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WIND-DRIVEN DEVICES FOR PUMPING WATER AND GENERATING ELECTRIC POWER

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WIND-DRIVEN DEVICES FOR PUMPING WATER AND GENERATING ELECTRIC POWER

FOREWORD

This report is one of a series of reports that is published under the Special Features section of the Technical Digest Service.

The material in this report, which was prepared by John F. Holman and Co., Inc., covers the machinery and techniques that are used in pumping water and generating electricity by windpower.

Mention of the name of any firm, product, or process herein is not to be considered a recommendation or an endorsement by the Agency for International Development or the U.S. Department of Commerce.

For further information and assistance, contact should be made with the local Productivity Center, Industrial Institute, Servicio, or the U.S. AID Mission.

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INTRODUCTION

The purpose of this publication is to provide basic information on windpower devices for pumping water and generating electricity. It is primarily for the benefit of isolated communities or single establishments which have little immediate prospect of connection to main power networks or which are located where combustion engine power is uneconomical. Windmills are economically feasible under the following conditions:

1. The use of wind-driven pumps is economical at any site where there is a reasonably good wind regime and where alternative methods of producing power are notably expensive.

Study of the wind regime at the proposed site is an important factor in assessing the economy of windpower. The study must be based on measured wind speeds at the site and full consideration should be given to the influence of topography on the average windspeed.

2. Wind-electric machines are economically justifiable under the same conditions. Small units for isolated premises have been satisfactory. Medium-sized plants for isolated communities are now commercially available. Capital costs, wind data for the site, and the cost of alternative means of power production are necessary economic data.

Although the windmill has a long history of supplying power to mankind, at present windmills are primarily useful to isolated communities or single establishments where there is little immediate prospect of connection to main power sources. For that reason, this book presents relatively simplified techniques for analyzing wind regimes under a variety of conditions and for judging those soil and topographical conditions which are significant in choosing windmill sites. Detailed plans are presented in Chapter 6 for the construction of two simple windmills, adaptable for pumping or electric power generating, which can be constructed on the site with a basic minimum of tools and parts. While by no means exhaustive, the intent of the book is to meet a need for a practical guide to the use of windpower in areas where more sophisticated sources of power are limited or unavailable.

I. A HISTORY OF WINDMILLS

Windmills and watermills, at first very simply built and later developed into more complicated and efficient machines, were installed wherever the wind was sufficiently strong, or flowing water was available. Obviously, the choice of sites for windmills was not so restricted as those for watermills which had to be built on the banks of streams. This comparative freedom in choosing the locations of windmills is an advantage over watermills and counterbalances, in some small degree, the disadvantage of their relatively large size for a given power capacity. Windmills, or wind-driven machines, fall into two categories: those with a vertical-axis rotor and those with a horizontal-axis rotor. The rotor is the essential part of the windmill—that part of the machine which is driven round by the wind, transmitting useful power from the shaft of the rotor to a corn grinding mill, a water pump, an electric generator or some other type of machine.

The earliest windmills known are those used by the Persians for grinding corn. They had a vertical axis carrying several large sails and were enclosed within a circular wall with openings to admit winds from different directions. A machine of this type must have some arrangement whereby the wind is allowed to press on the sails on one side of the vertical axis, while those on the other side, which move against the wind, must be screened from this pressure. Dutch windmills are an example of those using the horizontal axis. They were probably introduced in Europe in the 12th century. This type was developed until it became a very effective power unit and, although there may be exceptional circumstances which favor the construction of a machine with a vertical axis, future machines for all purposes are likely to have horizontal shafts.

Though vertical-axis windmills have the advantage of being able to accept wind from any direction, while those with a horizontal axis must be turned into the wind, they have the disadvantage of low rotational speed and low efficiency. The word "efficiency" is used here to express the fraction of the available power in the wind that is extracted by the windmill.

The windmills developed in European countries had horizontal shafts carrying four or more sails on a wooden framework, constituting the rotor. The sails were of canvas or some other strong cloth, which could be furled or spread according to the strength of the wind. Later they took the form of wooden slats hinged so that, in very strong winds, the slats could open to allow the wind to pass through the sail.

The sails had to be turned into the wind and this was done either by mounting the whole windmill on a turntable or by using a rotatable head at the top of a stationary tower. The latest form of the latter is that developed in Denmark following

the work of Professor P. La Cour at the State Windmill Station at Askov; a machine made by the Danish firm of Lykkegaard is illustrative of the modern tower windmill. Through bevel gears the rotor drives a shaft passing vertically down the lattice-steel tower at the foot of which is located the machine to be driven by the windmill. Another set of bevel gears converts the power from the shaft to driving power for a horizontal-axis machine which is usually an electric generator supplying power for farm purposes.

During World War II, in Copenhagen, a wind-driven machine for electricity production was developed that had propeller-type rotors with either two or three wooden blades driving direct current generators, through gearing, at the top of the tower. These machines varied in capacity from 50 to 70 kilowatts and had rotors of 18 to 24 meters diameter. Some of these windpower plants are still running successfully in connection with local electrical networks.

Several small wind-electric plants are now available with propeller-type rotors running at high speed and driving electric generators. The generator usually produces direct current and charges an electric battery which stores enough energy to provide a supply during calm weather. An example of an American machine is shown in Figure 1.

Modern Windmills

Two varieties of windmills are predominant today: the American or "turbine type" with a slow running multi-bladed wheel and the high-speed propeller type. The former is commonly used to pump water and the latter to generate electricity.

The American windmill has a number of galvanized sheet-steel sails, slightly curved to give a good aerodynamic shape. There are usually eight to perhaps 18 or 20 of these. They are carefully balanced and are carried on rings attached to tensioned wheel arms, the whole wheel being mounted on a shaft which runs in either ball bearings or babbit bearings, automatically oiled. The wheel diameter ranges from 6 feet to 18 or 20 feet.

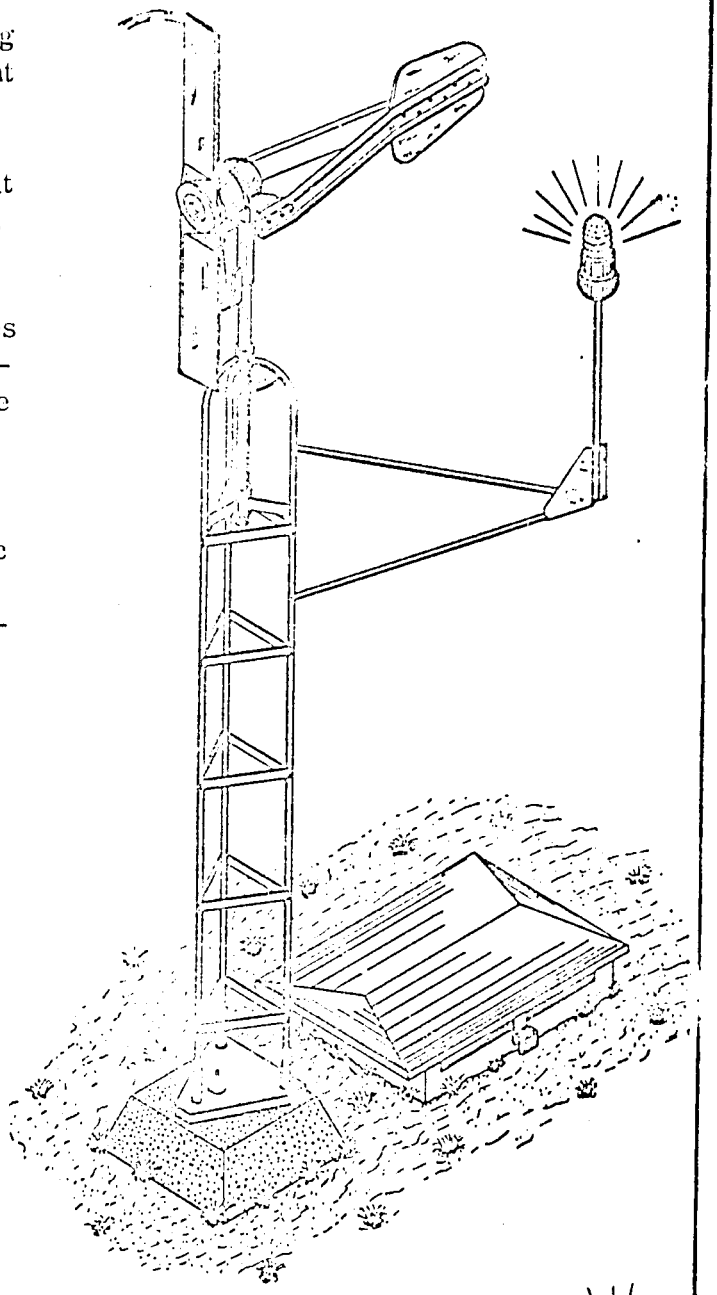
The American mill can be either direct stroke (by means of an eccentric cam) or back geared. The gear ratio varies from 2.33 : 1 to about 4 : 1. The windmill head is mounted on a turntable, usually running on ball bearings, so that the wheel can be turned into the wind easily by a shaped, galvanized sheet-steel tail vane. There is a windlass fitted at the base of the tower so that the wheel can be turned out of the wind manually if necessary; e.g., at times of exceptionally strong winds.

The wind shaft is offset slightly from the center of the tower so that, in strong winds, it turns towards the tail vane—which is fitted with a control spring—and thus presents a smaller surface to the wind. This "wind spilling" automatically controls the power output as the wind speed increases, but, because of the high inertia of multi-bladed rotors, the diameter for which this method is practicable is limited to about 24 feet. There is also a brake to bring the machine to rest and to hold it stationary.

This windpowered battery charging generator furnishes charging current in wind velocities up to 40 mph. At 7 mph windspeed, it will start to charge a 12v battery and at 40 mph it will charge a 12v battery at its max. charge rate of 18 amps.

The generator starts tilting the propeller out of the wind at velocities above 40 mph. This is done by pivoting the generator assembly below the axis of the generator and propeller. A hydraulic device between the generator assembly and the center post upright controls tilting. The hydraulic cylinder provides rapid tilting out of the wind and a slow return. This prevents slamming the generator back to the horizontal position when the wind suddenly stops. The assembly has been operated in high winds with gusts up to 75 knots.

The system consists of a permanent magnet generator and a solid state type rectifier. The generator provides 3-phase power to the silicon diodes mounted in the end bell. This changes the AC of the generator to DC for charging the battery. The silicon diodes block any reverse current that would flow back into the generator from the battery when the wind is not blowing. No reverse current relay is required.



Typical installation illustrating the use of a windpowered generator to provide operating current for an aircraft signal light in isolated areas.

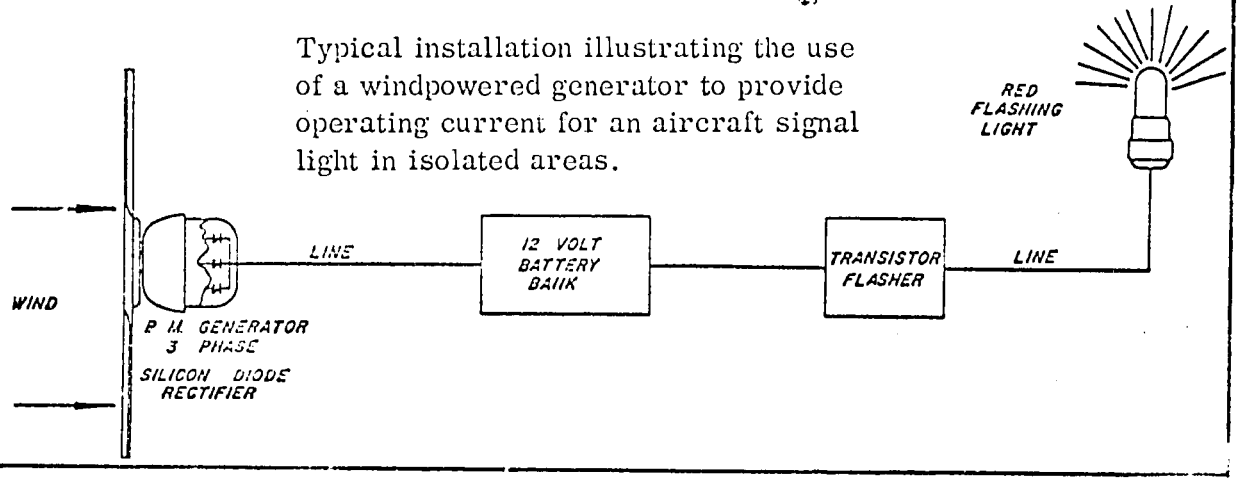


Figure 1. Windpowered Generator

The American windmill is considered a slow-running machine because of the low ratio between tip speed and windspeed (sometimes called the U/V ratio) which ranges between 1.1 and 2. The old-fashioned Dutch mill, with large sweeps, is of medium speed, with a U/V ratio of from 2 to 3. In total efficiency it ranks lower, extracting only 5 to 10 percent of the potential wind energy compared to 15 to 30 percent for the American mill.

The propeller type windmill has been developed only within the last 50 years. It may have two, three or four blades, modeled along the lines of an airplane propeller. The ratio of tip speed to windspeed ranges between 3 and 6 and the efficiency between 35 and 40 percent. It is designed mainly for generating electricity in isolated areas with strong, constant winds. If the user is to realize any advantage from this type of windmill, the aerofoil section must exactly follow a true streamline shape. Mills of this type are very difficult to construct in a home shop.

The propeller type windmill has several advantages over the multi-bladed type. It is lighter; the wear and tear is less; it is much quieter in operation, the wheel running with very little noise; and governing is usually much smoother. Little physical effort is required to put it out of operation when necessary. In very strong winds, the blades can be turned edgewise as their speed increases, thus decreasing the strain on the rotor. With a multi-bladed wheel, there is danger that a strong gust may strike a practically solid area and wreck the machine.

The major disadvantage of the propeller type wheel is that it has a lower starting torque than the multi-bladed type. For running a piston pump, where the wheel must start against a dead load, the turbine type wheel is preferable. It has been suggested that high speed windmills could be used to drive rotary pumps which demand only a small torque at starting, but very few machines of this type have been constructed. Most authorities agree that low speed windmills, driving piston pumps, should be used for general purpose, low power outputs. In more windy regions the greater initial cost of a high speed propeller type driving a rotary or centrifugal pump may well be worthwhile.

II. THE NATURE OF WINDPOWER

Movement and Direction of Wind

Natural winds are movements of air resulting from differences in atmospheric pressure which, in turn, are the result of differences in temperature causing corresponding variations in air density. The air flows from an area of high pressure to one of lower pressure and the windspeed depends upon the magnitude of this pressure difference. The actual velocity of the wind, in magnitude and direction, comes from a combination of the pressure-induced speed and that due to rotation of the earth's surface which carries air, adjacent to the surface, around with it. This surface speed varies from about 1,000 miles per hour at the Equator to zero at the poles and, therefore, its influence on the resultant wind velocity depends greatly on the latitude.

By far the most important characteristic of the wind is its variability in speed. At any specified point on the earth's surface, the wind, at a given instant of time, can have a speed ranging from zero to as much as 125 miles per hour (56 m/sec) or more. Even the windiest places have calm spells while the least windy are occasionally subjected to storms which bring high winds. One cannot, therefore, rely absolutely on power from the wind at a given moment however windy the chosen site may be and, on the other hand, one cannot safely reduce the mechanical strength of a windmill, destined for a relatively calm area, to any great degree. Nevertheless, the probability of there being power available at a particular time is much greater at the windy site, as is the probability that a machine erected there will have to withstand severe mechanical stresses fairly frequently.

