windward and leeward factored pressures are*:

windward: (0.89) (1.7)

leeward: (-0.79) (1.7)

The above data leads to the following linear loading pressures on a 15 foot wide column:

windward: 1275.2 kg/m (857 lb/ft)

leeward: -1117.5 kg/m (-751 lb/ft)

For a vane with 32 foot exposure area width, the linear loading pressures are:

o Top

windward = 5952 kg/m (4000 lb/ft)

leeward = -5208 kg/m (-3500 lb/ft)

o Bottom

windward = 3958 kg/m (2660 lb/ft)

leeward = -2946 kg/m (-1980 lb/ft)

A gravity load of 24.03 kg/m^3 (150 lb/ft^3) was used as the dead load for all parts of the structure. A uniform transverse load for the rings and an axial uniform load for the vanes and columns were used. Also a safety factor of 1.4 was included to conform with ACI requirements.

A preliminary analysis indicated that a wall width of about 10 ft would be required. In order to validate this conclusion, the following check was made. The column, vane, and ring cross sectional areas

column: 13.9 m^2 (150 ft^2); 4.6 m (15^1) x 3.05 m (10^1)

vane: 27.3 m^2 (294 ft^2); (obtained by numerical intergration)

ring: 9.3 m^2 (100 ft^2); 3.05 m (10^1) x 3.05 m (10^1)

were used as inputs into a structural design language computer program (STRU DL) to model the critical design forces and determine the maximum deflection at the top of the tower. The balance condition was then applied assuming that:

*Used to conform with American Concrete Institute safety requirements.

- o Each vane could be approximated by a rectangular cross-sectional element;
- o For a rectangular cross-section, the reinforcing steel is distributed uniformly over the periphery of the cross section. The amount of steel over each edge is proportional to the ratio of the side length to the perimeter of the rectangle.

The results showed that the 3.05 m (10 ft) wall thickness is more than sufficient to withstand the imposed stresses. However, even at this thickness, the top of the tower suffers a deflection of approximately .61 m (2 ft). Unless this deflection is of no concern, it was recommended that the 3.05 m (10 ft) vane thickness not be reduced. If the 2 foot deflection is considered excessive, the use of additional support rings may need to be incorporated into the design.

The results presented are considered preliminary. Further analysis should include the effects of internal pressure as well as the air flow over the vanes and the accompanying drag.

2. Second Vane Concept

A design aimed at improving the aerodynamic characteristics of the TWES tower was also examined (see Figure A-2). A structural analysis was performed on this design to specify the physical characteristics of the vanes necessary to withstand the required wind stresses.

The length, diameter and number of vanes were the same as the first concept. The design assumptions and data base for the second vane concept is given in Table A-2.

The lift loading was computed from the equation

$$P_L = C_L \rho \frac{V^2}{2} A$$

where: C_L = coefficient of lift (0.1 α)

α = angle of attack ($-15^\circ < \alpha < 15^\circ$)

ρ = mass density of air (0.00238 slugs/ft³)

V = free field velocity of air

A = chord length

The loading pressure and gravity loading were calculated in the same way as for the first concept. The cross section of the vane was modelled as a symmetric wing section*.

*The properties applied were obtained from "Theory of Wing Sections" by Ira H. Abbott and Albert E. VonDoenhoff, Dover Publications, 1958.

Table A-2

Design Assumptions and Data Base:
Concept #2

- o Tower located in flat open area
- o Linear variation of pressure with height above ground over 9.1 m (30 ft)
- o Stall angle of 15 degrees
- o Vanes have a symmetrical cross-section above the chord defining the extremities of the cross-section
- o In absence of more definitive information concerning the flow inside the tower, the following is assumed:
 - the vanes with an angle of attack $-15^{\circ} < \alpha < 15^{\circ}$ are subject to lift (either positive or negative)
 - the exposed vanes not within the above limit are subject to pressure loading
 - those vanes not satisfying either of the above conditions are subject to a suction force
- o Concrete strength = 4 ksi or 281.2 kg/cm²
- o Steel strength = 60 ksi or 4218 kg/cm²
- o The tower will be supported on columns with center lines collinear with the axis of the vanes.

