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Work performed for
U.S. DEPARTMENT OF ENERGY
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SUMMARY OF TOWER DESIGNS FOR LARGE HORIZONTAL AXIS WIND TURBINES

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SUMMARY

Towers for large horizontal axis wind turbines (machines with a rotor axis above 30 meters and rated at more than 500 kW) have varied in configuration, materials of construction, type of construction, height, and stiffness. For example, the U.S. large HAWTs have utilized steel truss type towers and free-standing steel cylindrical towers. In Europe, the trend has been to use only free-standing and guyed cylindrical towers, but both steel and reinforced concrete have been used as materials of construction. These variations in materials of construction and type of construction reflect different engineering approaches to the design of cost effective towers for large HAWTs.

Tower designs are reviewed beginning with the historic Smith-Putnam HAWT and progressing through the NASA/DOE Mod-5B presently being fabricated. Design goals and requirements that influence tower configuration, height and materials are discussed. In particular, experiences with United States large wind turbine towers are elucidated. Finally, current trends in tower designs for large HAWTs are highlighted. The material discussed in this paper will be beneficial to those companies contemplating the development and/or manufacture of large HAWTs. Foundation designs are not discussed in this paper.

INTRODUCTION

Towers for large horizontal axis wind turbines (LHAWTs) have varied in configuration, materials of construction, height, and stiffness. In this paper, a LHAWT is defined to be rated at 500 kW or more and to have a hub height above 30 meters. In the U.S., towers ranged in type from the stiff four leg steel truss tower to the rather flexible 12 sided free-standing cylinder (ref. 1). In Europe, on the other hand, LHAWT towers of the guyed cylinder type have been used in addition to the free-standing cylinder (ref. 2). By way of contrast, U.S. large wind turbine towers have been made of steel whereas in Europe reinforced concrete as well as steel has been a favored material.

It is not immediately obvious why such an array of tower configurations and materials of construction exists and whether any trends exist. The purposes of this brief paper are to (a) briefly discuss the important factors such as the goals, requirements, and loads which most influence the tower designs, (b) outline the general design approach, (c) list and describe in one article the towers which have been built for LHAWTs and most of those towers which, in

1985, have been designed and/or are under construction in the United States and Europe, and (d) point out the direction in which tower designs appear to be heading. The material presented herein is for the benefit of those persons and companies that are interested in the design and/or manufacture of support towers for LHAWTs. The foundation designs for the towers are not discussed because of space restrictions.

GOALS AND REQUIREMENTS

The primary requisite and goal for a wind turbine is that it be capable of producing electrical energy at a cost competitive rate. This implies that each major component of a wind turbine system be designed to be cost effective, including the tower. To achieve the goal of a cost effective tower requires that the designer strive to minimize fabrication, shipping, erection, and maintenance costs while at the same time achieving aesthetic and environmental acceptability. In addition to meeting these goals, the tower must also satisfy a number of important technical requirements.

The primary technical requirement for a LHAWT tower is that it support the rotor and the nacelle structure which contains the power train and auxiliary equipment. A second important requirement is that the tower safely withstand all of the loads imposed upon it by the wind and the environment during its service life, which is 20 to 30 years depending on the time chosen over which to amortize the wind turbine. In meeting this second requirement the tower characteristics, such as its natural frequency, shall not adversely affect the service life of other system components.

DESIGN LOADS

The primary loads and conditions that influence the design of a tower are those forces transmitted from the rotor and nacelle, and those imposed directly on the tower by (a) the infrequent extreme winds which can be as high as 50 to 70 mps (115 to 160 mph) depending upon the site; (b) the most frequent winds encountered under normal operating conditions (in the range from about 5 to 25 mps); (c) certain environmental conditions such as ice and snow accumulation and earthquakes; and (d) emergency conditions associated with equipment malfunction (refs. 3 to 6).

The extreme wind is the maximum wind speed that is expected at the site during the service life of the wind turbine. For design purposes it is conservatively assumed that this wind is steady, the machine is not operating, and the rotor blades are flat to the wind. The tower forces due to the extreme wind are usually the critical loads that significantly influence the tower design.