Although both the speed and direction of the wind at any given place vary greatly, the direction, at least, is not entirely random. For average conditions, two belts of high pressure continuously circle the earth, one between 30 and 40° north and the other between 30 and 40° south. Between them in the equatorial zone there is a low pressure belt. The high pressure belts produce persistent winds from the north in the northern hemisphere and persistent winds from the south in the southern hemisphere. The effect of the earth's high surface velocity in the tropical zones is to convert these persistent winds into northeasterly winds, north of the Equator, and into southeasterly winds, south of the Equator. Associated with this system are persistent westerly winds, in the belts 40 to 60° latitude in both hemispheres.

The meteorological services all over the world make continuous measurements of atmospheric pressure and these data provide the basis for the construction of isobars for any particular time. These isobars are lines joining points having the same atmospheric pressure at sea level and are corrected for temperature and

latitude. From the isobars the gradient wind, i.e., the windspeed due to pressure differences, can be calculated, but because of frictional and local temperature effects this calculated speed is not, in general, actually attained below an altitude of about 1,500 feet.

Power Production by Wind

When considering power production by wind, we are not interested in the winds at high altitude, but in those of up to one or two hundred feet above ground level. These surface winds are greatly affected by the topography of the area in which the windmill is to be located and by local obstructions in the form of rocks, trees, buildings, etc. These factors contribute to the tremendous variability of wind.

In a natural wind the speed is never strictly constant; even on a scale of seconds it varies continuously, though the variations may not be large enough to be troublesome for a windpower plant. The concept of a steady windspeed is true only within certain limits. Much depends upon the instrument used to measure the wind; if it is slow in response its indications may appear quite steady, although a quick response instrument would have shown rapid variations in speed. The magnitude of these variations, as well as their frequency, would depend on the gustiness of the wind at the time of measurement. Under stable weather conditions and at a site free from any obstructions near enough to interfere with the windflow, the speed fluctuations are usually of low frequency and small in magnitude.

The rapid variations in windspeed referred to above are more likely to be important from the point of view of the mechanical design of a windmill than in their influence upon the power output. The mean windspeed—on which these rapid fluctuations are super-imposed—does not usually change quickly. Although it is certainly possible for this mean speed to rise or fall by 50 percent within a few minutes, the more general experience is that hourly mean windspeeds can be used with some confidence in assessing power potentialities.

In many tropical and sub-tropical areas, diurnal variations in hourly windspeed are clearly marked; during a stated season of the year it is often possible to predict the daily speed of the wind with some degree of certainty. Thus, for example, in a coastal area the windspeed may be almost zero throughout the night, beginning to rise as daylight comes and increasing to maximum value soon after midday with a subsequent fall to zero in the early evening. In the temperate zone, however, especially in those areas lying in the tracks of storms, diurnal variations are usually marked by storm disturbances and no predictions of daily windspeed are of much value. In certain special geographical conditions the diurnal variations in windspeed are very small. Thus, for example, on the island of St. Helena, which has no land mass sufficient in size to cause daily temperature variations, the yearly mean windspeed varies from 18 to 21 miles per hour, regardless of day or night.

In wind surveys and in the consequent estimation of energy obtainable from the wind at a given site, we are interested mainly in hourly average windspeeds, but,

for some purposes, the structure of the wind is of interest. By the term "structure" we mean the detailed behavior of the wind, including its rapid changes in speed and direction both horizontally and with height above ground.

Fluid flow, which includes airflow, may be laminar or turbulent. In laminar flow, the air may be considered as flowing along streamlines without any whirling motion and without any mixing of its layers whereas in turbulent flow, mixing of the air in the layers takes place due to a whirling motion or eddies superimposed on the main flow. In general, natural winds in the open are turbulent; although, when the wind flows over a hill with a good aerofoil shape, something approaching laminar flow may be assumed in calculations on its acceleration.

The eddies are more or less circular disturbances which travel with the wind and which, according to their direction relative to that of the main stream, create gusts and lulls. The axes of these eddies are oriented in all directions so that, in a gusty wind, rapid changes of both speed and direction of the wind at any given point may occur.

For many years, meteorologists have taken a considerable interest in the relation between windspeed and height above the ground. The underlying facts are that, while the wind at great heights (several thousand feet or more) takes up a speed dependent mainly on atmospheric pressure differences, wind near the ground is impeded by frictional drag caused by the ground surface. We have, therefore, fast moving upper air "sliding" over slower-moving air. The influence of one layer on the speed of another depends on the degree to which there is an intermixing of the air in layers.

Weather conditions vary so much, from place to place and from time to time, that it is impossible to state any law for the vertical wind gradient which can be accepted as precise under any specified conditions. Nevertheless, a statistical law for the average windspeed over level ground has been formulated as the result of the work of many investigators. This is that the average windspeed V_h, at height h, is proportional to the height raised to some power α which is of the order of 0.17 but which, unfortunately, itself varies according to the time of the day, the climatic conditions, the actual values of the windspeed and other factors. If, however, we accept this law we find that over level country, the ratio of the average windspeed at 150 feet (45 meters) to that at 50 feet (15 meters), is $\frac{150}{50}^{0.17} = 1.2$. The speed increases by 20 percent as we ascend from 50 feet to 150 feet; this is useful information if we are considering the question of the height of the tower for a windmill. Assuming that the tower is to be at least 50 feet high, is it worthwhile to build it higher to obtain the benefit of increased windspeed? To answer this question we need to know the annual wind regime at the site, the purpose of the windmill and, especially, the variation in the cost of the tower with added height; a knowledge of the vertical wind gradient is certainly a basic requirement for any such calculations.

It should be noted that at coastal sites the effect of altitude is reduced so that when a site is almost surrounded by the sea—as it will be on a promontory—the ratio of windspeeds at different heights must be multiplied by a correction factor which is fractional (e.g., 0.7).

The law given above does not apply to windspeeds over hilltops. The effect of certain shapes of hills causes an acceleration of the windspeed at low heights over the summit because of a compression of the lower stream of air by that above (Figures 2 and 3). This effect disappears at a height above ground which depends upon the actual relative dimensions of the hill. From such experience as exists on this question, it appears that it will usually be quite significant up to a height of one or two hundred feet above the summit. Increased windspeed at the levels near the ground reduces the vertical wind gradient; i.e., there is less advantage to be gained by building higher towers on a hilltop.

To indicate the order of this reduction, on a hilltop, the ratio V150/V50 will probably be about 1.1 instead of 1.2 as calculated for level ground.

It is important to consider the gustiness of wind and the effects upon the stresses set up in the blades of a windmill. There is evidence that the diameter of some gusts may be less than that of the circle swept by the blades of the windmill rotor. Thus, the blades may be subject to heavy stresses. Changes in speed of up to 15 feet per second, or even more, can occur in as short a time as .04 second. Wherever such gusts are encountered, the blades will have to be heavily reinforced. In the windy areas of Scotland, for example, gusts of 130 miles per hour occur once or twice a year in non-hurricane conditions.

Wind Data for Pumping Water and Generating Electricity

Basically the same kind of wind data is needed for both these purposes. A complete record of hourly average windspeeds will afford all the information, but the analysis following the collection will differ slightly. In water pumping, there must be provision for storage of the water which means, in effect, storage of energy because pumped water represents the expenditure of energy. In the generation of electricity, energy storage, except on a small scale for purposes of high priority, is much more expensive than water storage.

Wind-produced electricity can be used for many purposes at random times as and when it happens to become available. If there is no wind for some days, these purposes cannot be served; the work must wait until the wind returns.

When water pumping is the sole object of the windmill, provision must be made for a supply of water continuously, either directly from the wind-driven pump or from the reservoir which it has filled. The windmill output throughout the year must, therefore, be studied closely with special reference to demands on the reservoir on a day-to-day basis.

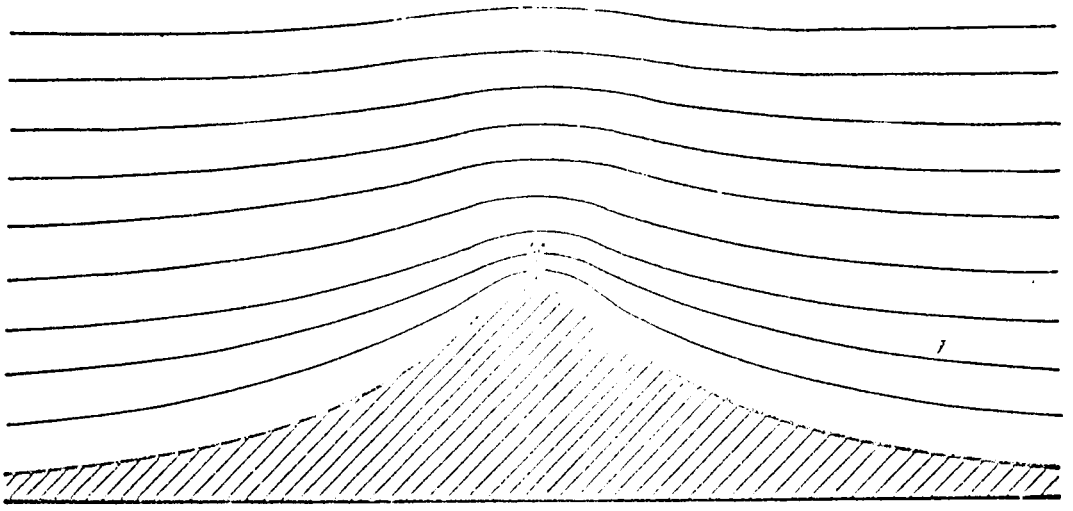


Figure 2. Air Flow Over Hill With Pointed Top

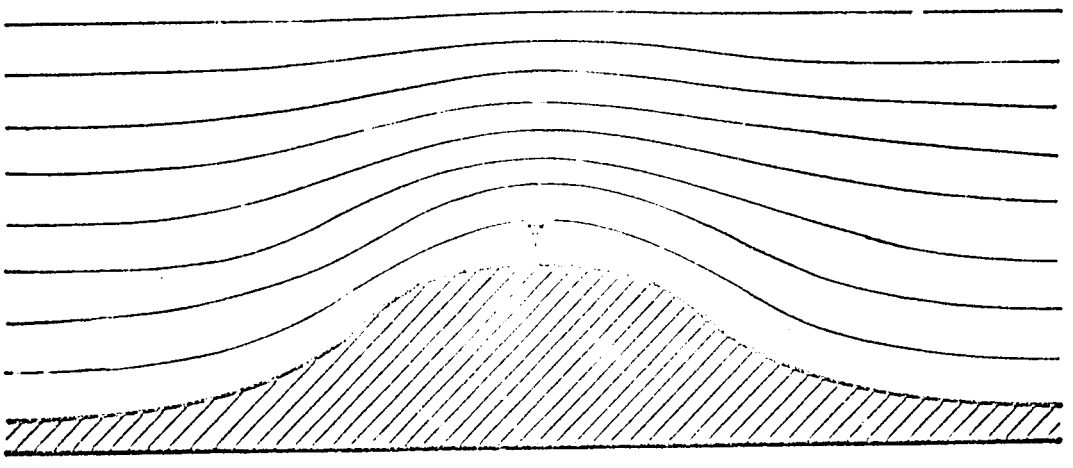


Figure 3. Air Flow Over Hill With Flattened Top

When windpower is to be used directly, without storage, it is important to know at what hours during the day there will be enough wind for purposes which could be fulfilled during those hours. For example, it would be a disadvantage if the wind blew mainly at night during the season of the year when power could be used for the threshing of grain. On the other hand, power at night would be useful for lighting and heating.

Wind is, of course, a free and inexhaustible source of energy but its economy and practical potentialities depend upon the cost of harnessing it. To gain an impression of the problem involved, we can consider the wind as a horizontal stream of air moving at a speed which is, in fact, continually varying in both magnitude and direction but which remains steady enough, over significant periods of time, for it to exert a usable pressure on any object placed in its path. This pressure is proportional to the square of the windspeed while the power in the windstream is proportional to the cube of this speed. The formula for this power P, is $P = k.A.V^3$ where A is the cross-sectional area of the windstream exposed to the blades and V is the windspeed. The factor k is a constant, the value of which depends upon the density of the air and on the units used for the measurement of P, A and V. If P is expressed in horsepower, A in square feet and V in miles per hour, k has the value 0.0000071. Other values for this constant, with different units for P, A and V, are given in Table 1.

Table 1. Values of coefficient k for different systems of units

Unit of power P	Unit of area A	Unit of velocity V	Value of k
Kilowatts	Square feet	Miles per hour	0.0000058
Kilowatts	Square feet	Knots	0.0000081
Horsepower	Square feet	Miles per hour	0.0000071
Watts	Square feet	Feet per second	0.00168
Kilowatts	Square meters	Meters per second	0.00064
Kilowatts	Square meters	Kilometers per hour	0.0000137

III. WINDMILL SITES

Probably the most important factor involved in generating power from the wind is the selection of a good site. It should be borne in mind that because windpower increases as the cube of the windspeed, an increase in average windspeed of even one mile an hour, when the average is, for example, 10 miles an hour, may mean an increase of 20 percent in the average power to be obtained from a windmill so that it is vitally important that the most favorable sites should be found.

Choosing the windiest site in a small area is a simple matter—the higher the better is a good rule of thumb. However, in rough terrain, hills with steep sides and sharply pointed tops should be carefully examined since they are often sources of "dead spots" and eddies.

If windpower possibilities for an area of considerable size—perhaps several hundred square miles—are to be studied, the first step is to obtain information on windspeeds and prevailing wind directions from such meteorological stations as already exist. Long term records will give reliable guidance as to which are the windiest districts and on the choice of site from the point of view of exposure to prevailing winds.

The next step in the survey is a study of the topography of these windiest districts. As stated previously, windspeed increases with altitude so that high ground—if such exists in the area—should be sought. Moreover, some hills are better than others. The type to look for should have fairly steep but smooth slopes and a broad, level crown. When the wind blows over this kind of hill, its speed over the summit is accelerated due to compression of the streamlines by the upper layers of air; i.e., the Venturi effect.

Thus the ideal hill would be of approximately conical shape, though with a smoothly rounded top, so that winds from all directions would be similarly accelerated. It would be an isolated hill, lying in a coastal plain with no other high ground within perhaps two or three miles. Windspeeds are higher near a coast than inland because of ground friction. It has been suggested that a ridge lying athwart the prevailing wind will give the best results, but, although this may be true if the wind direction remains constant for a large part of the year, it is found that, for variable wind directions, the gain when the wind blows directly across the ridge is offset by the loss when it blows in other directions.

After selecting the sites at which the measurements are to be made, the next step is to set up the measuring installation. It might be supposed that elaborate

equipment giving a continuous record of windspeed and direction should be installed, but this is not necessary. Only hourly average windspeeds are needed, these can be measured with a cup-counter anemometer. This instrument has cups mounted on the ends of spokes radiating out from a vertical axis. The cups are designed to rotate exactly at windspeed. The anemometer has a cyclometer type of indicator, and the difference between any two readings gives the miles (or kilometers) of wind which have passed during the time interval between them. The average windspeed over this time is then calculated by dividing the wind movement by the time.

If this time interval is one hour, the run-of-wind in the period between successive readings is numerically the same as the hourly average windspeed. This fact leads naturally to a variant of the simple cup-counter anemometer; namely, the electric cup-contact anemometer. In this instrument through gearing, the rotating system of cups drives a device which in an electric circuit makes a contact once for some selected value of wind run, e.g. for a run of two miles of wind. If the circuit includes a coil-operated pen, or marker, which makes a mark on a recorder chart at each contact, it is possible to take a record of the run of wind per hour, the chart running at a constant speed and receiving also a mark at the end of each hour.

