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THE DESIGN AND CONSTRUCTION OF LOW-COST WIND POWERED WATER PUMPING SYSTEMS*/

(Item 5(b) of the provisional agenda)

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*/ This paper has been prepared by Mr. Marcus M. Sherman, consultant on wind energy. The views expressed in this paper are those of the author and do not necessarily reflect the views of the ESCAP secretariat or the United Nations.

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I. INTRODUCTION - DESIGN PROBLEMS

Recently there has been an increasing demand for information on designs of water pumping windmill systems suitable for construction with low cost locally available materials and skills. However the general unavailability of properly documented technical information on indigenous wind pumps is a major factor limiting more widespread implementation of wind pumps in rural areas.

At each different locality, because of the complex interrelationships of the variables of wind characteristics, water supply, materials and skills determining a wind pumping system design, adaptation of low cost wind pumps to new areas without modification or redesign has had limited success. This paper is an attempt to alleviate these problems by specifying the interrelationship of the variable design factors and presenting the design process as a sequential flow of information analysis, rational decisions, and calculations.

Figure 1 (sequential flow chart indicating design process for water pumping windmill systems) is presented as a guideline to those interested in the development of wind pumps. The following discussions will elaborate on each component of that chart.

II. PRELIMINARY INVESTIGATIONS

Many thousands of locally constructed windpumps are in use throughout the world. Many of these designs are the result of many years of trial and error experience confined to a single location. If effective windpumps are to be used on an appropriate scale in a relatively short period of time it is imperative that a rational design procedure including quantification of the major design variables be available to development workers. Though surveys of local wind characteristics and local water pumping requirements are best undertaken by national or district authorities, it is important that a survey of windmill types and pump types be internationally comprehensive. This information on windmills and pumps should be presented in a format useful to semitrained technical workers.

A. SURVEY OF LOCAL WIND CHARACTERISTICS

A reliable determination of local wind characteristics must be made, especially for the period when water pumping is most needed. Summarized average hourly wind velocities (figure 2) are required for preparation of monthly velocity frequency curves (figure 3), monthly power frequency curves (figure 4) and monthly power duration curves (figure 5).

The maximum wind velocity, and directional distribution of winds (figure 35) should also be determined.

B. SURVEY OF LOCAL WATER PUMPING NEEDS

A survey of local water pumping needs should primarily determine the total pumping head and the daily water demand on a monthly basis for each of several agricultural and domestic uses.

C. CLASSIFICATION OF WIND ROTORS

Several different types of wind rotors are generally known however their construction and performance characteristics have not been comprehensively classified into a format desirable for design purposes. Complete information for comparative analysis of rotors should include, starting velocity, rated velocity, maximum operating velocity, tip speed ratio, rated efficiency, range of diameters, construction materials, rotor solidity (total swept area divided by total frontal area of blades) root chord,[*] tip chord,[*] tip angle,[*] root angle,[*] air foil section[*] and velocity/power graph. Measurement of these parameters of the known low cost wind rotors would have a major benefit on the design and development of new hybrid wind pumping systems.

The relevance of different rotor types to wind powered pumps is discussed below.

1. Horizontal axis rotors

(a) The classic Greek type sail wind rotor is widely used in Greece[1] [2], Thailand[3] [4], and China[5] [6] for wind powered pumps because of its high starting torque, low starting speed, low weight and cost, and its ability to be easily adjusted to higher wind velocities. It consists of 6-12 triangular cloth sails each attached to a wooden spar along its longest edge and held tight by a rope leading from the free corner to the adjacent spar tip or circumferential wire between each spar tip. (figures 6, 7, 8, 9, 10) Radial wires, leading from the tip of each spar to the tip of a central axial spar, brace the spars against wind pressure.

/Maximum

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[*] When relevant.

Maximum rotor solidity is about 45-50%. Sail area can be reduced by wrapping each sail one or more times around its spar. This type of rotor appears to be the most appropriate design for use in areas with limited resources of materials and skill. It has been further developed by the Brace Research Institute[7] (figure 10) for use in developing countries and recently been tested in Sri Lanka,[8] India[9], Malaysia[10], (figure 9) and Ethiopia[11].