Under normal operating conditions, the tower is subjected to a combination of direct wind forces and dynamically induced forces. These include dynamically induced forces encountered during startup and shutdown operations. During normal operation the winds are generally nonuniform and unsteady. Such winds generate unsteady forces on the rotor blades which are transmitted to the tower and, to a lesser extent, on the tower directly. These unsteady forces during startup, power generation, and shutdown can result in fatigue damage and, perhaps, failure. Therefore, to ensure that the tower will not fail in fatigue, it is necessary to know the unsteady characteristics of the wind and to properly include their effects in the design.

Another source of wind-induced excitation is the vortices that peel off the leeward side of a cylindrical tower. These vortices are periodic and induce oscillatory forces on the tower that can excite it if the tower and vortex shedding frequencies are in resonance.

The more important emergency load cases are those resulting from (a) sudden loss of the generator load, or (b) unbalanced rotor forces caused by a malfunction of a rotor control element such as a pitch actuator. These types of loads are infrequent, but because they can be large, they must be included in the tower design. The loss of an entire blade is not usually an emergency load case for LHAWTs designed in the United States. For some LHAWTs designed in other countries, such as Sweden, loss of an entire blade is an emergency load case.

In addition to forces induced by the wind and turbine operations (mentioned above), the effects of low temperature and moisture must be considered. Very low temperatures, below -31 °F, are known to affect the fracture toughness of steel. Moisture, particularly in a salt air environment, can lead to excessive corrosion which can shorten the tower life if the tower is not protected against it.

Finally, the tower design must take into consideration the forces on the tower during earthquakes, handling, transportation, and field assembly. While these forces are not usually critical to the design of the tower, their effects must be assessed.

DESIGN APPROACH

The design of a support tower may be begun by superimposing the extreme wind loads upon the dead loads associated with the system. The extreme wind loads are usually calculated with the blades parked and flat to the wind. All wind azimuths with respect to the axis of rotation must be considered to ensure that the critical case has been used. For design of the tower, this is expected to occur with the rotor located downwind of the tower. For this orientation, the tower bending moment due to the wind will directly add to the dead load bending moments associated with the nacelle and rotor. The tower is then sized to resist these loads. At this conceptual design stage, various tower configurations may be considered. As soon as a design can be shown to be unacceptable (not economical, not associated with ease of construction, etc.), it is rejected and dropped from the list of possible acceptable designs.

Those designs remaining on the list are then checked for the various combinations associated with normal operating conditions, environment conditions and emergency conditions. The appropriate wind characteristics including wind shear, surface roughness, gusting and turbulence must be included when calculating the associated loads. Since these loads are time-varying, it is necessary to perform fatigue analyses for the various loads to determine whether the designs are adequate. The natural frequencies of vibration of the wind turbine system also must be determined for the various tower configurations. Designs that are inadequate are then modified or rejected. Designs may be rejected for factors such as tower shadow effects, shipping considerations, field assembly considerations, foundation design considerations, noise, aesthetics, etc.

Wind-induced vibration of the tower must also be investigated. In steady wind conditions vortices are alternately shed from the sides of cylindrical structures which can lead to swaying motions. If the vortex shedding frequency coincides with a natural frequency of vibration, resonance will occur. This condition must be checked for the complete wind turbine structure and for the tower alone. If the tower alone is associated with resonance, temporary strakes (helical strips) can be installed on the outside of the tower during construction until the equipment is attached at the top of the tower to break up the vortices.

Finally, a cost analysis of the complete LHAWT system is performed for all designs which have not been rejected. In these analyses, the total costs associated with each tower design must be considered. The total cost includes a consideration of fabrication costs, shipping costs, erection costs and maintenance costs. The preferred tower design is that which satisfies all the goals and requirements, and which is associated with the minimum cost. Final design of the tower is then completed for this tower.

U.S. LHAWT TOWER DEVELOPMENT

The first megawatt LHAWT constructed anywhere was the 1250 kW Smith-Putnam machine (ref. 7). It was built in 1940 and operated near Rutland, Vermont from 1941 to 1945. Since 1975, under sponsorship of the U.S. Department of Energy (DOE) and under NASA management, five intermediate size and six megawatt size HAWTs have been built and operated: the 100 kW Mod-0; four 200 kW Mod-0A's; the 2000 kW Mod-1; and five 2500 kW Mod-2's (ref. 2). Another multimegawatt HAWT, the 4000 kW WTS-4, was built for the U.S. Department of the Interior by the Hamilton-Standard Company. Only the Mod-0, four of the Mod-2's, and the WTS-4 remained in operation as of July 1985. In table I are summarized the principal features of the above-mentioned machines with emphasis on the tower characteristics. (The Mod-0 and Mod-0A machines, though intermediate in size, are included to provide weight versus height data for truss type towers at the lower end of the weight and height scales.)