In another type of recorder a narrow paper tape is moved forward by a short distance for each contact produced by the anemometer. A time switch is used to operate a pen or marker so that a dot is made on the tape at hourly intervals. The distance between successive dots represents the run-of-wind. This type of instrument is designed particularly for economy and for simplicity of operation.

The best procedure is, therefore, to install on the summits of the hills or, if there are no hills, at well-exposed sites, anemometers of the cup-contact type with some form of recorder giving information from which the hourly average windspeed can be obtained easily. The process of changing the recorder chart at intervals about a week should be simple so that it can be done by unskilled labor.

The anemometer itself should preferably be mounted on a pole. A height of 10 meters (32 feet, 8 inches) is suggested because it is the standard used by the meteorological services and it is sometimes desirable to use the same height so that wind records can be compared without the use of corrections. However the terrain should be studied closely because, in the case of very sharp rises and dips, 10 meters is often inadequate to tap the strongest wind currents.

A cup-counter anemometer when read at lengthy intervals, e.g. weekly, does not give hourly windspeeds; it only integrates run-of-wind from which an annual average windspeed can be obtained eventually. Nevertheless, if the weekly readings are plotted on a graph, it is possible to distinguish very easily the relative windiness of a number of sites. Indeed, sites can be placed in order of windiness after an observation period of a few months.

The World Meteorological Organization has networks of observation stations where wind measurements are made with those of rainfall, solar radiation, and

other climatic factors. It has formulated internationally acceptable methods of measuring the wind.

Two difficulties arise from accepting, for windpower purposes, windspeed values from meteorological observation stations. The sites of the stations are seldom chosen with regard to any especially high degree of windiness because the climatic data obtained are to be taken as averages for the area surrounding the station rather than as extreme values. The second difficulty arises from the different methods of measurement used. The most complete information on windspeeds and directions is gained from recording anemometers, an example of which is the Dines anemometer. Anemometers give continuous recording of speeds and directions, and analysis of their charts provide data on hourly windspeeds and on the gustiness of the wind as well as on the direction from which the wind is coming. Instruments of this kind are expensive to purchase and to install, and they need skilled maintenance. Therefore, they are not used universally. This is especially so at the minor observation stations of which there are large numbers all over the world, including those at airports where information is needed on the windspeed at particular moments rather than on a long term.

Frequently anemometers which give instantaneous windspeeds are used: they are indicating instruments, not recorders, and their readings are noted at certain specified times in the day. The windspeed values thus measured are certainly useful as a general guide but do not form an accurate basis for a statement of hourly speeds.

IV. PUMPING WATER

General Considerations

The direct pumping of water by a windmill is subject to a number of limitations. Unlike the wind-electric plant, the wind pump gives the user no opportunity to vary the loading conditions significantly; he must accept it as it is and make the best use of it. Further, when using the commonest form of installation—the piston pump—there is little choice of site with a wind pump because it must be installed vertically above the water to be pumped even though the location may not be especially windy. Other limitations are the availability of water at a depth shallow enough to be reached by the pump and the reservoir capacity.

Thus the devising of a major plan for water pumping is not a simple engineering operation but demands knowledge of the geological and geomorphological conditions of the area concerned. Before large scale plans are undertaken, as distinct from an individual pump near some known wells, experts skilled in geology and ground water hydrology should be consulted.

The water table in any given area is a surface which can be reached more easily in the valleys than on the hilltops in the area. The actual depth of this table, the contours of which do not always correspond with those on the ground surface above it, depends on many factors, topographical and geographical, and on the distance of the area from any main source of water such as a lake or a river. A well, driven into the underground layer of water, may be found to have limited capacity because of the rate at which new water flows in to take the place of that which is withdrawn by pump. This rate depends upon the nature of the subsoil adjacent to the well. Sometimes horizontal tunnels are driven underground to lead water into a well and so increase the rate of inflow. It is important to consider the amount of flow since it would be uneconomical to use a pump of greater capacity than the potential inflow.

Another problem is the salinity of underground water. Especially in coastal areas, underground streams or layers of brackish water often lie at no great distance from those of sweet water. It is necessary to make sure that the water to be pumped has a sufficiently low salt content for it to be used for animal consumption or irrigation.

Men and animals can usually tolerate more salt in their drinking water than is permissible for the irrigation of crops. It is not easy to give definite figures for drinking water because people and animals in dry areas, who become accustomed

to drinking saline water, sometimes use water with a salt content of 2,000 or more parts per million, although 1,000 parts might be considered the desirable limit.

For irrigation, the degree of salinity that can be tolerated depends, to a considerable extent, upon the rainfall in the area. Salt accumulates in the top few inches of the soil, especially if drainage is poor. It can be leached out only if there is sufficient rainfall (or other alternative supplies of sweet water) with adequate drainage. In general, the question of soil salinity is a complex one and specialists should be consulted if it becomes a problem, especially since different crops vary widely in their salt tolerance. (Table 2)

Table 2. Uses of waters of different salt contents

Proportion of chlorides, expressed as NaCl, in grams per liter in the irrigation water	Suitability for irrigation
less than 0.5	suitable for all irrigation
0.5 to 1.0	suitable for most irrigation
1.0 to 1.5	slightly high chloride content, usable for most irrigation but precautions needed for use on sowings of delicate varieties
1.5 to 2.0	definite chloride bias but usable for irrigation except for sowings of delicate varieties
2.0 to 2.5	high chloride content but usable with suitable precautions
2.5 to 3.0	high chloride content but still usable for certain crops
3 to 4	very high chloride content, practically unusable for irrigation
above 4	salt water entirely unsuitable for irrigation

In areas with mixed underground waters, sweet water may over-lie brackish water in the well so that, after a certain period of pumping, the output becomes too brackish for use and the pump must be stopped until the well can refill with usable water. In this situation it is often advisable to install several wind pumps, each of relatively small capacity and about a hundred yards apart, rather than to attempt to produce the same quantity of water from one large pump.

The Operation of Pumps

At this point, an explanation of the operation of pumps may be useful (Figure 4). When a pump is set in working order in a well, the atmospheric pressure on the water inside the pipe is exactly equal to the pressure on the water outside of the pipe, so that the water remains at rest, but as soon as the plunger is moved up and down in pumping, the air in the pipe below the cylinder is pumped up, thus leaving a partial vacuum and then the pressure of the air inside of the pipe (below the cylinder) becomes less than the pressure on the outside, so that the atmosphere pressing on the water outside of the pipe forces the water up into the suction pipe.

When air is removed from a suction pipe, water is forced up into the pipe to replace the air that has been removed; thus as air is pumped from the pipe, the water rises until it reaches the cylinder; it then rises above the plunger and is lifted to the surface, independent of any atmospheric pressure. A column of water, at sea level, 33.95 feet high, will exert the same pressure per square inch as the atmosphere, therefore the atmosphere will sustain a column 33.95 feet high in a perfect vacuum; however, 22 or 25 feet is about the practical limit.

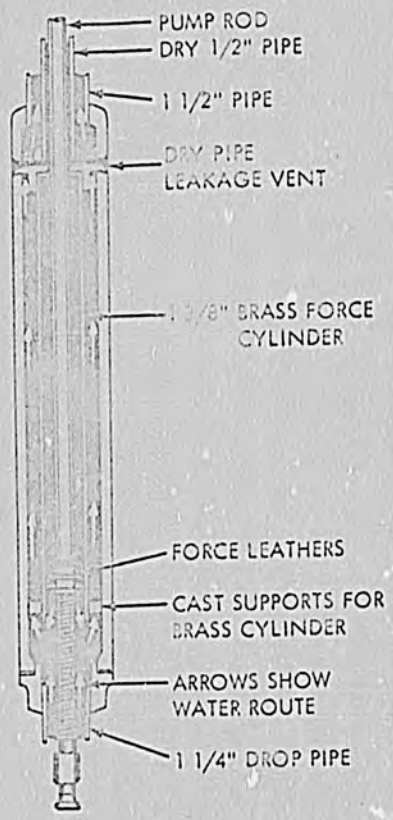


Figure 4. Force Pump, Detail

Types of Wells

The kind of well to be sunk in a given locality depends on soil conditions, topography and climate. A discussion of the various types of wells in general use follows.

The capacities in gallons given in Table 3 are for a single acting pump, making one complete stroke (or revolution).

To obtain the amount of water discharged per minute, multiply the capacity per stroke by the number of strokes per minute.

The weight of water lifted is not determined by the size of the pipe in the well, but by the diameter of the cylinder. The size of the pipe, provided it is not too small, has little effect on the power required. For every foot the water is elevated, the exact lift is .434 pounds for every square inch of the area of the plunger of the cylinder. To allow for ordinary friction, one-half pound is usually estimated for every foot the water is elevated. By referring to Table 3 the precise weight of water the mill is lifting at every stroke can be readily determined, provided the distance from the surface of the water in the well to the top of the tank and the size of the cylinder are known.

Table 3. Capacity of pump cylinders

Diam. of Cylinder, In.	Length of Stroke in Inches, with Capacity Per Stroke in Gallons					Area of Circle of Cylinder in Square Inches
	4	6	8	12	16	
1	.0136	.0204	.0272	.0408	.0544	.7854
1¼	.0416	.0625	.0833	.1249	.1666	2.4043
2	.0544	.0816	.1088	.1632	.2176	3.1416
2¼	.0688	.1033	.1377	.2071	.2754	3.9760
2½	.0850	.1275	.1700	.2550	.3400	4.9087
2¾	.1028	.1543	.2057	.3085	.4114	5.9395
3	.1224	.1836	.2448	.3672	.4896	7.0686
3¼	.1438	.2156	.2875	.4313	.5748	8.2957
3½	.1666	.2499	.3332	.4998	.6664	9.6211
3¾	.1914	.2871	.3828	.5743	.7658	11.0440
4	.2176	.3264	.4352	.6528	.8704	12.5660
4½	.2754	.4131	.5508	.8262	1.1016	15.9040
5	.3400	.5100	.6800	1.0200	1.3600	19.6350
5¼	.4114	.6171	.8228	1.2343	1.6456	23.7580
6	.4896	.7344	.9792	1.4688	1.9584	28.2740
7	.6664	.9996	1.3328	1.9992	2.6656	38.4840
8	.8704	1.3056	1.7408	2.6112	3.4816	50.2650
10	1.3600	2.0400	2.7200	4.0800	5.4400	78.5400
12	1.9584	2.9376	3.9168	5.8752	7.8330	113.0980
18	4.4064	6.6096	8.8128	13.2192	17.6100	254.4700

The above rule will not hold good, however, if any part of the pipe between the cylinder and the tank is less than one-half the diameter of the cylinder. It is much easier to raise water at the rate of 25 feet per minute through 3-inch pipes than to raise it at the rate of 225 feet per minute through 1-inch pipes. These are the comparative rates of speed with a 3-inch cylinder. In the first instance the pump simply lifts the weight of the water above, while in the other much additional power is wasted in forcing the water against the cylinder cap until an outlet can be made through the small pipe.

Drilled Wells. Wells are drilled where the source of water is beneath strata of hard rock. Few people, however, have either the equipment or the experience to enable them to do a satisfactory well-drilling job. It is generally recommended that construction be undertaken by professional drillers who are equipped and experienced.

Fine sand may wash into the well or it may choke the screen and limit the yield. If sand washes into the well, it must be bailed or floated out. Solid carbon dioxide dropped into the well will cause violent bubbling and is sometimes effective in working loose any sand that is choking the screen. It may be necessary to remove the screen if it is possible to do so. The infiltration of sand can be materially reduced by forming a layer of gravel around the screen.

The yield of drilled wells is sometimes increased by shattering the rock or other solidified material with dynamite. This is called shooting or torpedoing and may create opening to adjacent passageways carrying water. Because of the uncertain results and liability of damage to the well or loss of existing supply, it should be employed only as a last resort.

Wells for an average farm are drilled two to eight inches in diameter, but the trend is toward wells six inches or more in diameter. For a given water-bearing stratum the yield is roughly proportional to the diameter. Drilled wells are pipe-cased through silt, sand, or any other loose material likely to cave in. If it is found

necessary to case through drift (loose material) located below hard rock, casing of a smaller size may be used. The top of the well, therefore, should be large, so that if it is found necessary to reduce this size, the bottom will not be too small. Generally it is safest to case the well all the way to the water-bearing stratum.

Jetted Wells. Where no rocks or boulders are present, wells may be constructed by the jetting method. The three principal parts of the outfit are a well casing of the size desired, a small pipe fitted with a nozzle at one end and attached to a hose at the other, and a force pump. The work may frequently be done by hand methods.

A well may be jetted down to a depth of 20 feet in a few minutes by an experienced man with two or three helpers. Water forced down through the small pipe cuts the earth loose. The earth is floated to the surface around the casing until the water table is penetrated, after which it is floated up through the casing. Water may be delivered to the site in a truck and forced through the jet with a power pump. For sandy soils, 40 pounds of pressure is adequate. For tight clay soils and hardpan, pressures up to 200 pounds or more may be required.

The quantity of water needed is usually small. A well four inches in diameter and 18 to 20 feet deep can be jetted in sandy soil with 75 to 100 gallons of water. Clays and hardpan will need more. The nozzle should not project more than two inches beyond the lower end of the casing.

The end of the casing may be notched to give it a sawlike effect for penetrating gravel and ordinarily a drive weight is required to force it down. The jet pipe, or inner tube, should be turned slowly, while drilling, to insure a straight hole. A wrench that wraps around the casing should be used to prevent crushing.

The use of the casing as the suction-lift pipe of the pump is not recommended. The casing should be large enough to permit the use of a cylinder attached to the drop pipe of the pump. Where possible, the cylinder should always be submerged below the casing level.

Driven Wells. Driven wells are common in areas where water-bearing material can be reached without encountering hard rock and where water is abundant. Soil through which a pipe can be driven, however, cannot always be expected to protect ground water from surface contamination.

A driven well consists of iron or steel pipe forced into a water-bearing bed. In the driven well's simplest form, two- to three-inch extra-strength wrought pipe is cut into convenient lengths, and fitted with a well point. Well points consist of a forged steel point, a screen, and a short section of pipe threaded to fit a standard pipe coupling. The top of the drive pipe must have a heavy cap or a steel drivehead to prevent battering the pipe when it is driven. All pipe joints should be coated with red lead or graphite and oil, and screwed together tightly with pipe wrenches; otherwise the threads may be stripped or the couplings split.

Bored Wells. Water is sometimes obtained quickly and inexpensively by boring a well with an earth auger. The auger may be turned and lifted by hand or by mechanical means such as the post hole attachments on a farm tractor. This method of boring is limited to small diameters, and even with mechanical power it is limited to shallow wells in relatively soft materials free from boulders. Wells up to 24 inches in diameter may be bored with mechanical outfits. Bored wells are cased with standard well casing.

Dug Wells. When shallow wells are dug, one or two men at the bottom loosen the earth and shovel it into buckets, while others at the top, lift buckets with a windlass.

Curbs for dug wells may be of stone, brick, concrete block, poured concrete, vitrified tile, or corrugated pipe. Wood soon decays and should not be used. At least the upper 10 feet of masonry curbs should be laid in cement mortar to make them watertight. Considering cleanliness, tightness, durability, and cost, perhaps the best curbings are vitrified sewer pipes or hard-burned drain tiles. Sometimes the pipes are placed with the bell joint downward, but such an arrangement makes it impracticable to cement the joints. The space between the curb and the sides of the excavation should be filled with clean sand and gravel up to the top of the water-bearing stratum, the coarser material at the bottom. Surface water will be prevented from moving along the concrete casing if puddled clay or concrete is used to backfill. The curb should be brought at least one foot above the ground and be surmounted by a concrete platform in which is cast a manhole and pump stand. The manhole should have a tight-fitting iron or concrete cover.