(b) The steel multiblade fan rotor consists of 8-24 curved sheet metal blades mounted on two concentric steel rings supported by 5 or 6 tensioned steel spokes. Rotor solidity is 90-100% (figure 11). Local adaptations of this design[15] have been developed in India[12], Syria[13], Thailand[14] and Indonesia[16]. It is characterized by a very low starting velocity of 6-8 km/hr and high starting torque. It is always used in connection with a piston pump. This type of rotor is most appropriate for industrial manufacture and use in areas where the necessity for long time durability and reliable unattended operation can justify the large capital expenditure required.

(c) A very simple and durable rotor consists of 4 rectangular curved steel plate blades twisted to low pitch at the tip and high pitch at the root. (figure 12) Rotor solidity is about 35%. It is commonly used in Holland and Denmark for small scale drainage and cattle watering. This rotor type has also been used on low cost wind pumps at some salt works in France for water pumping (figure 13). Optimization of this type of rotor for use in developing countries is in progress in Holland.[17] This type of rotor seems to have considerable potential for use in low cost water pumping systems because of its simplicity of construction, durability and good aerodynamic efficiency.

(d) The Princeton sail wing wind rotor was developed in 1960. It consists of two sails, each of a double thickness of cloth supported by a rigid straight leading edge, rigid tip and root sections and a trailing edge cable stretched between the tip and root sections. The ratio of root chord to tip chord is about 3:1. The sail is cut with a catenary arc trailing edge which allows equal chord tensions to be developed along the length of the sail as a function of the tension at the trailing edge cable (figure 14). The aerodynamic performance of this rotor is similar to conventional rigid construction rotors, however the structural weight is reduced at least one half. Cost and complexity of construction is significantly less. Detailed plans of the original Princeton design are available.[18] Detailed plans of an adapted version used for water pumping are also available.[19]

(e) Highspeed propellor type wind turbine rotors are not usually considered for water pumping but they are successfully used for this purpose in Thailand (figure 15)[20] and they may be adapted to high speed centrifugal pumps. A turbine

/rotor

rotor windpump design has been proposed by Stam[20]. These rotors are characterized by high starting velocity, high rotational speed and low starting torque. Most high speed rotors are carved from wood though some are made from aluminium by casting or rib construction[21], others are fiberglass[22][23]. Any attempts to use high speed rotors for pumping should be in connection with pumps requiring low starting and constant operating torque such as square pallet chain pump, centrifugal pump, chain pump, archimedes screw etc.

(f) The classic Dutch type of wind rotor consisting of 4 spars supporting a wooden lattice covered with cloth sails is best adapted to very large machines where high power output at low rotational speed and high torque are required. Modern use of this type of rotor for water pumping is rare and its use in new hybrid designs will be limited primarily by the large amount of skilled wood craftsmanship required to construct the lattice structure.

(g) Several other horizontal axis rotors have been used that incorporate 4-8 fixed rectangular blades of wood, or fiber mat construction; their cost, efficiency and durability is quite low. Generally speaking a rotor blade can be made from any flat thin material including metal, cloth, wood, plastic, bamboo and fiber mats, with appropriate supports.

2. Vertical axis rotors

Many different varieties of vertical axis wind machines rotating in a horizontal plane have been reported through history.[24] The primary advantage of these rotors is that they can accept wind from any direction and thus do not require any mechanism for orienting them towards the direction of the wind. However their construction is usually very bulky and requires a large quantity of materials in relation to the effective collection area. These rotors have maintenance difficulties as a result of all of their weight resting on one thrust bearing at the base of the main shaft. Aerodynamic efficiency is low because the rotor blades turn simply as a result of direct wind pressure which is a function of the square of the wind velocity (V^2), unlike horizontal axis rotors which extract wind energy as a function of the cube of wind velocity (V^3). Also only about 50% the rotor blades are doing work while the other 50% are returning up wind. Two classic vertical axis rotors which may however have some practical importance for modern applications, due to their light weight construction are the Chinese vertical axis wind pumps (figure 16) and the Turks and Caicos Islands vertical axis sail rotors. (figure 17) These rotors may be particularly adaptable to the Persian wheel and Mhote type of animal powered water lifts in addition to continued traditional use with square wooden pallet chain pumps.

(a). Vertical axis wind rotors were used in the Turks and Caicos Islands, British West Indies for pumping of salt water to evaporating ponds for salt production.

/These

These rotors consist of six triangular cloth jib sails supported along their long edge by a vertical pole, and held by a rope tied from the loose corner to the adjacent vertical pole. Each vertical pole is supported by two horizontal wooden poles which radiate out from the central, vertical main shaft. A similar jib sail rotor utilizing 8 sails has been proposed for use in Thailand (figure 18).