Of the HAWTs mentioned above, seven were constructed with four-leg truss type towers: the Smith-Putnam machine, the Mod-0, Mod-0A's, and the Mod-1. The Mod-1 truss type tower is shown in figure 1. Subsequently, the Mod-0 truss tower was replaced with a 12-sided cylinder braced with 4 struts. (This was done to study the dynamics of a wind turbine system with a more flexible tower.) One LHAWT has a slightly tapered, steel 12-sided cylindrical tower: the WTS-4. This tower was made of brake-formed segments which were welded together and is shown in figure 2. The rest, the five Mod-2's, had free-standing untapered steel circular towers with steel conical bases as shown in figure 3.

The Mod-0 and Mod-0A were considered to be experimental wind turbines. They were the first of their kind to be built in the present era. The primary objective of these was to gain experience and acquire a data base needed for developing cost effective machines. To ensure successful and safe operation, the Mod-0 and Mod-0A towers, as well as the other components, were conservatively designed. Each of these wind turbines and the Mod-1 had a rotor with two blades rigidly attached to the hub which, in turn, was rigidly attached to the low speed shaft; that is, the rotors were not teetered. Furthermore, the rotors were downwind of the towers. In this configuration, and in a gradient wind field, the rotor imparts high bending and high torsional moments to the tower at the dominant frequency equal to the blade passing frequency (two per revolution for two blade rotors). At the time the Mod-0 and Mod-0A machines were designed, computer codes with which to analyze their dynamic behavior were not readily available. To ensure the tower did not have a first bending and a first torsional frequency equal or close to two per revolution, the truss tower was chosen and designed to have its first bending and torsional frequencies above this value. The result was that the Mod-0 and Mod-0A towers were quite stiff; as a consequence they also were heavy and expensive.

The Smith-Putnam wind turbine was the end result of many design and cost studies aimed at developing the HAWT as a cost-effective source of renewable power. The hub height selected was 36 m. Its four-leg truss type tower was considered to be a cost effective tower concept at that time. It was built using standard structural elements such as channels, I-beams, and angles. (The weight was not available in any publications.)

The Mod-1 was also designed with cost effectiveness as a goal. As in the Smith-Putnam project, the Mod-1 was the end product of a conceptual design and cost study aimed at identifying the most promising size and configuration of future cost effective wind turbines (ref. 8). Accordingly, a stiff truss type tower was chosen and designed. However, experience with fabrication and assembly of the Mod-1 showed that the truss concept was not cost effective for megawatt size LHAWTs. A follow-on design improvement and cost reduction study indicated that an upwind, teetered, two-blade rotor atop a somewhat flexible cylindrical tower would result in lower tower loads and a lower cost megawatt size LHAWT concept. Additionally, the use of a more flexible tower would be associated with the magnitudes of forces exerted on other components of the LHAWT being reduced. These findings led to the inclusion of the teetered rotor and the more flexible cylindrical tower into the design of all subsequent U.S. LHAWTs which are operating, namely the Mod-2's and the WTS-4, and in the more recent designs that are being built, such as the Mod-5B and the Westinghouse 600 kW WWG-0600. The features of the Mod-5A, Mod-5B and the WWG-0600 are presented in table II. The Mod-5A design will not be built since the project was terminated in late 1983.

The terminology commonly used to describe the flexibility of a LHAWT tower is soft-soft tower, soft tower, and stiff tower. A soft-soft tower has its first bending frequency of vibration with equipment mounted on top at a value less than the frequency of rotor rotation. A soft tower has its first bending frequency between one and N times the frequency of rotor rotation where N is the number of blades. The stiff tower has its first bending frequency at a value more than N times the frequency of rotor rotation. The Mod-2's and the Mod-5B were constructed/designed with soft towers. The only U.S. LHAWT constructed with a soft-soft tower was the WTS-4.

EUROPEAN LHAWT TOWER DEVELOPMENTS

Five experimental LHAWTs are in operation in Europe: the two 630 kW Nibe A and B wind turbines in Denmark (ref. 9); the 3000 kW Maglarp and 2000 kW Nasudden machines in Sweden (ref. 10); and the 3000 kW Growian wind turbine in

West Germany (ref. 11). Eight have been recently designed, some of which are being built. Some of the principal features of these fifteen machines are given in tables I and II. (Several intermediate size HAWTs are included in table II to provide weight and height data for cylindrical towers at the lower end of the scale.)