Although labor for digging represents little actual outlay of money, the cost of a dug well properly constructed is often greater than that of a drilled well.

If a pump is to be set on the platform, a short piece of well casing may be embedded in the concrete to provide an opening for the drop pipe and cylinder. A firm, watertight joint between the pump base and the concrete is made by using expansion bolts or anchor bolts and a gasket. Expansion bolts are screwed through the pump base into holes in the concrete. Anchor bolts to fit the holes in the base are embedded in the concrete when it is poured. Ordinary bolts with the thread-end up and a large flat washer on the head in the concrete will answer the purpose.

Dug wells properly located, constructed, and protected are more likely to be satisfactory than any other type except drilled wells. The advantages are that they have longer life and larger volume, thus permitting more rapid pumping, lower lifts and easier inspection and cleaning, with less trouble from quicksand and air leaks.

Types of Pumps

The American multibladed windmill driving a piston pump is familiar all over the world. It is usually sold as a complete unit. This type of windmill works well only with a piston pump.

When water is to be drawn from a spring or stream, where a windmill cannot conveniently be placed directly over the source of supply, a siphon pump is used (Figure 5). The base of the pump contains the cylinder with its valves and plunger. The base is always full of water, which keeps the pump constantly primed. If a foot valve is used on the end of the suction pipe, the pump will always be ready to deliver water with the first stroke of the piston.

These pumps are made with cylinders from two to six inches in diameter. The smaller sizes are furnished with a windmill connection, or with a windmill top and handle. The smaller sizes have a 12-inch stroke and are suitable for 8-foot, 10-foot, or 12-foot windmills. The larger sizes have a 16-inch stroke.

The siphon operates as an airtight, inverted U-tube. The flow through the discharge leg of the siphon tends to form a vacuum in the other leg, which immediately fills with water if the distance from the water surface to the top of the siphon is not too great. The theoretical height to which water can be raised with a siphon is identical with that of a leak-tight pump, but because of pipe friction, air leaks, and vapor pressure, the siphon can seldom be relied on to lift water more than 20 to 25 feet.

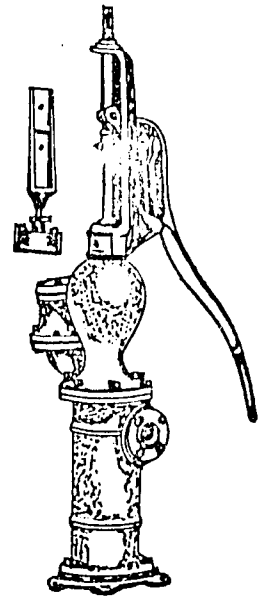


Figure 5. Siphon Pump

The elimination of air leaks is necessary. Pipe joints must be effectively sealed, because even a slight leak may be enough to break the vacuum and cause the siphon to fail. The siphon can be primed by attaching an ordinary shallow-well pump at the lower end, priming and operating as if pumping from a well. Once the flow is started, it will continue indefinitely without pumping if the water level at the inlet remains unchanged. Water should not be drawn off too rapidly—the pipe must always be completely full. Pipe friction must be considered in a siphon just as in a pump. The intake must be far enough below the water surface to prevent air from entering.

Back Geared or Direct Stroke Windmills

Purchasers of a turbine-type windmill must usually choose between a back geared or direct stroke type of mill. An extensive test at Cheyenne, Wyoming, revealed that both types of power transmission were about equal in amount of work done when the back geared mill was set at a ratio of 3.3 to 1. The direct stroke mill required a heavier wind to start, rapidly increased to its maximum, and then rapidly descended from the maximum more slowly and continued over a greater time. The direct stroke type may be a little better when the wind velocity is high for a considerable length of time, while the geared type is better suited to heavy

pumping loads and lower wind velocities. Another advantage of the direct stroke type is that it has less machinery and suffers less wear than the geared mill.

Economical Size of Windmill

Unlike all other types of prime movers, the weight and cost of windmills increases with size faster than does the power they yield. The power varies as the square of the diameter of the mill wheel, while the weight should vary as the cube of the diameter, in order to give equal rigidity and security to all sizes. Thus, a 20-foot mill weighs seven times as much as a 10-foot mill, yet it has less than four times as much power. Tables 4 and 5 show methods of calculating water yields under given circumstances.

Table 4. Pumping rates and h.p. for different diameters of wind pump, with 100 feet head and assuming 20% efficiency throughout

Wind-speed m.p.h.	6 feet		8 feet		10 feet		12 feet		14 feet	
	h.p.	gals/hr	h.p.	gals/hr	h.p.	gals/hr	h.p.	gals/hr	h.p.	gals/hr
5	.0047	10	.0083	17	.0125	25	.019	38	.025	50
7	.0128	25	.0228	42	.036	72	.051	102	.069	138
10	.0372	75	.066	132	.10	200	.15	300	.20	400
12	.064	128	.115	230	.18	360	.26	520	.35	700
14	.102	204	.183	366	.29	580	.41	820	.56	1,120
16	.153	306	.273	546	.43	860	.61	1,220	.83	1,660
18	.218	436	.389	778	.61	1,220	.87	1,740	1.20	2,400
20	.297	594	.53	1,060	.83	1,660	1.19	2,380	1.60	3,200
22	.398	796	.71	1,420	1.11	2,220	1.60	3,200	2.2	4,400

Clarification: Imperial gallons (equals 1.2 U.S. gallons).

Windmill Towers

The towers for the slow-running type of windmill most commonly used are made in heights which vary from 25 feet to about 60 feet. The tower should be high enough for the wind-wheel axis to be well above any trees, or other obstructions, lying within a distance of 200 to 300 yards. There should be a clearance of some 10 feet between the height of these obstructions and the lowest point of the periphery of the wind wheel. On flat ground there is some advantage in increased windspeed to be gained by building a high tower, but this is not usually worthwhile at a hilltop site because there the increase of windspeed with height is not so marked.

Towers are usually built of galvanized rolled angle steel. They may have three corner posts; though four, which give a stronger tower, are more commonly used. Girts connect the corner posts horizontally at about 5-foot intervals and tensioned

steel rods are used as cross-braces to give more strength. Anchor posts and earth plates are fitted at the bases of the corner posts and castings, and foundation bolts are provided so that the tower can be bolted to the concrete blocks in the ground.

Table 5. Annual output of water for a given wind

Windspeed		Annual duration	Output rate	Total output
m.p.h.	m/sec.	hours	m^3/hr.	m^3
7	3.15	600	0.3	180
8	3.6	500	1.4	700
9	4.05	500	2.3	1,150
10	4.5	400	3	1,200
11	4.95	500	3.7	1,850
12	5.40	450	4.2	1,890
13	5.85	450	4.7	2,115
14	6.30	300	5.2	1,560
15	6.75	300	5.7	1,710
15 plus		1,700	6	10,200
		Total 5,700		Annual Total 22,555 m^3

The duration of windspeeds above 15 m.p.h. (7.2 m/sec.), for which the output is assumed to be at the full rate of 6 m^3/hr., is 1,700 hours. It will be seen that the total annual output, in this case, is thus calculated as 22,555 m^3.

Installation and Maintenance

The most obvious recommendation is to follow the manufacturer's instructions carefully when installing a windmill: different designs call for different methods of erection. Probably the most important general points are: (a) That the foundations for the tower must be very well made to insure adequate strength of the tower which, throughout the life of the machine, will have to withstand very heavy pressure in gales; (b) that the tower itself must be built up systematically with proper attention given to the tightening of bolts and the tensioning of braces; and (c) that the wind wheel must be assembled strictly according to the manufacturer's instructions, insuring that all the sail pieces are attached in such a way that there is no distortion and that the wheel is well balanced.

The operation of the machine is automatic and calls for very little attention except for starting up and shutting down according to the demands on the pump. Maintenance consists of regularly oiling the moving parts and periodically inspecting the whole installation to make sure that no parts have been broken or loosened in storms. Several windmill and plumbing arrangements are shown at the end of this book.

V. GENERATING ELECTRICITY

The only major difference between water-pumping and electricity-generating windmills is that wind-electric machines run at a high speed to minimize the cost of gearing for an electrical generator. The rotors are of the propeller type with usually two or three blades so that the starting torque is low and a relatively high wind speed is needed before any power can be generated. Thus the cut-in wind speed for a wind electric plant may be as high as 10 or even 20 miles per hour (at a very windy site) instead of 6 or 7 miles per hour which is sufficient to start a water-pumping windmill.

On the other hand, the power generated can easily be transmitted, without excessive loss, over distances up to perhaps several hundred yards. This means that the windmill may be located at the windiest site in the immediate area, whereas the water-pumping plant must be located very close to the well, where the wind speed may not be so high. The practicable distance for such transmission depends on the generating voltage and the capacity of the wind-electric machine: for low voltages and small capacities there is a limitation to only a few yards distance from the premises to be supplied.

Types Of Wind-Driven Generators

There are two types of wind-electric plants suitable for areas without main electricity distribution networks. The first is the small unit of up to about one to one and a half kilowatt in capacity, with a direct current generator and a battery for storage of the full output. The second is a machine of larger capacity—up to about 50 kilowatts—with either a direct current or alternating current generator with or without a battery. In this second case the battery is generally of limited capacity and is intended for the storage of only a fraction of the total output, to supply essential loads. Most of the energy generated is used as random power, as and when it is generated. See Figure 1.

In the past, small wind-electric machines have been quite successful. Unfortunately, several manufacturers have ceased production because of the diminishing demand as the main power networks spread to the remoter areas. There can be little doubt that the need for such machines still exists, especially in less developed areas, and it is to be hoped that production will resume.

The small unit generally uses a two or three bladed propeller, with minimum diameter of six feet and maximum of ten feet, rotating at high speed and driving a direct current generator. In the smallest machines the drive is direct, but a gearbox is used as the size increases. A tail vane holds the wind rotor into the wind. A speed

controlling device is used. This may be operated by the tail vane turning the rotor out of wind at higher wind speeds—the axis of the rotor being slightly offset from the main supporting axis on the tower—or it may take the form of an airbrake governor.

A furling device enables the machine to be shut down from the foot of the tower. The battery, along with its associated control panel, must include a device to prevent the current reversing and driving the windmill generator from the battery.

The support for the machine (a pole or tower) should be high enough to keep it well clear of the adjacent buildings, otherwise it will be screened from the wind. A usual height is 40 feet (12 or 13 meters). There should be a ladder or some other means of ascending the tower to attend to the machine if this becomes necessary, and it is important to assure that the support is held rigid—either by guys or by using a heavy pole well set into the ground—to avoid vibrations that have a harmful effect on the machine.

The generator voltage of the small wind-electric plant is usually low; 6, 12, 24, or 32 volts being common. This low voltage is used because of their small size and to reduce the number of two volt accumulators needed in the storage battery. A low voltage calls for only a short run of cable from the generator to the battery and load circuit in order to avoid excessive voltage drop caused by the resistance of the cable. Thus, for example, if the size of the cable appropriate to the current to be carried is used, there will be a pressure drop of about one-tenth of a volt per yard run of cable. If the length of this cable is 50 yards (as it may be because the length needed to reach from the generator to ground level alone may be 12 yards) the total voltage drop will be 5 volts. If the voltage of the generator is 24 volts, nearly 20 percent of the pressure, and, therefore, 20 percent of the power, will be wasted in the cable. This voltage drop is approximately the same whatever the generating voltage so that a higher value of this voltage is an advantage.

The storage battery is an essential part of a small wind-electric plant. At times of high wind the battery is charged and it stores electrical energy for use when the wind speed is too low for power generation. A plant of this kind can thus be considered as being a battery-charger and the name wind-charger is often used.

Two types of battery can be used—alkaline or nickel-iron type, or the lead-acid type. The latter is more common and has the advantage of a high voltage, 2 to 2.5 volts per cell, against only 1.5 to 1.75 for the alkaline accumulator. Although it may be rather more expensive, the alkaline battery is very robust and less liable to damage by irregular operating conditions than the lead-acid battery. It is not, however, so successful with low charging rates.

Battery sizes are specified in terms of their ampere-hour capacity which is a measure of the product of the current in amperes and the time of discharge in hours that can be obtained before the voltage falls to the lowest permissible value of 1.8 v per cell. This capacity may vary from 130 to 450 ampere hours and, of course,

the greater the capacity, the longer the period of calm weather which can be prepared for.

As an example, for a 200 watt unit the maximum generating voltage may be 15 volts, and six lead-acid cells would be used, these having a voltage of 2.5 volts when fully charged. The ampere-hour capacity recommended would be 230 ampere hours. Charging of the battery would begin at a wind speed of 7 miles per hour and the set governed so that maximum output would be reached at 23 miles per hour.

The annual output of small wind-electric machines is not generally very high because of the limitations placed on site selection because of the need to be near the premises to be supplied. Probably 1,000 to 1,500 kilowatt hours per kilowatt is a fair range of annual output to be expected. Wincharger Corporation, a manufacturer of these machines, states that usable energy outputs per month from a 200 watt plant, average 20 to 30 kilowatts for sites with annual average wind speeds from 10 to 14 miles per hour. These figures correspond to a range of 1,200 to 1,800 kilowatt hours per year per kilowatt.

The cost of small wind-electric plants, complete with battery, control gear, and stub tower but without the supporting pole, is from $600 to $1,000 per kilowatt of capacity. Compared with the cost of energy from an electrical network in an urban area, this works out to a relatively high charge per kilowatt hour, but it is not excessive for such purposes as electric lighting, the operation of radio sets, and small domestic uses in remote areas.

It is necessary to give occasional attention to lubrication and to insure that no parts of the machine have become loose. The battery needs more frequent care. It should not be overcharged nor over-discharged and the cells should be topped with pure water when the level of the acid falls below the tops of the plates. The voltages of the cells and the specific gravity of the acid should be measured occasionally to check that all are in order.

Larger Wind-Electric Plants

Plants in this category range from 8 to 100 kilowatts in capacity. Several have been produced, although none are yet in common use. They differ from the small windmills described previously by having an alternating-current generator rather than a direct-current one and by generating 200/240 volts, single phase, or 380/440 volts, three phase.

Because of the high cost of batteries for the storage of an amount of energy corresponding to a power output of ten or more kilowatts, no attempt is made to store enough energy to give the full output during calm weather. A low capacity battery, charged through a rectifier, can be used so that essential, small loads can be supplied, but the main loads, requiring several kilowatts of power, are supplied only when there is sufficient wind.

Another feature is the use of a fantail—a multi-bladed wind wheel mounted at right angles to the main rotor—instead of a tail vane for orienting the windmill so that it is brought into the wind. Sometimes two fantails, one on each side of the main shaft of the windmill rotor, are used. The supporting structure for medium-sized windmills may be a guyed steel tube but it is usually a lattice-steel tower for the larger machines.

Can the large windmill compete on a cost basis with the diesel or gasoline generator? No correct answer can be given. The British firm of Dowsett Holdings, Ltd. claims a cost per kilowatt hour of 1.8 cents for its 25 kilowatt machine as compared to 3.9 cents for a diesel electric generator. But it should be noted that the Dowsett Holdings windmill operates at maximum efficiency in a 25 mile an hour wind. A steady wind of this velocity is hard to find. In the final analysis, the economy of the large wind-electric machine can be assessed accurately only if the capital charges on the plant, the wind data for the site, and the cost of alternative means of power production are known.

VI. CONSTRUCTING A WINDMILL

Following are detailed instructions for the construction of two windmills which can be built in a home workshop.

The first is a six-foot mill of approximately 1/10 HP (assuming an average wind of 16 MPH), sufficient for running a small grindstone or running a 30-watt dynamo. The second mill, 10 feet in diameter, can deliver approximately 1/4 HP under the same wind conditions.