(b) The Savonius rotor has been well documented (figure 19)[25] its use for practical water pumping has been generally discredited.

(c) The Darius rotor consists of 2 or 3 constant chord air foil blades bent into a catenary curve and fixed at each end to a vertical axis which is supported by guy wires at the top and connected to a power utilization device at the base (figure 20)[26]. The advantages of this rotor are that, unlike other vertical axis rotors a minimal support structure is required, the proportion of materials to total swept area is very low (solidity about 5%) and efficiency is high. The main disadvantage of this rotor is that it is not self starting and construction of the blades from fiberglass reinforced plastics or extruded aluminium is quite expensive. Although it has only recently been developed for electricity generation[27] it may have some potential for water pumping. Experimental work with a Darius rotor powered water pump has recently been undertaken at the National Aeronautical Laboratory in India. The possibilities for constructing a modification of this design using air foil blades curved from wood should be investigated.

(d) The cydogiro vertical axis rotor is similar to the Darius rotor in that it has a high efficiency of about 60%, a very low solidity and minimal support structure requirements (figure 21). This rotor consists of two or three straight symmetrical air foil blades supported vertically from horizontal support arms fixed to the vertical central power shaft. Orientation of the blades is reversed twice during each rotation so that maximum lift is achieved during the full circle of rotation.[28] High speed small diameter designs have considerable vibration problems, however development work on larger diameter models with more blades operating at lower speeds may reduce vibrations. Further development of this rotor is currently in progress at Reading University, Cranfield College of Technology, U.K.

3. Three novel concepts

Three novel concepts for utilizing wind power for water pumping have recently been proposed. Though these ideas have not yet been given full scale demonstration their simplicity of operation and low cost construction makes them worthy of further consideration.

(a) The flapping vane wind pump has been designed for use with deep well piston water pumps, though it may be adapted to diaphram pumps, or to a crankshaft

/flywheel

flywheel drive to produce rotary motion. This device consists of a long lever with a cloth vane mounted on a horizontal axis at the end of the long arm and vertical reciprocating power rod at the fulcrum end. The vane can swing freely about its axis within the range of an upper and lower angular stop. Action of the wind on the vane alternatively depresses and lifts the lever arm with resultant power applied to the reciprocating rod near the fulcrem. The lever fulcrum is mounted on a pedestal which can rotate on top of the tower in order to allow the vane to automatically orient itself to the direction of the wind (figure 22). This device is calculated to pump 100 m^3/day from a depth of 40 meters with a wind velocity of 16 km/h, when the vane area is 29 m^2 and the lever arm is 20 m long[29], With increasing wind velocity the amplitude of the up and down motion of the lever arm decreases and the frequency increases so the system is self regulating.

(b) A tree pump has been proposed that corverts the horizontal motion of a tree trunk swaying in the wind to vertical motion via cables and pulleys to reciprocating vertical motion of a piston pump. In this device the only cost is for the pump and power transfer mechanism. The wind collector (leaves and branches) and the support structure (tree trunk) are free. This method is limited to sites with tall unsheltered trees.

(c) A parachute pump has been proposed by Dr. U. Hutter of the University of Stuttgart, Germany as a low cost method of supplying power to traditional animal powered Mhote pumps (figure 23). This system is composed of a large parachute whose circumference ropes are tied to the lift rope of the Mhote bucket. The force of the wind on the parachute pulls the bucket to the top of the well at which point a rope attached to the centre of the parachute becomes tightened and collapses the parachute so that it may be returned to the starting point by the operator and the Mhote can return down to the base of the well. The parachute is then again allowed to fill with wind to begin another lifting cycle. With this system the only expense is the wind collection device (parachute). The pump and transfer mechanism are pre-existing and there is no need for a support structure.

D. CLASSIFICATION OF WATER PUMPS

A comprehensive international classification of all types of small pumps used for water pumping is urgently needed. This classification should include the following information regarding each type of pump: typical schematic diagram, normal range of lift, normal range of output, construction materials and skills, usual mode of power supply, efficiency, range of operating speed. The following discussion briefly reviews those water pumps which may operate with wind power.

1. Reciprocating pumps

Most reciprocating pumps have the disadvantage that the torque load on them is not constant, thus requiring a higher wind velocity to start them and higher stresses on the system when in operation.