Figure A-2
Wing Vane Design Concept

The support rings were estimated to be 9.1 m (30 ft) wide based on the use of a photograph of the current Grumman model. Use of this distance and a 15 degree angle of attack indicated that the vane chord length would have to be 28.3 m (92.7 ft). This chord length defined a minimum thickness of 1.8 m (6 ft) measured at a point located on the axis at a distance of 30% of chord length from the apex; the cross section was approximated by a NACA 0006 wing.

Lift and drag coefficients for this wing were obtained*. Since the drag coefficient was much smaller than the lift coefficient, the effects due to the drag force were neglected. Also, the lift force was replaced by a lift force and a pitching moment acting at the centroid of the cross section. The cross sectional area was calculated (using numerical integration) to be 28.8 m^2 (310 ft^2). The centroid of the cross section was located and the centroidal moment of inertia was calculated.

The investigation started with a maximum cross sectional thickness of 1.8 m (6 ft) for the vanes. This was the minimum for which lift and drag coefficients were available. Preliminary analysis indicated that this cross section could withstand the bending and axial stresses. Therefore a 1.2 m (4 ft) thick vane was also analyzed. The cross sectional area for this vane was determined to be 19.3 m^2 (208 ft^2). The centroid was located and the centroidal moment of inertia was calculated using the same lift coefficients assumed for the 6 ft case.

In both the 4 ft and 6 ft cases, the support columns were determined to be 9.1 m (30') x 3.05 m (10'), yielding a 27.9 m^2 (300 ft^2) cross sectional area. The rings varied in thickness from 1.5 m (5') for the 1.8 m (6') vanes to .91 m (3') for the 1.2 m (4') vanes.

The STRUDL program was again used to determine the various forces, moments and deflections. Two support rings were assumed for each case. It should be noted that in the case of the 1.2 m (4 ft) vane, the use of an additional intermediate ring was analyzed; however, no significant differences from the two ring case were noted.

A stress investigation was performed based on the balance condition determined in the same way as the first concept. This stress analysis incorporated the following assumptions:

- o Cross-sectional properties can be computed based on the uncracked section; however, these properties as computed by considering the concrete section only (not the transformed cross-section).

*Van Doenhoff, A.E. and I.H. Abbott, "Theory of Wing Sections", Dover Publications, P. 452, 1958.

- o Maximum stresses occur at points of intersection of the principal axis of the cross section with the perimeter of the cross section.
- o A steel to concrete ratio of $\rho = 0.01$ is used since this represents the minimum amount of reinforcement allowed for columns. Two-thirds of this reinforcement is on the longer side of the major principal axis at an average distance of 9.4 m (30.9 ft) and one-third of the reinforcement on the other side of the major axis at an average distance of 4.7 m (15.4 ft). The average stress in the reinforcement is F_y/s , where F_y is the yield point of the reinforcement.

The computer solutions indicated that the deflections obtained (about .3 m (1 ft) for 1.8 m (6 ft) vanes and .7 m (2.3 ft) for 1.2 m (4 ft vanes)) were within the structurally acceptable range. Stress calculations also indicated satisfactory results.

The effect of reducing suction pressure was also investigated by reducing the forces due to suction by 50%. This causes a considerable reduction in the bending moments produced. This could be a significant factor if a more comprehensive analysis of flow both inside the tower and outside justifies this reduction.

Although the analysis indicates the vane cross-sections to be satisfactory for axial and bending stresses, the shape may produce undesirable effects due to buckling. This effect was not fully studied. However, the buckling tendencies can be reduced by using additional rings at intermediate points.

The width of the columns was chosen to be relatively large to conform with the dimensions of the vanes. In view of the large cross-sectional areas and based on the results of the analysis, the columns will be able to sustain the applied loads and moments. Similar conclusions may be drawn in the case of the rings.