A Six-Foot Mill

In order to simplify the machine as far as possible, the mill has been designed with fixed head, so that the wind must be in one of two opposite directions to give a maximum effect. It should therefore be set up with the front wheel facing in the direction of the prevailing wind. Where the two principal prevailing winds are, say, southwest and northwest, the best direction for the axis of the mill would probably be north and south. A fixed mill like this is suitable for a town dweller, where long rows of houses confine the wind to definite directions.

The vanes (see Figures 6, 7, 8) can be either fixed or allowed to revolve partially upon the arms. If fixed, the mill will run in opposite directions with opposite winds, and while this need not matter for such operations as pumping, it would not be satisfactory in other work. A simple device has, therefore, been adopted; when the wind blows from what may be called the back of the mill, the sails will automatically reverse and so cause the direction of rotation to be always one way. The maker who prefers to have the sails fixed may ignore this arrangement and screw the vanes firmly to the arms, which need only to be tapered off and not rounded in section. The alternative arms required in this case are sketched in Figure 8C (two views), and of course require less work on their construction.

The mill, as shown in Figures 6 to 9, has six whips or arms mounted upon a triangular hub to which they are all bolted. The six whips are formed from three hardwood sticks, each making a pair of arms. The sticks will be 1 1/2 inches square in section and 6 feet long; the central portion for a length of 22 inches should be tapered from 1 1/4 inches diameter at the root to 1 inch diameter at the tips. Good sound straight wood should be selected.

The hub, shown in detail in Figure 6B, should be very carefully made. Form an equilateral triangle of the size given from a piece of very sound non-splitting hardwood. The hole for the axle must be truly bored and fit well so that the sails will all run in true plane and square to the axle. The three sticks must be bolted to

the hub, each with two 3/8-inch galvanized bolts, with good-sized washers, every care being taken to fix each stick at right angles to the shaft. For further security, another 1/4-inch or 3/8-inch bolt will join each pair of sticks at their crossing; note that in one case (see Figure 7C) a piece of packing of the same thickness as the sticks will be required. The bolt in this case must also be longer.

The axle will consist in this case of a short length of stout mild steel tubing. The size is not important—it is shown as 1 inch outside diameter, and should not be less. This is not so much for strength as for better attachment to the hub with its far-spreading sails.

The hardwood hub should be fixed to the axle by a couple of 1/4-inch split pins going right through, as seen in Figure 6B. These can be put parallel with two of the sticks, and should fit well so as to allow no backlash.

The bearings should be of brass, formed as in Figure 9. These bearings are carried in hardwood pedestals, and secured by hardwood caps bolted down over them. A recess is made in the cap, and blocks are provided on the base to prevent side movement of the brasses. If possible, oil cups or other similar lubricators should be fitted. A cover of thin galvanized sheet iron may be fitted to the working parts. The details of the forward bearing are sufficiently indicated in the three views, Figure 9. The rear bearing is exactly the same.

The power of the mill may best be transmitted by means of a pair of bevel-wheels, as shown in Figure 7A. Various ratios of speed can be obtained according to the wheels used. As shown here, the wheels have a speed ratio of two to one; and a light, true running shaft, 5/8 inch or 1/2 inch in diameter carries the lower wheel. If this shaft must be of any great length, or if much of it must be unsupported, a greater diameter is desirable; here again tubing can be substituted for solid rod. For pumping purposes a crank may be arranged either as an overhung crank on the tail end of the shaft, by an eccentric as described in the last chapter, or by cranking the shaft itself, the throw being made suitable for the pump to be used. A light wooden connecting-rod should be used if this plan is adopted.

The method of carrying the vanes and also the device for automatically swinging them to suit the wind are shown in Figures 6C, 8A, 8B. The vanes are formed of 3/8-inch boards, the edges being tapered off as shown in Figure 8B. Any timber not liable to warp in sun and weather will be suitable.

The supports or hinges, clearly seen in Figure 8A are of 3/4 x 1/8-inch galvanized hoop iron, bent to fit around the arms at the places assigned to them. They are attached to the vanes by 1/4-inch flat-headed galvanized bolts, with large washers next to the wood. A screw projecting from the arm just beyond each bearing prevents the vane from slipping off. Each vane should swing easily without shaking.

Because of the unbalanced shape of the sails, they will swing according to the direction of the wind, and means are provided to allow them to take up a position either way at the best angle for general work. This is shown in Figure 6C; the black lines show how the sails would set with the wind in the direction given and the direction of rotation. The dotted lines indicate the condition when the wind blows from the opposite quarter. The device consists of pairs of short cross-bars screwed to the backs of the arms and bolted, with packing between, at their crossing. As the angle each way is important, care must be taken, by cutting away the cross-bars or providing packing, if either is necessary, to secure an angle of about 25°. A template cut to the correct angle should be used to adjust the vanes in each case.

The timber framing on which the mill is erected needs no description beyond that afforded by the sketches, but it should be remembered that stiffness is essential not only for safety but also to avoid strain on the vertical shaft and loss of power. Cross-bars can be bolted in at intervals if this shaft is long, and bearings fitted upon them.

Each piece of finished timber in the mill itself must be carefully painted before being built up. Three coats of paint are recommended, and the last coat should be mixed with outside varnish. Regular oiling is necessary. In order to avoid working the mill unnecessarily, a brake or lock mechanism should be fitted.

A Ten-Foot Mill

A general elevation is given in Figure 10, to a scale of 1/4-inch to the foot. The tower is built up of four 3 x 3-inch vertical members, 12 feet high, each placed at the corners of a square, with 4-inch space between each pair of uprights. These uprights are braced by struts of 3 x 3 timber starting below the circle of vanes, one strut on each side, and each bolted to two uprights, as shown. The lower ends of struts are lodged into two horizontal diagonals, which are halved over each other at their crossing so as to lie level. The lower ends of uprights with a little shaping will also fit alongside these diagonals and must be securely bolted to them with 1/2-inch bolts. Bolts or straps must also secure the diagonals to the feet of struts. Four 3/4-inch bolts not less than 3 feet long must be carried down at the four ends of the horizontal members into pockets of rough concrete of 2 or 3 cubic feet each. The holes above the concrete must then be very firmly filled in and rammed. If the ground is soft or yielding, a greater depth and more concrete must be employed. This timber should be creosoted and all bolts should be galvanized. Large washers under the nuts of the 3/4-inch bolts are required.

A more detailed side elevation of the head, tail, and part of the arms is given in Figure 11 to a scale of 3/4-inch to the foot. This shows the movable head casting A carried on the bearing casting B. Both of these are detailed still further, to a scale of 1 1/2 inches to the foot in Figures 12A, D and require little explanation. The shaft of A is turned to ride easily in the bored hole in B, and is fitted with brass bushings for the axle and vertical shaft. The casting B is securely bolted to the top

of the 3 x 3 uprights with 1/2-inch bolts. Packing pieces, C, in Figures 11 and 12D are to insure correct spacing. Note should be taken of the sheet of zinc or lead, D, Figures 11 and 12A, which is first laid on top of the uprights, with a suitable hole in the middle to allow the shaft of B to pass through, and is then dressed down, as shown, to protect the timber from moisture. It should hang clear of the timber to avoid capillary action.

The tail, employed to keep the mill facing the wind, is also shown in Figure 11 at E. It is carried by two angle irons, 1 1/2 x 1 1/2 x 1/4 inches, F and G, which are bolted respectively to the top and bottom of head casting A with 3/8-inch bolts. The position of these angles is indicated (in dotted lines) in Figures 12A and 12B at F. A sheet of zinc forms the tail surface and is riveted to the brackets with 1/4-inch rivets about 4 1/2 inches apart. Four stiffeners of 1 1/4 x 1/8-inch hoop iron run vertically across the surface, dividing it into three equal spaces. Both angles and stiffening strips should be galvanized.

The shaping of one of the eight arms for the vanes is shown in Figure 13 and the outline of sail in Figure 14. The assembling of these parts is indicated in Figure 11, but it is necessary to turn to Figure 15A to see in greater detail the method of fixing the automatic gear. Each of the eight sails has an independent set of levers to actuate the central sliding rod. It must be remembered that the wind impinging on an unbalanced sail attempts to turn it on its hinges, as shown in the plan in Figure 15B. Regarding the short side of sail (the so-called leading sail), it describes an arc of rather less than a right angle, until it lies flat in the plane of the wind's direction. The chord of this arc, or rather of that described by a projecting pin J (a piece of 5/16-inch rod bent as shown), forms the path of the lower arm of lever K, (fully illustrated in Figure 16A), the other arm of which, being at right angles, must move vertically up and down as compared with the sail movement. This actuates the 3/8-inch rod L (detailed in Figure 15C), which in its turn works lever M. The planes of movement of the levers K and M are not coincident, producing on the sliding rod N an in-and-out movement according to the amount of the wind's pressure. The lever K is supported at the special angle required (seen in plan in Figure 15B) by a bracket O (Figure 16A) bolted to the arm. The top arm of the lever is made with a return end in order to give a long bearing, and the bottom end slotted to allow the necessary play for the pin J, due to the path of the latter being an arc.

Returning now to the sliding rod N, it will be seen that the motion of the eight levers M is transmitted to it through the special turned nut P, Figure 15E. The various possible positions of the forked end of lever require that the section of this nut be turned to the curves shown. A lock-nut on the outer side enables P to be screwed up to the most suitable position, and there secured in place by the lock-nut.

Examination will show that the tendency of any wind action of the sail is to force rod L nearer the center of mill, and so to drive rod N to the right as looked at in Figures 11 and 15A. This has to be met at the other end of N by the counteraction of a weight, R, carried by a cranked lever, S, indicated in a diagram in Figure 11, and

more fully in Figures 16C and F. The lever, the short end of which is doubled or looped (see left-hand view in Figure 16E) in order to pass on both sides of the loose pin bearing T, is hung from the upper tail-angle F by a 1/2-inch screw, a securer bearing being obtained for this by tapping into the block U, which is riveted to an angle, see section, Figure 16F. The arrangement of the end of rod N and pin block T is more clearly shown in Figure 17A. Figure 16B gives an end view of pin bearing, T.

The weight, R, should be cast double, one piece having a slot or recess cast on one side as shown in Figure 16D. It is difficult to fix on the exact weight that may be required, as this depends not only on the views of the maker as to the power which he desires the mill to exert at its maximum, but also on the friction of the numerous joints in the levers. It is, however, recommended that a trial be made with a weight of about 10 lbs., corresponding with the full lines in the drawings given. If the mill sails are found to open too easily with this weight—which is, however, doubtful—it can be shifted further along the lever arm, or, if this is found insufficient, another disc can be added as shown dotted on the left in Figure 16D. A light galvanized chain, running over a pulley in the top angle of tail and hanging with a loop to within 6 feet of the ground level, is used to lift the weight when the owner desires to stop the mill; this action opens all the sails so as to present only their edges to the wind. The other end of the chain is looped back to a point near the outer end of the tail to avoid entanglement with the uprights or the running shaft. A hook attached to the chain in proper position W, can be hitched under the lower angle of the tail by taking the chain sideways a little, when hanging the weight for any length of time.

The large central casting, X, appears in several figures, notably in Figure 15A and in front elevation in Figure 17A. It is undoubtedly the most serious undertaking in the whole construction and must probably be put into the hands of professionals. This casting carries the eight arms and makes a secure connection to the axle. It is backed by the smaller annular casting Y, Figure 17B, which is bored to fit well over the turned part of X. Three very well-fitted 1/2-inch screws at 120° secure the boss to the shaft. These screws must not project inside the shaft far enough to touch the sliding rod N (see Figure 15A).

The casting X carries also the eight little brackets Z for the levers M (see Figure 17A). These brackets are of cast iron, and the pins may form part of the casting.

A little further stiffening of the sail-arms is obtained by the use of the tension-rods TR, detailed in Figure 17C. These are 1/4-inch galvanized rods; one end turned over for an inch at right angles and the other screwed and lock-nutted. The tension put on these must be even and not too great, but they, as well as other screws and bolts in the machine, will probably require tightening up once or twice when the weather has had its effect on the timber.

The arms should be 1/2 inch thick with the edges chamfered off both sides. Three battens, 2 x 1 1/4 inches of sound hardwood must be well screwed across, and the hinges, three in number, will come opposite these, on the other side of the sail. These hinges should be of the strongest make, of T shape, and galvanized. They are shown in the plan, Figure 16A.

The axle is a piece of steel pipe, solid drawn, and 1/4-inch in diameter. It should be true to begin with, so that the very lightest skimming in the lathe will make it a good journal. It carries the usual bevel-wheel, indicated in Figures 11 and 15B, and gearing with another of the same size on the vertical shaft. Both wheels are 4 inches on inner diameters, but may be more or less if required, the casting A being altered if necessary. The vertical spindle would be a piece of 3/4-inch cold rolled steel shafting, and should have bearings also at bottom end and half-way down the tower, presuming the spindle is carried down to the ground as shown in Figure 10. A pair of bevel-wheels is also required to transmit power to a horizontal shaft.

All possible metal parts should be either galvanized or of sheet zinc. The castings should be free from rust, dirt, and grease, and painted with good red lead paint well rubbed in. It is better still to warm the castings to about 100° F. when putting on the first coat. Three coats of the red lead paint, thinly put on, and a finishing coat of gray or black paint are required to make a good job. The woodwork should be creosoted. This does not apply to the arms and vanes, which require painting. The most suitable paint is pure white lead with a dash of ochre.

Steps, formed from any suitable timber, should be nailed up at least two sides of the verticals to enable the owner to reach the head of the mill for oiling, etc.

A mill of this power, especially if used to drive a lathe or other workshop tools, should have a simple cut-out device—such as a sliding coupling actuated by a handy cord or chain, so as to throw the mill out of gear in case of an accident. A brake is not so necessary, as the automatic gear is designed as much as possible to keep the machine at uniform speed. Under normal output this speed should be from 80 to 100 revs. per minute, varying slightly according to the setting of the sails. These, in their flattest position—that is, with a light wind—should lie at an angle of about 20° to the plane of revolution of the wheel.

It may be desirable to apply the windmills described above to the generation of electric power. Figures 18, 19 and 20 illustrate the principal features of such an application.

Figure 19 diagrams the switch which automatically makes the connection between the dynamo and accumulators when the wind is of sufficient force to generate current.

A belt arrangement, Figure 18, maintains the dynamo at a proper speed when the mill is going too fast. Here A, C and D are pulleys with curved faces; B is a wide flat-surfaced pulley; B and C are fixed on one shaft, carried on a light timber frame EF which is hinged at E and carries a weight G at the other end. Figure 20 diagrams the entire apparatus necessary for a wind-driven electric plant.