Of the five wind turbines in operation, three (the Nibe A and B, and the Nasudden) have towers made of reinforced concrete that were constructed using the well developed slipforming technique. In fact, these appear to be the only concrete towers in Europe or the U.S. supporting LHAWTs. The Maglarp tower is a free-standing untapered circular steel cylinder; whereas, the Growian is a guyed untapered steel cylinder, and appears to be the only guyed tower on a LHAWT anywhere. Concrete towers, as shown in figure 4, were chosen for the Nibe A and B in part because reinforced concrete is widely used in large structures in Denmark and because such towers were used in many wind turbines that were built in the 1940's. In addition, reinforced concrete towers have been shown to be cost effective in Denmark (ref. 12). This is reflected in the use of reinforced concrete towers for the five new 750 kW LHAWTs now (1985) under construction.

The Maglarp and Nasudden LHAWTs utilized cylindrical towers each of a different material, steel and reinforced concrete, for the purposes of a comparative evaluation. An evaluation of these two wind turbine systems was completed in late 1984, and it was concluded that, when mass produced, both the Nasudden and Maglarp machines would produce electricity at a competitive rate (ref. 13). This suggests that both types of towers would be acceptable and therefore cost effective.

The experience with the Growian is not yet available. However, it may be correct to infer that guyed towers are not a preferred concept for megawatt size wind turbines since the latest West German megawatt design (the WEC-60) has a free-standing cylinder on a conical base (ref. 14).

When the new generation of European LHAWTs are reviewed (table II), it is clear that a free-standing cylinder, either tapered or untapered, with or without a conical base, is the preferred type of tower. All except the five Masnedo, the Orkney-60 and the WEC-60 machines will use steel as the material of construction. The Masnedo wind turbine towers are being constructed of reinforced concrete. The Orkney-60 LHAWT tower is a hybrid, as shown in figure 5: a reinforced concrete conical base with an inverted steel conical top. The WEC-60 LHAWT tower is also a hybrid: a steel cylinder on a conical reinforced concrete base. Here a concrete base was selected since the turbine is sited off-shore.

CURRENT TRENDS

Some general trends can be discerned from an examination of the relation between tower weight and rotor axis height plotted in figure 6 using the data of tables I and II. In figure 6, the plotted points are grouped where possible according to tower type and/or construction materials. Some points are for towers that are unique; therefore, trends for these towers are not discernible. An analysis using only this relationship is admittedly a rather simple one because other factors such as the rotor diameter, and the tower natural frequencies also influence the tower weight. Nonetheless, some useful trends can be seen.

A line drawn through the points for the Mod-0, Mod-0A, and Mod-1 truss towers has the steepest slope (weight increase with rotor height). Only at small heights does the truss tower appear to have a weight advantage with respect to other steel towers. Since the truss tower, for rotor heights associated with LHAWTs, is heavy, it can be expected to be expensive and stiff. Accordingly, the stiff steel truss tower is probably not an economical concept for a LHAWT.

A line drawn through the points representing the various steel cylindrical towers has a much gentler slope. For rotor heights associated with LHAWTs they offer considerable weight savings with respect to steel truss towers. Since cylindrical towers offer a weight reduction and also have a smaller cross section than truss towers, they are more flexible. This attenuates the magnitudes of the dynamic forces acting on the various components of a LHAWT. It is concluded that a steel cylindrical tower is a cost effective concept for a LHAWT. This conclusion is substantiated by the fact that more steel cylindrical towers have been constructed to date than any other type of tower supporting a LHAWT.

The line drawn through the points representing the various free-standing steel cylindrical towers in figure 6 applies only to those with a natural bending frequency above one per revolution (1P), or soft towers. The only other free-standing steel cylindrical towers are those of the WTS-3 and WTS-4, which are a soft-soft towers. This line indicates that the tower weight in kilograms increases approximately as the rotor axis height in meters to the 2.85 power.