/(a)

(a) The single acting cylindrical piston pump is most frequently used in wind powered pumping systems. It consists of a cylinder with an inlet pipe and valve at the base, a leather sealed piston with one way valve and a water outlet at the top. Water is passed through the pump only on the lifting stroke of the piston, this type of pump is used to pump water from any depth, operating speed is up to 40 strokes per minute.

(b) A square wooden single acting piston pump is commonly used by fishermen in Eastern Canada (figure 24) and has recently been adapted to wind power.[30] A sqaure wooden pump powered by the wind has been proposed for use in Thailand.[31] Height of lift is limited by the amount of water pressure that can be held by the wooden joints.

(c) The double acting piston pump is similar to the single acting cylindrical except that there is no valve or passage of water through the piston, rather water bypasses the piston cylinder through pipes and valves under pressure of the piston during both the upward and downward stroke. (figure 25) The advantage of this pump is that the load on the power source is much more constant, however it is not usually used in wind pumping systems because any compression load on the down stroke would buckle the long piston rod leading to the top of the tower: this problem may be avoided if a very short piston rod is connected to an immediately adjacent rotary power transfer which is in turn powered by a long belt leading directly from the wind rotor shaft.

(d) The diaphragm pump

A diaphragm pump consists of a cylinder closed at the bottom end and with a circular diaphragm of rubber or some flexible material fixed at the top end. A reciprocating connecting rod is fixed to the centre of the diaphragm and upon vertical movement causes volumetric displacement in the cylinder. An arrangement of valves allows water movement in only one direction through the cylinder (figure 26). The difficulty with this type of pump is the high rate of wear on the diaphragm at its connections with the cylinder and connecting rod. A diaphragm pump has been developed by Brace Research Institute for use with the oil drum Savonius rotor design.

(e) The inertia pump is a very simple and efficient device that depends upon the vertical inertia of a body of water in a reciprocating pipe to expel water at the end of the upstroke of the pipe (figure 27). A one-way flap valve in the pipe is closed during the up stroke and inertia is imparted to a fresh volume of water by some lifting force on the pipe. This pump must operate at a constant frequency which is dependent upon the mass of water in the pipe and the pipe itself. This recently popularized pump has probably not yet been used with wind power.

/2.

2. Continuous rotary motion pumps are well adapted to operation by wind power because they demand a constant torque load and generally operate at a variable low speed.

(a) The square wooden pallet chain pump or "dragons bones" is commonly used in China and South East Asia for lift up to 3 meters. This type of pump consists of rectangular wooden pallets or paddles mounted on a continuous wooden chain that runs up an inclined square open wooden trough. The paddles and chain pass around a large wooden power gear wheel at the top and around a small passive gear wheel at the base of the trough which is submerged in water (figure 26). This type of pump is commonly used with Chinese vertical axis wind pumping systems and with Thai high speed wooden rotors and Thai sail rotors.

(b) The round steel washer-chain pump is used in conjunction with human and animal power. This pump consists of a continuous steel chain upon which are mounted steel discs with rubber or leather washers. This chain passes around an upper gear wheel, down the well, under the water source, around and then up into the bottom of a pipe with inner diameter the same as the washers. Water is lifted up within the pipe and expelled at the top (figure 29). A square wooden adaptation of this pump is shown in figure 30.

(c) Large diameter slow speed centrifugal pumps have good potential for low lift pumping, the "Meadow Mills" of Holland are fitted with centrifugal pumps 1 meter diameter, 0.20 meter high, having 4 wooden blades. These 30 per cent efficient pumps have an output of up to 100 m^3/hour in a strong wind (figure 31). Further design development and quantification of design variables of these pumps should be undertaken.

Another type of centrifugal pump is the centrifugal reaction pump. This pump consists simply of a vertical pipe with a "t" joint at the top from which extend two pipes whose length is dependent upon the rate of rotation of the assembly in operation. An orifice at the end of each pipe arm points 90° away from the arm (figure 32). When the assembly is filled with water and rotated in the direction opposite to the orifices the water is forced out through the orifices by centrifugal force and replenished by water coming up through a valve in the bottom of the vertical pipe. This pump is well adapted to variable low speeds and construction is simple. One of these pumps connected to a 3 meter diameter high speed wind rotor, pumped 30 m^3/h to a head of 4.5 meters in a 29 km/h wind.[32/]

/(d)

(d) Axial flow pumps have good potential for low lift pumping because of their relatively simple construction and high efficiency. The use of these pumps with wind rotors is unknown, however it has been suggested that axial flow pumps would be appropriate for high volume pumping of sewage wastes in oxidation ponds.[33] Theoretical studies of wind powered axial flow pumps have been carried out at N.A.L. Bangalore, India.