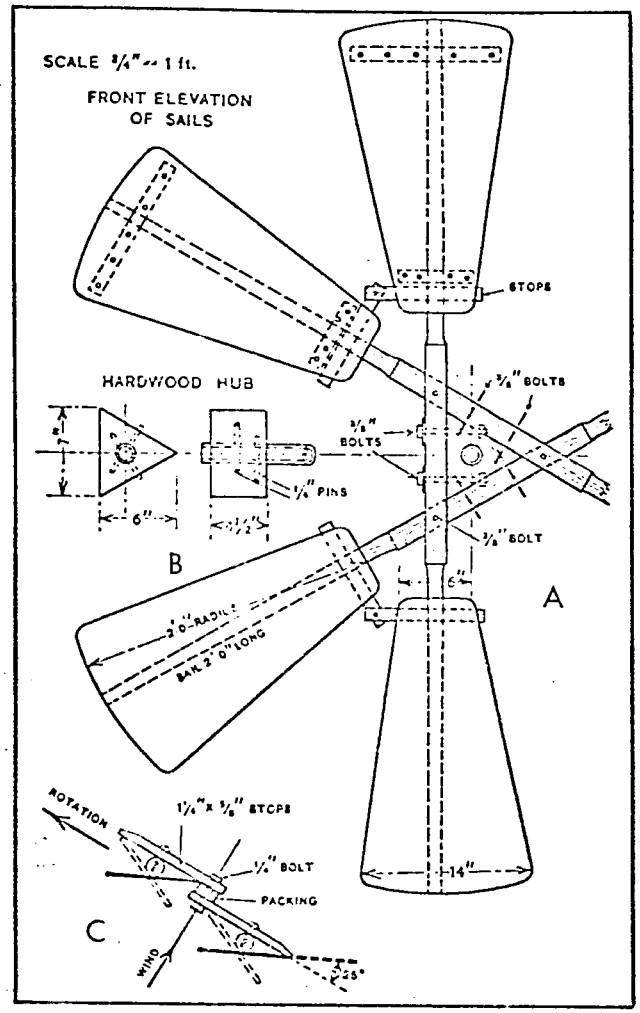


Figure 6. A. Front View of Sails for 6-Foot Windmill (Two Sails Not Shown). B Hub to Carry Whips. C. Diagram of Stops, Etc. for Reversing Sails

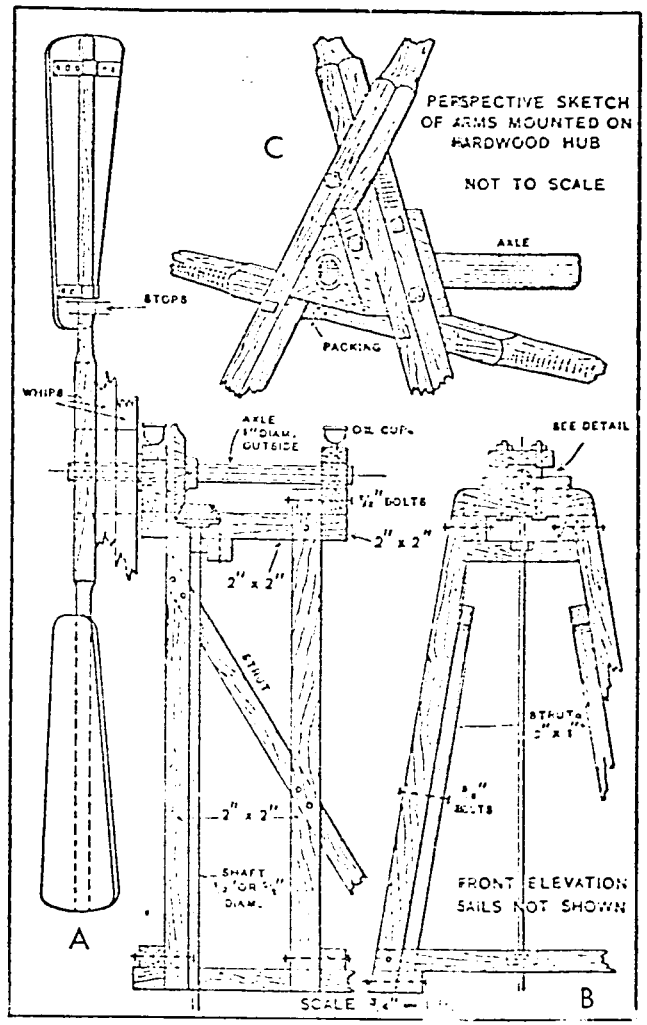


Figure 7. A. Side Elevation of 6 Foot Windmill B. Part Front View of Mill, Sails Removed. C. Showing Whips Mounted on Hub.

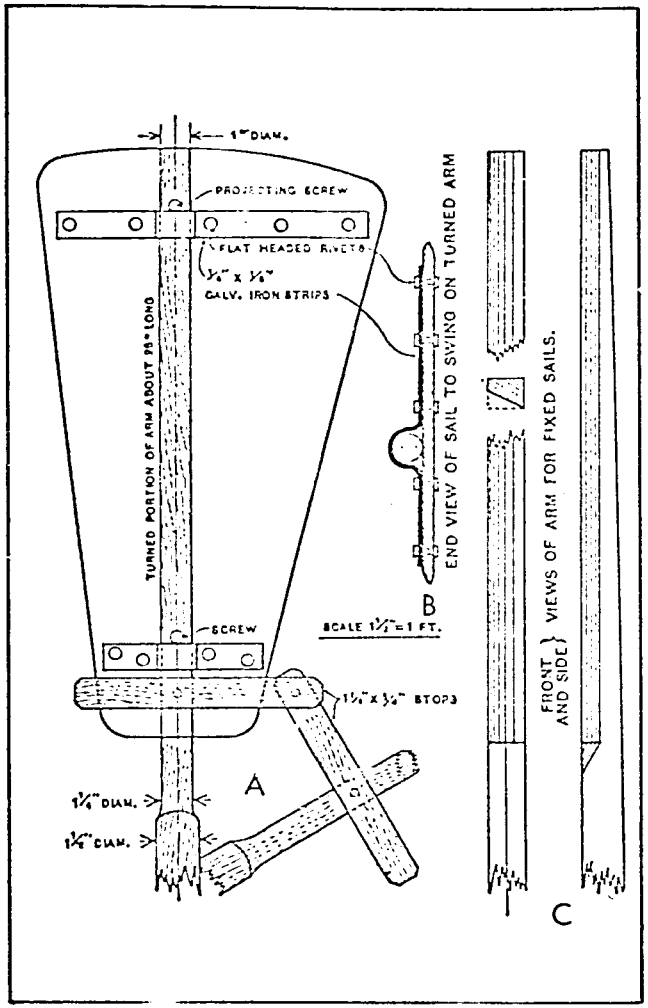


Figure 8. A. Sail Mounted on Whip, With Stops for Automatic Reversing. B. End View of One Sail and Hinge. C. Two Views of Arm for Fixed Sails.

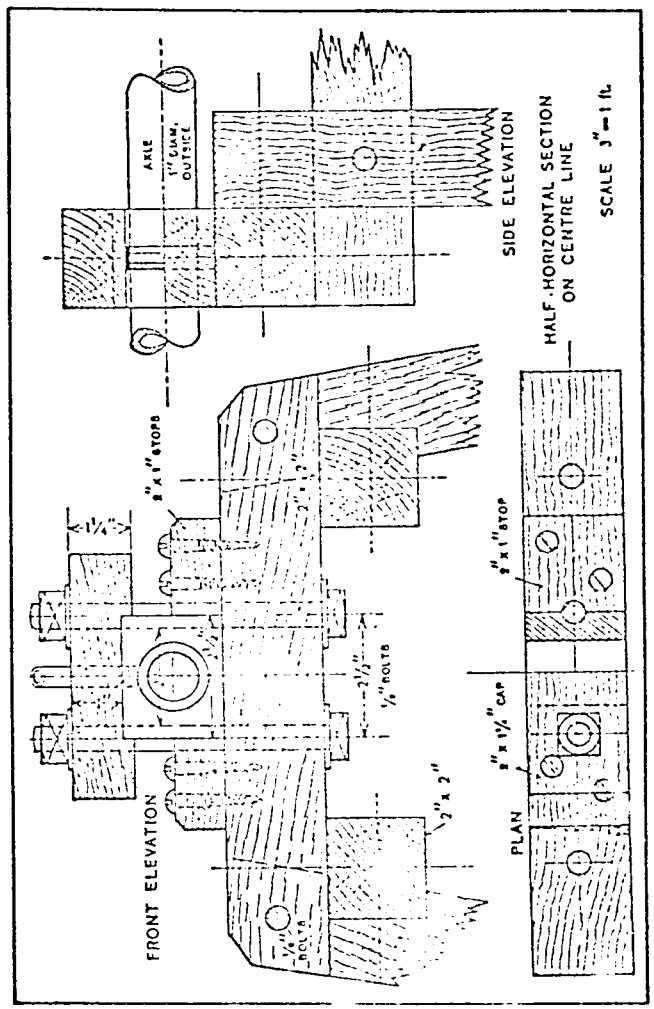


Figure 9. Three Views of Front End Bearing for 6-Foot Windmill.

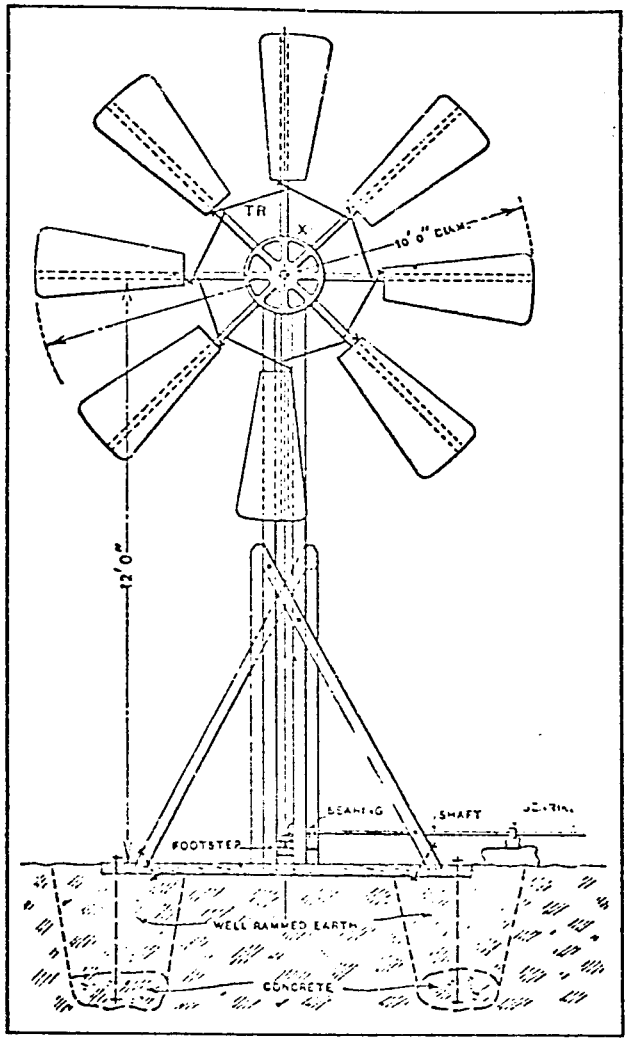


Figure 10. Front Elevation of 10-Foot Windmill.

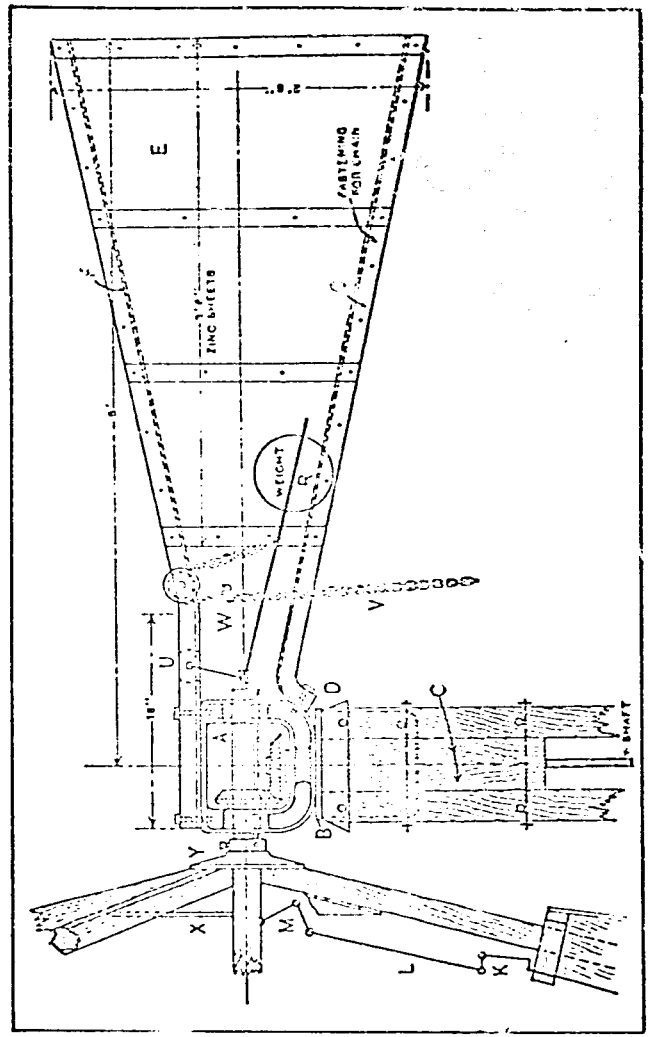


Figure 11. Side Elevation of Head, Etc., for 10-Foot Windmill.

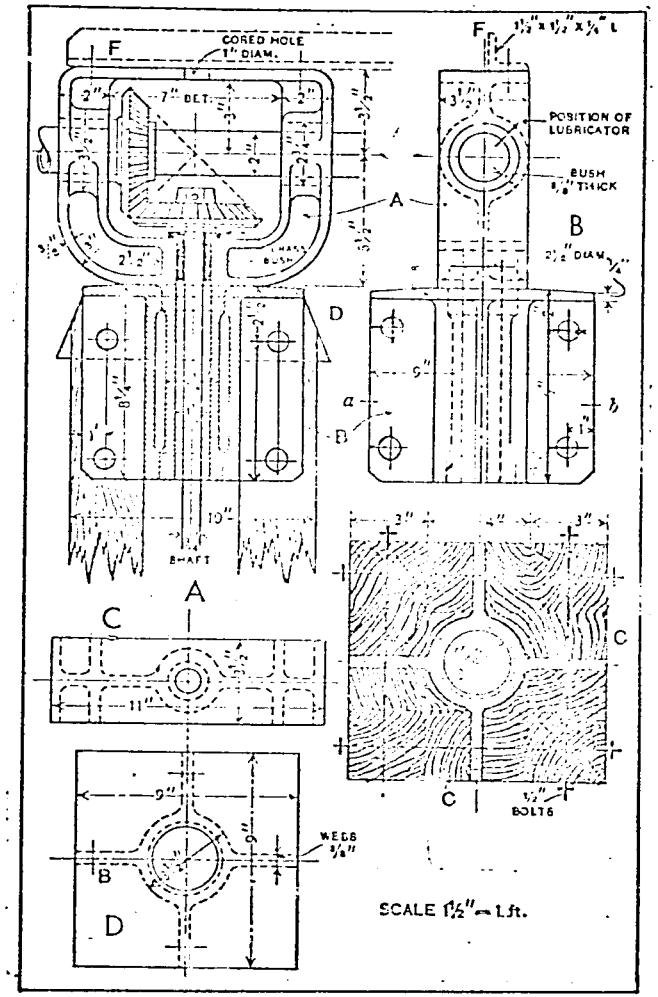


Figure 12. A. Two Views of Movable Head Casting and Bearing Casting. B. Plan of Movable Casting. C. Plan of Fixed Casting. D. Section Plan on A B, Showing Vertical Timbers.

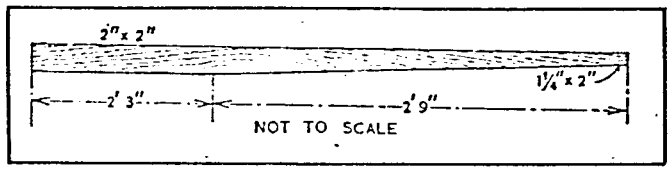


Figure 13. Shaping of Arm or Whip.