The line drawn through the points representing the various free-standing reinforced concrete cylindrical towers closely parallels that drawn through the points representing free-standing steel cylindrical towers. This line is defined by only two points - the Nibe A and B and Masnedo towers (which all have the same characteristics) and the Nasudden tower. These towers are regarded as cost effective by their designers (refs. 12 and 13). Since these two lines are parallel, it is concluded that the most cost effective tower is that utilizing the material that can be constructed and maintained most economically. The construction cost per pound of reinforced concrete relative to structural steel is considerably less and may vary widely from site to site. Hence, the selection between free-standing reinforced concrete and free-standing steel cylindrical towers can not be made merely be comparing the plots in figure 6. The local unit construction costs must be included. Additional operating and maintenance items, such as painting, must be considered since two different materials are being compared. From figure 6, it is concluded that free-standing reinforced concrete and free-standing steel cylindrical towers offer the most promising cost effective concepts for support towers for LHAWTs.

The other tower configurations plotted in figure 6 are each unique. As such, no trend of tower weight with rotor height can be developed.

The WTS-3 and 4 towers are interesting because of what they reveal about the effect of the natural frequency on tower weight. Both towers have a natural frequency below 1P: 0.35 Hz for the WTS-3 tower and 0.28 Hz for the WTS-4 tower (which is about 80 percent that of the WTS-3). A comparison of the tower weights shows that the weight of the WTS-4 tower is about one half of the WTS-3 tower weight. This comparison clearly demonstrates that a significant reduction in tower natural frequency results in a significant reduction of the tower weight. A comparison of the Mod-2 and Mod-5B, which are nearly identical configurations except for the rotor diameter and rated power, illustrates the effect of a change in rotor diameter and power plus increased design conservatism. These three factors drove the tower weight up by 40 percent.

Some comments can be made about the Orkney-60, Growian, and WEC-60 towers even though they are unique. The Orkney-60 has the same rotor axis height as the Nibe A and B, and Masnedo machines, a much larger rotor area diameter, and a considerably heavier tower (2.55 times heavier). This larger weight probably reflects the effect of the larger rotor diameter and possibly a greater stiffness. The guyed tower of the Growian also has its first natural bending frequency below 1P. Even though its weight is not high in relation to its height, it was judged to be too expensive because of the costly guy cables (ref. 14); this may be one reason for the shorter steel cylindrical tower on the reinforced concrete base of the WEC-60.

CONCLUSIONS

Based upon the information available, it can be said that the general trend, with few exceptions, has been away from stiff towers toward flexible towers. The favored type today is the soft, free-standing cylindrical tower; some of which are on conic bases, some are tapered, and others are untapered. (Often a conic base is not used for structural considerations, but rather to provide space for a control room at the base of the tower.) The use of a soft tower eliminates the potential problems associated with the rotor passing through resonance as it accelerates to operating speed.

Favored materials of construction are both steel and reinforced concrete. Often the literature contained statements indicating that neither steel nor reinforced concrete offered a clear-cut cost advantage. The selection between these two materials is site-sensitive. The material chosen will depend upon unit costs associated with the materials and upon the local construction technology.

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TABLE I. - SUMMARY OF TOWERS ON OPERATING MACHINES (MID-1985)

HAWT name, country [ref.]	Rated power, MW	Rotor diameter, m (no. of blades)	Ht. to rotor axis, m, (rpm)	Tower type	Tower materials	Tower weight, kg	1st bending frequency, Hz (no./rev)
Mod-0 Mod-0A U.S. [3]	0.10 .20	38 38 (2)	31 31 (40)	4-leg truss for both machines	Steel structural members	20 900	2.2 (3.33P)
Mod-1 U.S. [4]	2.0	61 (2)	43 (34.7)	4-leg truss	Steel structural members	163 000	1.85 (3.2P)
Mod-2 U.S. [5]	2.5	91 (2)	61 (17.5)	Cylinder on a conic base	Rolled steel plate	115 700	.38 (1.3P)
WTS-4 U.S. [2]	4.0	78 (2)	80 (30)	12 sided cyl., slightly tapered	Brake-formed steel plate	135 000	.28 (.563P)
WTS-3 MAGLARP Sweden [10]	3.0	78 (2)	80 (25)	Cylinder, no taper	Rolled steel plate	281 000	.35 (.84P)
KAMEWA NASUDDEN Sweden [10]	2.0	75 (2)	77 (25)	Cylinder, tapered	Reinforced concrete	1 500 000	1.04, 1.17 (2.49P, 2.8P)
NIBE A & B Denmark [9]	.63	45 (3)	45 (34)	Cylinder, tapered	Reinforced concrete	262 000	1.29, 1.34 (2.28P, 2.36P)
GROWIAN West Germany [13]	3.0	100.4 (2)	100 (18.5)	Guyed cylinder	Steel plate and cables	235 000 (includes guys)	.44 (1.43P)