(e) Archimedes screws are very simple, up to 80 per cent efficient devices that have been used for large scale drainage up to 5 meter lift in Holland with wind power. Three basic versions of the archimedes pumps are known[34].

(1) The type with a rotating cylinder made of strips of wood and having a spiral partition inside; this requires a footstep bearing below the water level and demands a fairly sophisticated level of construction skill; it can be made large in diameter and so suitable for slow speed operation (figure 33); the performance of such a screw 2.745 m (9 ft) long, 0.563 m (22") diameter, lifting through 1.3 m (4.3 ft) at a speed of about 30 rpm gives an output of 32.4 m^3/h (7,200 gal/ h).

(2) The type in which the outer casing is stationary and the helical rotor is supported on bearings at either end, attached to the casing, so as to rotate with a small clearance between the edge of the 'Helix' and the outer cylinder. This type of helical screw is made by rolling a flat steel strip between rollers set at an inclination to each other to squeeze one edge of the strip and hence cause it to curl into a helix; which is then welded to an inner cylindrical pipe. These screw pumps are normally of smaller diameter and run at a higher speed than type (1), e.g. 5" diameter at up to 200 rpm, 16" diameter at up to 127 rpm.

An advantage of this form of Archimedes screw is that the casing and rotor form a self-contained assembly which does not require external bearings but only simple supports to maintain it at the correct angle and axial position.

(3) A third method of constructing an Archimedes screw is to coil a section of pipe into a cylindrical helix. A particular type has recently been evolved for field drainage in which the tubing is corrugated with a fine pitch to strengthen it and to allow coiling to a small radius. This could form the basis of a simple low-cost pump, since the most of the construction could be done locally. For example, a stout bamboo could serve as the main axle and the coils of pipe could be held in place by lashing with rope, wire or any suitable local fibre, using longitudinal strips of bamboo or other wood to form a supporting cage on the inside of the coils.

(f) The peristaltic pump consists of a flexible hose upon which a series of rollers is depressed and rolled along the length of the hose in order to "squeeze" water through the tube (figure 34). This type of pump has reportedly been adapted to a Greek sail wind rotor at the Malaysian Agricultural Research and Development Institute.[10/]

III. DATA ANALYSIS AND CRITICAL DECISIONS

A. DETERMINATION OF RATED WIND VELOCITY AND WATER DEMAND

Total duration of each wind velocity based on hourly average wind velocities should be summarized for the month(s) of greatest water pumping demand (figure 2) and monthly velocity frequency curves (figure 3) and power frequency curves (figure 4) prepared for determination of optimum rated velocity. A power duration curve should be prepared for determination of the load factor (figure 4). If continuity of water supply is most desired a velocity slightly less than that of maximum velocity frequency should be chosen, however if maximum output is the goal the maximum velocity of maximum power frequency should be chosen. A wind power rose indicating distribution frequency of wind directions should be prepared (figure 35). Daily water demand should be summarized on a monthly basis.

B. SELECTION OF ROTOR

The selection of a type of rotor is a most difficult process that requires careful consideration of construction requirements, local skills and materials and operating and performance characteristics. Unfortunately the precise characteristics of the main types of low cost locally constructed rotors are unknown. During selection of rotors for economical water pumping a reasonable compromise must be made between high reliability, durability and maintenance free operation on one hand,and low construction cost on the other. Increased labour input will generally result in lower capital input.

Selection of a rotor is also dependent upon the type of pump to be used. To maximize the efficiency of power transfer,the torque, speed and power characteristics of the pump and rotor should be as similar as possible.

C. SELECTION OF PUMP

Selection of a type of pump depends on the total pumping head, the type of rotor and the local materials and skills available for construction. The use of traditional local pumps whenever possible will reduce the problems of introducing a new technology of wind energy utilization.

D. DETERMINATION OF DESIRED PUMP OUTPUT

The starting, rated and maximum operating velocity of the wind rotor must be known to determine the load factor (figure 4). Division of the daily water demand by the load factor will yield the desired output rate of the pump. If this rate is greater than the maximum output of the type of pump selected, the need for a pump with greater output, a reduction in water demand or the use of more than one pump is indicated.