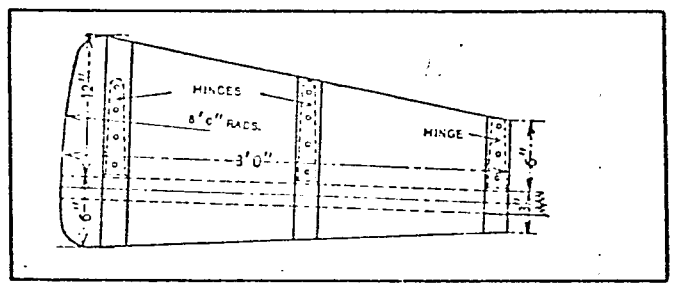


Figure 14. Outline of Sail for 10-Foot Windmill.

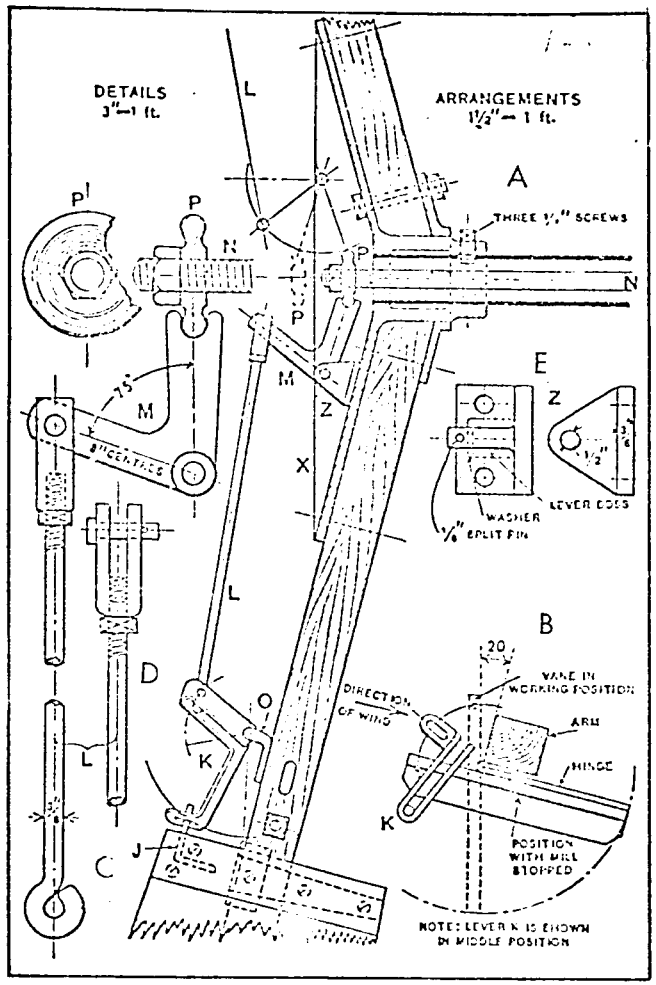


Figure 15. A. Arrangement of Automatic Regulating Gear for 10-Foot Windmill. B. Plan of Inner End of Sail, Showing Extreme Positions. C. Two Views of Push Rod L and Lever M. D. Pin Bearings for Levers M. E. Turned Nut on Sliding Rod N.

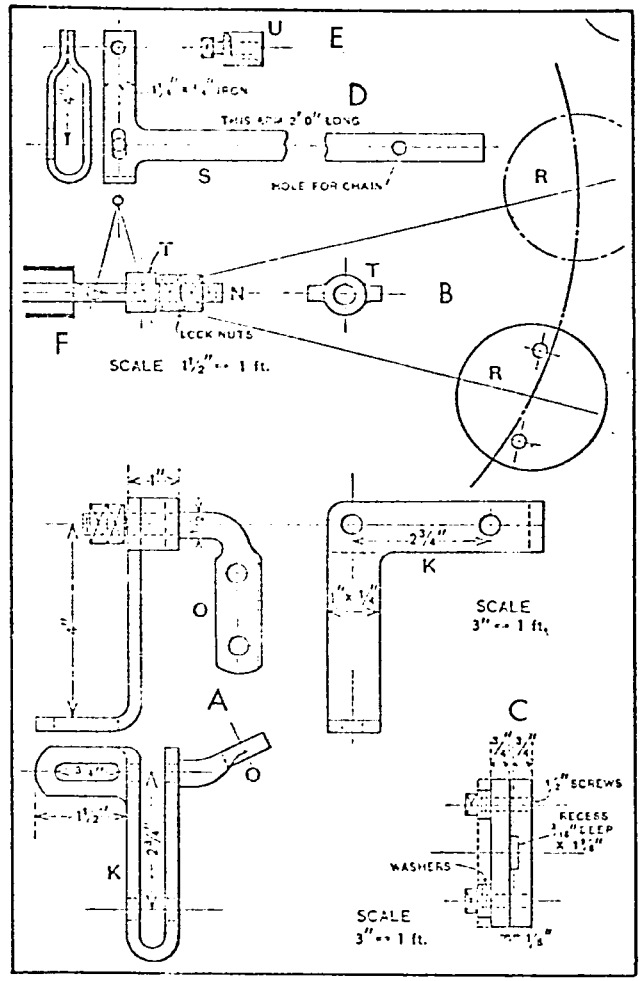


Figure 16. A. Three Views of Crank K. B. End View of Pin Bearing. C. End View of Weight R. D. Side and End Views of Weight Lever. E. Section of Angle Iron F with Stiffening Block. F. Tail End of Sliding Rod and Pin Bearing.

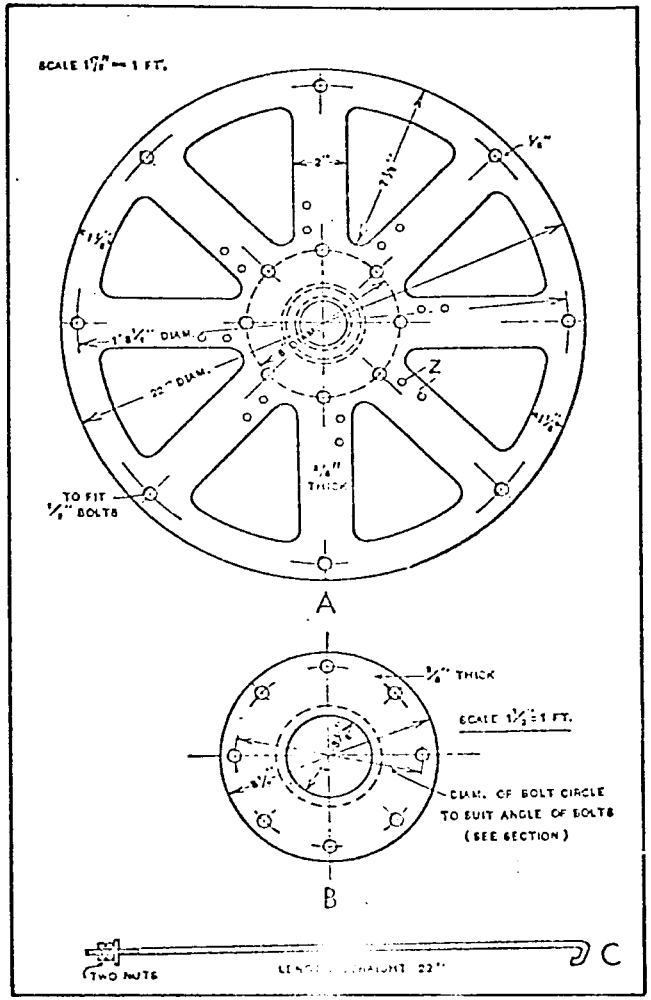


Figure 17. A. Central Casting. B. Annular Casting. C. Rod, Side View

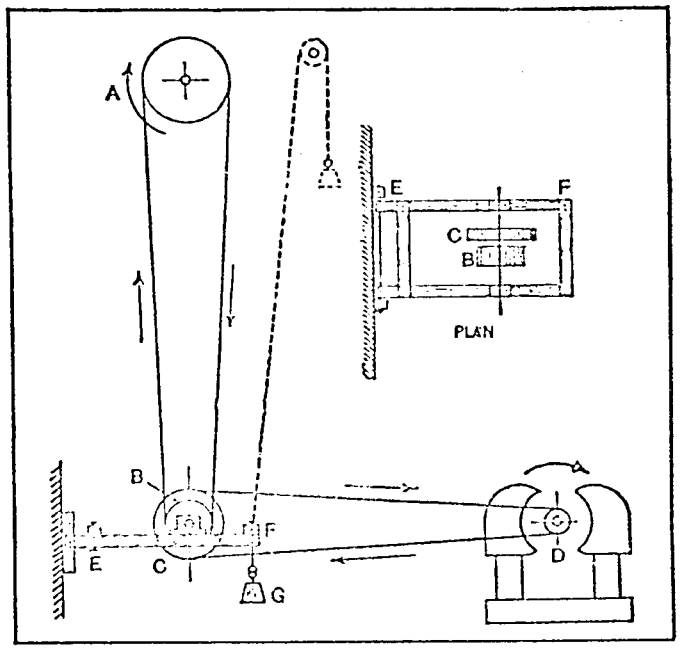


Figure 18. Driving Belt Arrangement for Wind Electrical Plant

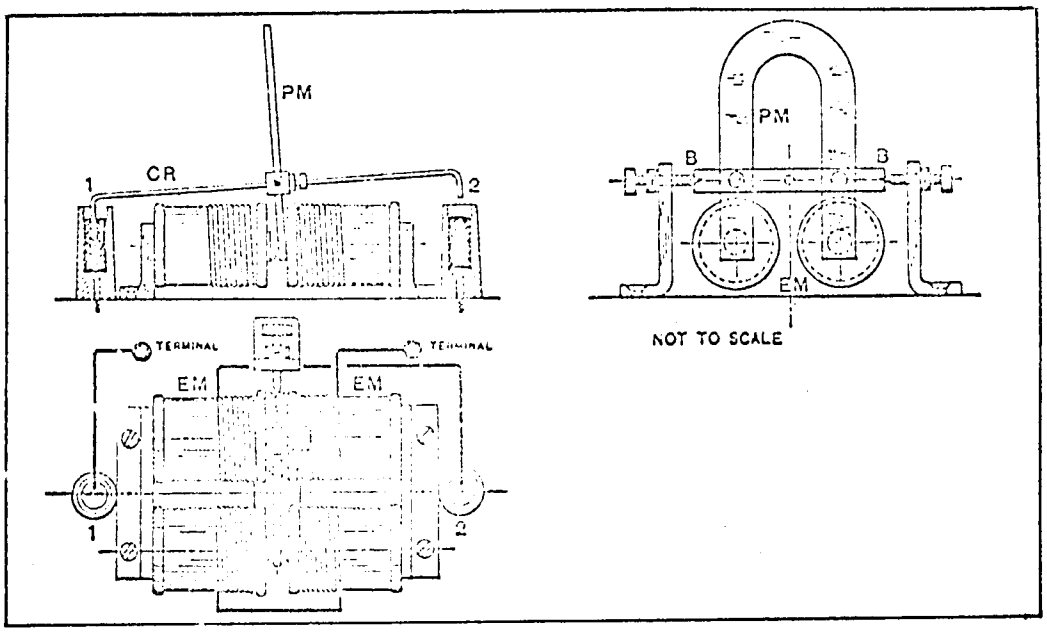


Figure 19. Automatic Switch for Wind Electrical Plant

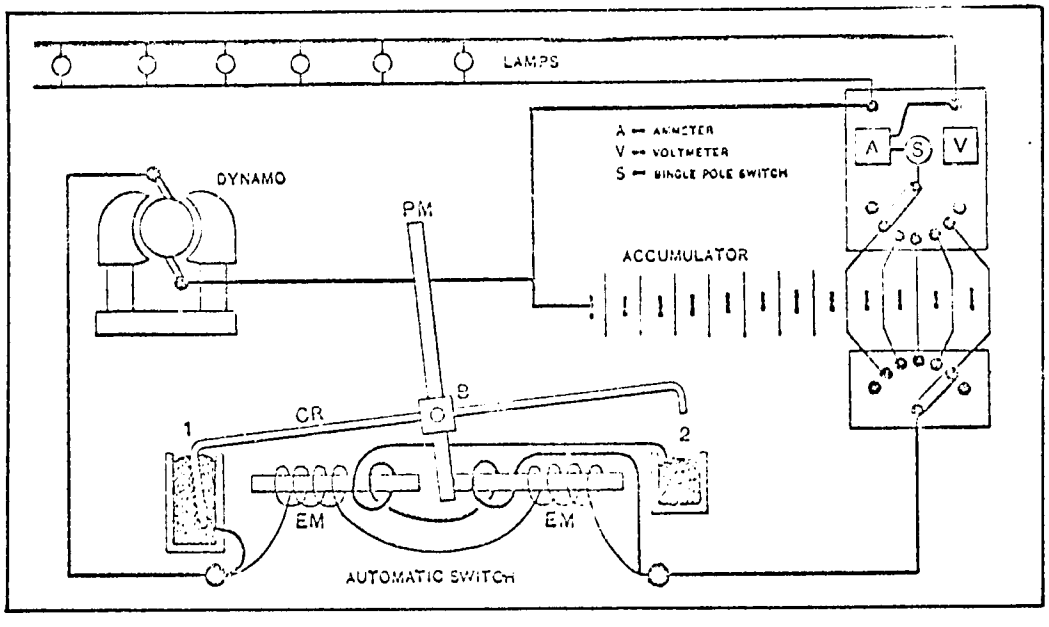
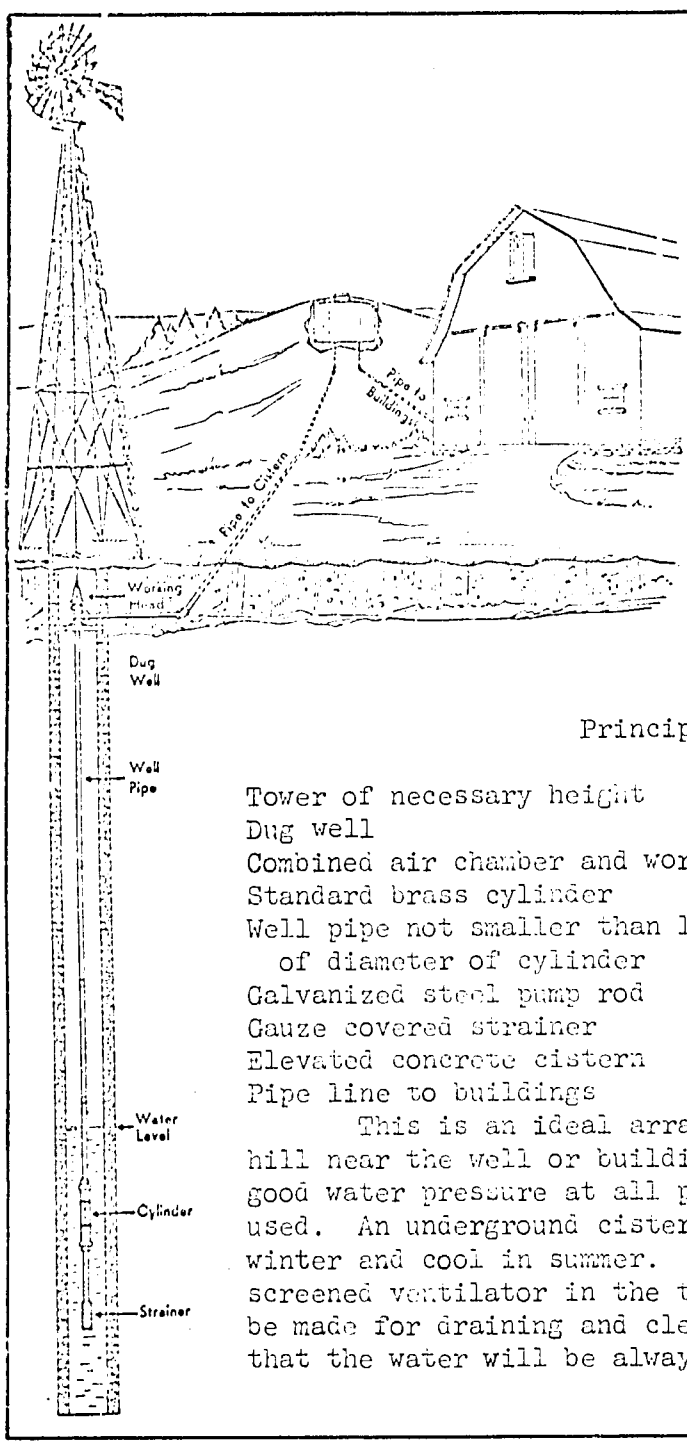


Figure 20. Diagram of Connections for a Wind-Driven Electrical Installation



Principal Features

Tower of necessary height
Dug well
Combined air chamber and working head
Standard brass cylinder
Well pipe not smaller than 1 1/4-inch and not less than 1/2 of diameter of cylinder
Galvanized steel pump rod
Gauze covered strainer
Elevated concrete cistern
Pipe line to buildings

This is an ideal arrangement where there is a hill near the well or buildings high enough to give good water pressure at all places where water is to be used. An underground cistern keeps the water warm in winter and cool in summer. The cistern should have a screened ventilator in the top, and provision should be made for draining and cleaning it occasionally, so that the water will be always pure and clean.