TABLE II. - SUMMARY OF TOWERS ON LHAWTs DESIGNED AND/OR UNDER CONSTRUCTION IN MID-1985

HAWT name, country [ref.]	Rated power, MW	Rotor diameter, m (no. of blades)	Ht. to rotor axis, m (rotor rpm)	Tower type	Tower materials	Tower weight, kg	1st bending frequency, Hz (no./rev)
Mod-5A U.S. [6]	7.3	122 (2)	76 (13.5 or 116.5)	Cylinder with conic base	Rolled steel plate	276 000	0.34 (1.5P,1.23P)
Mod-5B U.S. [14]	3.2	98 (2)	76 (13 to 17)	Cylinder with conic base	Rolled steel plate	162 000	0.26,0.5 (1.2P,1.7P)
WWG-0600 U.S. [15]	.625	43 (2)	37 (43)	Cylinder with conic base	Rolled steel plate	40 900	0.883,0.889 (1.23P,1.24P)
MASNEDO Denmark [12]	.75	40 (3)	45 (34)	Tapered cylinder	Reinforced concrete	262 000	1.29,1.34 (2.28P,2.36P)
HWP-300	.30	22 (3)	22 (45)	Cylinder with conic base	Rolled steel plate	22 300	1.8,2.02 (2.4P,2.69P)
HWP-750 England [17]	.75	45 (3)	35 (30)			29 400	1.7 (3.4P)
ORKNEY-60 England [18]	3.0	60 (2)	45 (34)	Cylinder with conic base and inverted conic top	Reinforced concrete cyl. base, rolled stl. conic top	670 000	1.35 (2.38P)
GAMMA Italy [19]	2.0	70 (2)	56 (18.3 or 27.5)	Untapered cylinder	Rolled steel plate	150 000	0.5 (1.67P,1.25P)
WEC-60 West Germany [13]	1.2	60 (3)	46 (19.8 to 24.2)	Cylinder with conic base	Rolled stl. cyl., reinforced concrete base	60 000 150 000 incl. found.	0.93 (2.8P,2.3P)
WPS-30 Netherlands [20]	.375 .455	30 (3) 30 (3)	30 (27 or 55) 35 (27 or 55)	Cylinder with 3 stepped sections	Steel pipes or rolled stl. plates	18 500 22 500	n/a
WEG-25 England	.25	25 (3)	25 (48)	Tapered cylinder	3 steel tubes slip joined together	9 000	1.32 (1.6P)

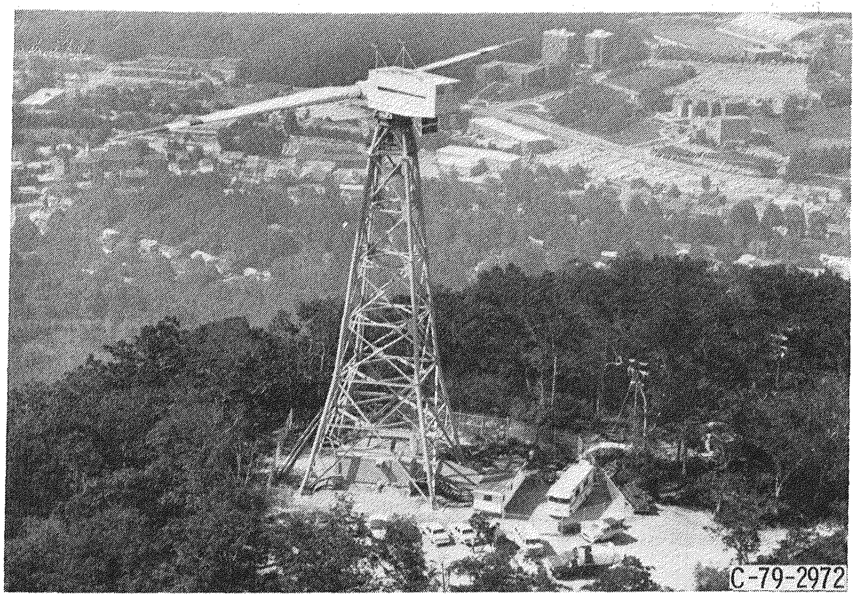

Figure 1. - Mod-1, 2 megawatt wind turbine. Truss tower fabricated from circular pipe and standard structural steel elements.