Figure 21. Water Supply System, Cold Climate

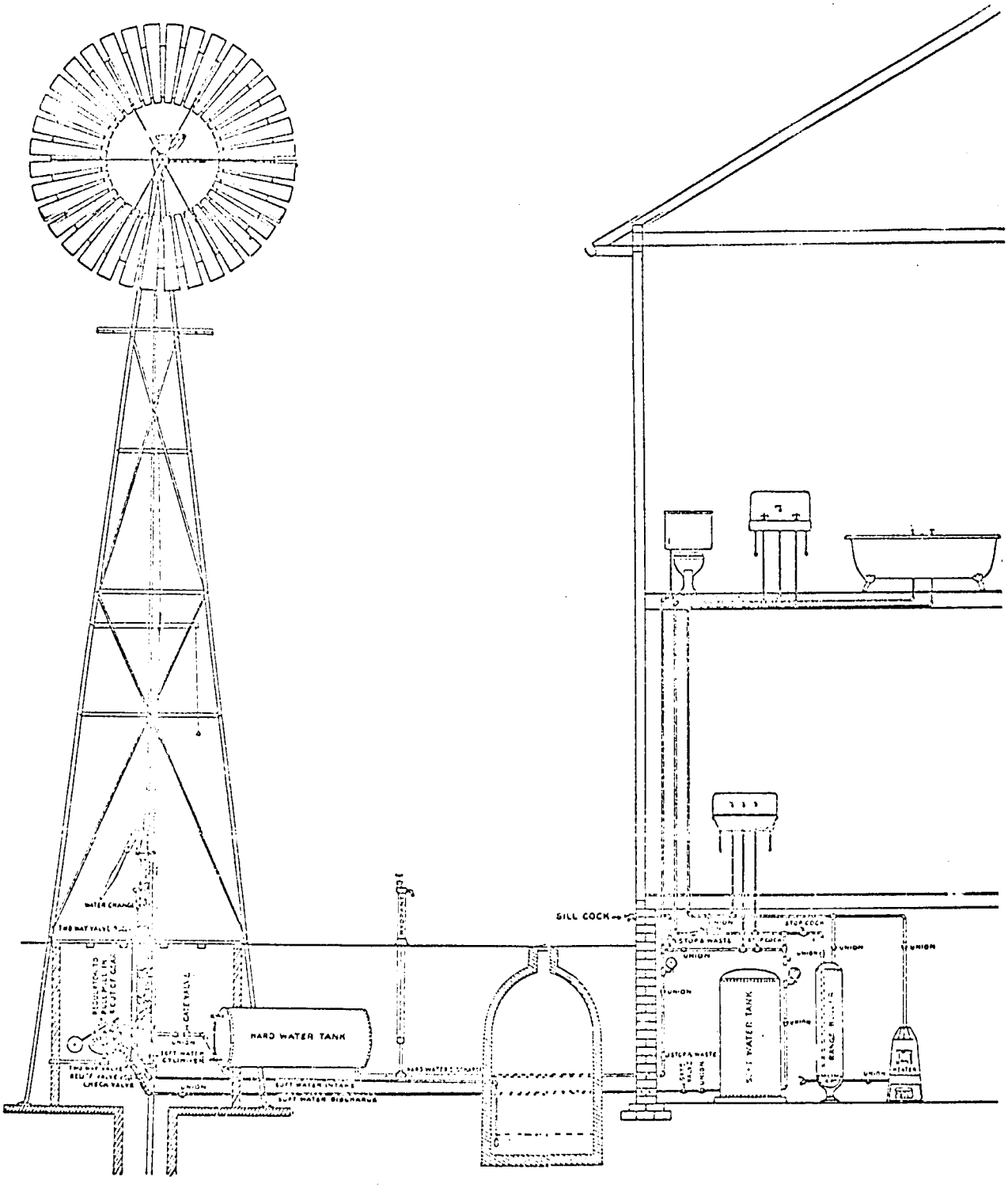
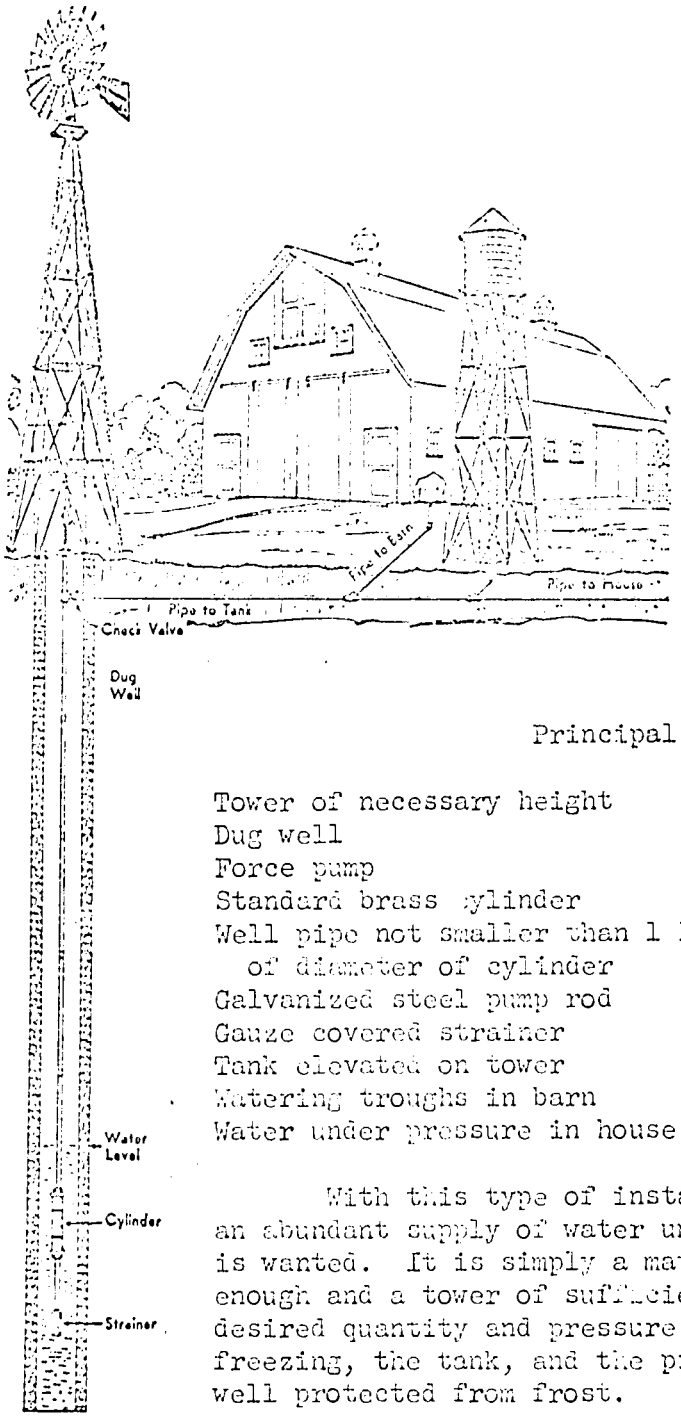


Figure 22. Windmill Pneumatic Supply System

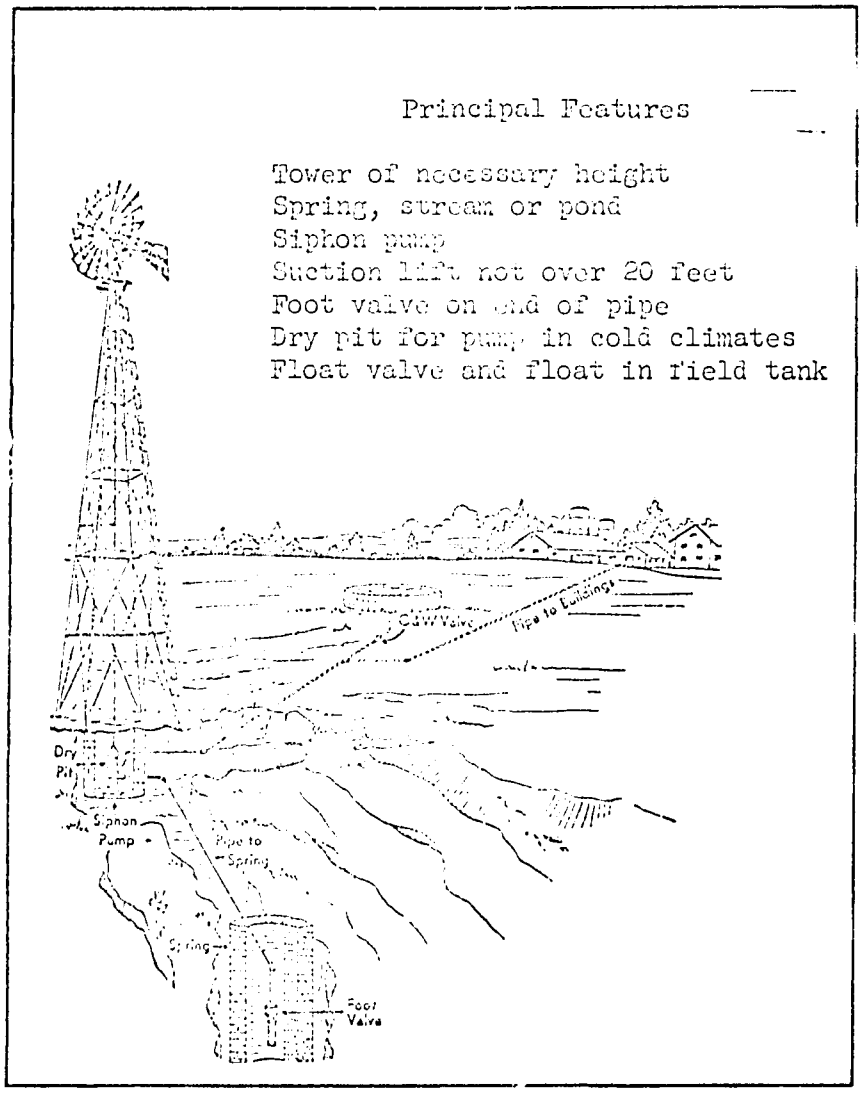


Principal Features

Tower of necessary height
Dug well
Force pump
Standard brass cylinder
Well pipe not smaller than 1 1/4-inch and not less than 1/2 of diameter of cylinder
Galvanized steel pump rod
Gauze covered strainer
Tank elevated on tower
Watering troughs in barn
Water under pressure in house

With this type of installation it is possible to have an abundant supply of water under good pressure wherever it is wanted. It is simply a matter of using a tank large enough and a tower of sufficient height to obtain the desired quantity and pressure. Where there is danger of freezing, the tank, and the pipes leading to it, must be well protected from frost.

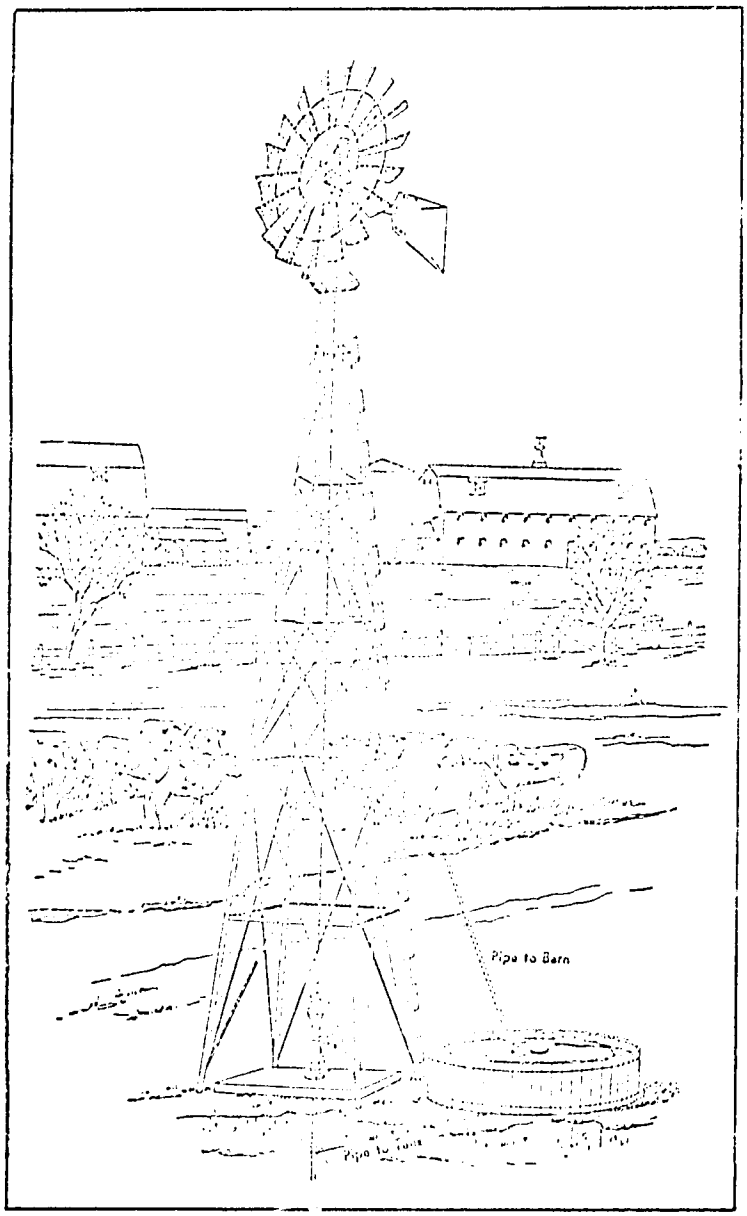
Figure 23. Water Supply System, Mild Climate



A siphon pump is used when the windmill cannot be placed over the water source.

A check and waste valve should be used where the pipe branches off for the field tank so that it can be drained when not used in freezing weather.

Figure 24. Siphon Pump System



With this kind of arrangement one will supply water for both pasture and barn. The use of a float valve and float will keep the pasture tank always full and the surplus water can be pumped to a storage tank in the barn. If the distance between the barn and well is not too great, an automatic regulator can be used to shut off the mill when the storage tank is full.

Figure 25. Pasture and Barn Combination

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