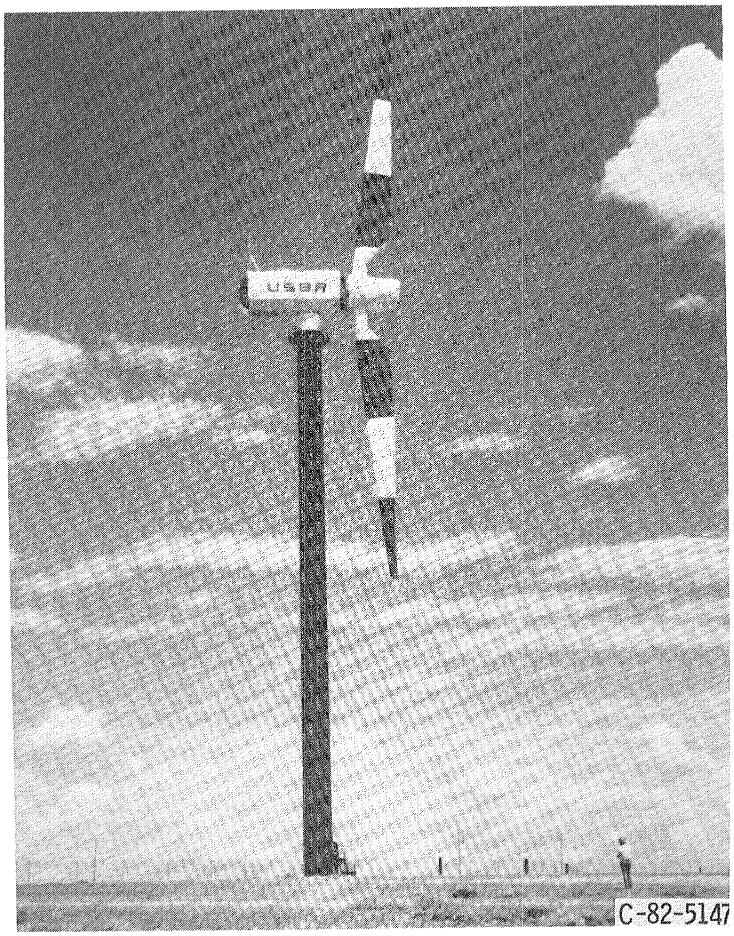

Figure 2. - WTS-4, 4 megawatt wind turbine. Tower is a 12-sided steel cylinder, slightly tapered.

Figure 3. - Mod-2, 2.5 megawatt wind turbine. Tower is a steel circular cylinder on a steel conic base.

Figure 4. - Nibe A, 630 kW wind turbine. Tower is constructed of reinforced concrete by slip forming.

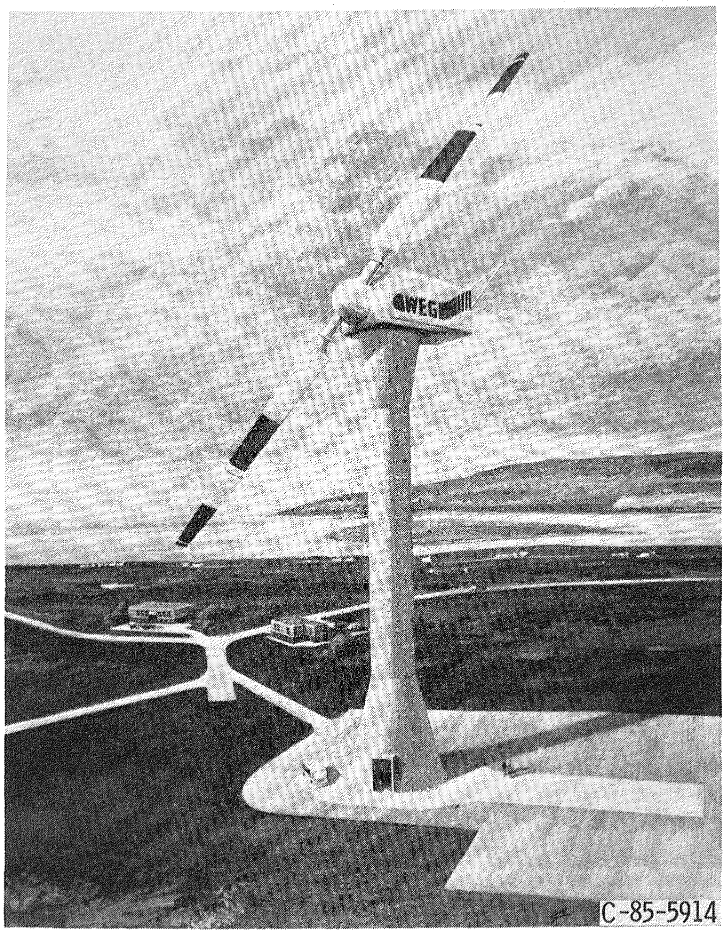

Figure 5. - Orkney-60, 3 megawatt wind turbine. Tower is constructed of reinforced concrete cylinder and conic base, and inverted rolled steel conic section.

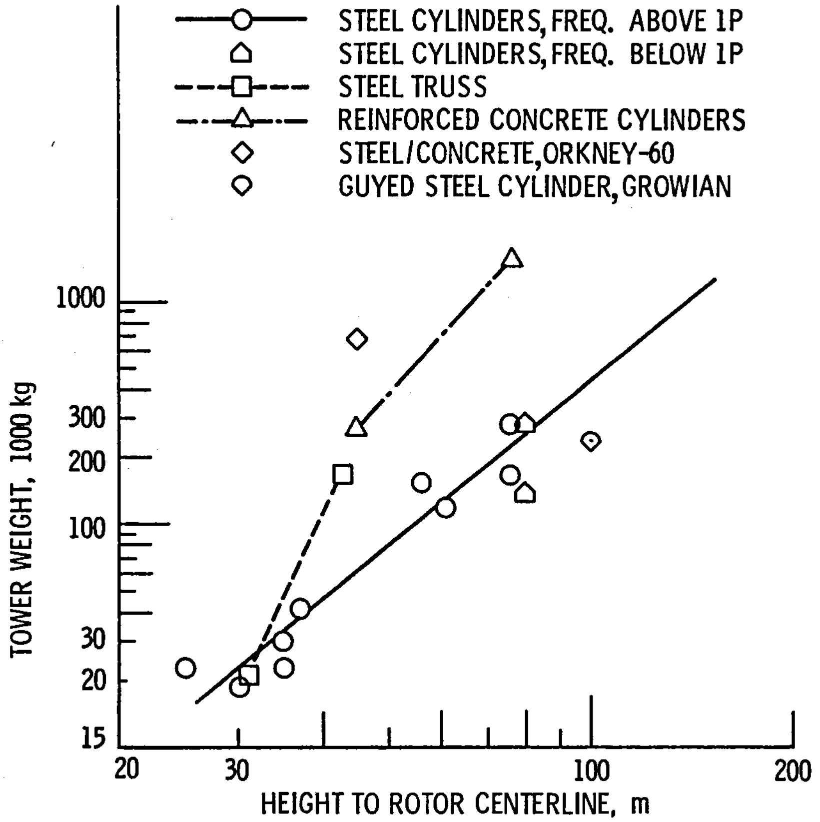

Figure 6. - Relation between tower weight and rotor axis height. (WEC-60 not plotted for lack of weight data.)

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16. Abstract
Towers for large horizontal axis wind turbines, machines with a rotor axis height above 30 meters and rated at more than 500 kW, have varied in configuration, materials of construction, type of construction, height, and stiffness. For example, the U.S. large HAWTs have utilized steel truss type towers and free-standing steel cylindrical towers. In Europe, the trend has been to use only free-standing and guyed cylindrical towers, but both steel and reinforced concrete have been used as materials of construction. These variations in materials of construction and type of construction reflect different engineering approaches to the design of cost effective towers for large HAWTs. Tower designs are reviewed beginning with the historic Smith-Putnam HAWT and progressing through the NASA/DOE Mod-5B presently being fabricated. Design goals and requirements that influence tower configuration, height and materials are discussed. In particular, experiences with United States large wind turbine towers are elucidated. Finally, current trends in tower designs for large HAWTs are highlighted. The material discussed in this paper will be beneficial to those companies contemplating the development and/or manufacture of large HAWTs. Foundation designs are not discussed in this paper.

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