E. DETERMINATION OF THE RATED ENERGY REQUIREMENT OF PUMP

Determination of the rated energy requirement of the pump is calculated according to the following formulae:

$$E\ (\text{kW}) = \frac{M^3/\text{sec desired output}}{\text{Pump efficiency}} \ X \ \text{meters head} \ X \ 9.807$$

$$E\ (\text{hp}) = \frac{\text{U.S. gallons/sec desired output}}{\text{Pump efficiency}} \ X \ \text{feet head} \ X \ .0151756$$

F. DETERMINATION OF THE NEED FOR AN ORIENTATION MECHANISM

The need for an orientation mechanism is determined by analyzing the frequency of each wind direction. (figure 35) In many tropical and especially coastal areas the wind blows mainly in either of two opposite directions. In such cases a use of fixed axis rotor can save considerable construction expense. If an orientation mechanism is required the choice of manual or automatic orientation will depend on the frequency of change in wind direction.

IV. COMPONENT DESIGN AND MATCHING

Each of the many different types of wind energy conversion devices is composed of a combination of individual components which serve a precise function in the system. The primary factors determining the design of each component are; its function, physical stress as a function of wind velocity and energy load, materials available and skills and tools required to work with these materials. The matching of individual components into a system should aim to have all components able to withstand similar maximum stress loads and to have a minimum number of different materials, skills and tools necessary for assembly of the system.

Though many types of water pumping windmills are generally known, the construction details and performance characteristics of each component of these windmills is not documented. A detailed survey of component characteristics should be undertaken on an international scale in order to provide a "catalogue" of proven components which could be used in the design of new hybrid wind powered water pumping systems.

A. CONTROL MECHANISMS

Mechanisms to control rotor blade angle, blade area, pump stroke and stop the rotor should be incorporated into the design in order to allow the pumping system to operate under a maximum range of wind velocities without damage. The attack angle of rigid blades may be controlled by centrifugal governors or blade coning. Attack angle of non-rigid sail blades is controlled by manual or spring adjustment of the trailing edge tension. Area of sail blades is controlled by furling. Pump stroke can be adjusted by changing the fulcrum point of a lever (figure 7).

B. ROTOR RADIUS

The radius of the rotor depends on the cube of the rated wind velocity, rotor efficiency, power transfer efficiency and the energy requirement of the pump (E) according to the equation.

$$E = (K \times 3.14 \times R^2 \times V^3) \times 0.5926 \times (eff_r \times eff_t)$$

Where E = rated energy requirement of the pump in kilowatts

K = the constant 0.0000137

R = rotor radius in meters

V = wind velocity in km/hr

0.5926 = theoretical maximum wind energy extraction by ideal rotor

eff_r = efficiency of rotor assuming 100% eff. for ideal power

eff_t = efficiency of power transfer

The maximum size of the rotor will often by limited by the maximum length of spar material available or by the height of tower materials. For safety reasons the lowest point of the rotor should be at least 1.8 meters above ground.

C. PUMP SIZE

The size of the pump is a direct function of the rated output, speed of operation and efficiency. Materials or power available will usually determine the maximum pump size.

D. POWER TRANSFER MECHANISMS

The function of the power transfer mechanism is to transfer the rotary motion of the wind rotor to the pump. The design of the power transfer mechanism depends upon the type of pump used (reciprocating or rotary motion) and the type of rotor (horizontal or vertical axis). For rotary pumps, differences in speed within a range of 4:1 between rotor and pump can be compensated for by single step pully or gear transfer. Additional transfers are undesirable because of efficiency losses. Rotary motion of the main horizontal shaft can be converted to vertical rotary motion by gears and transferred to ground level by a rotating power shaft. A recycled automobile rear end gear differential can be efficiently and cheaply used for this purpose, with the benefit of a 4:1 speed increase. Horizontal rotary motion of the main shaft can be transferred to horizontal rotary motion at the ground by the use of an upper and lower pully and a steel chain or cowhide belt. Several advantages to this method are that construction is cheap and easy, optimum pump speed can be obtained by careful calculation of pully diameters and it is not necessary to have the chain or belt pass through the centre of the turntable. Vertical reciprocal motion is usually created by a crankshaft and passed down through the centre of the turntable to the pump by a steel or wooden connecting rod, which incorporates a swivel to prevent the rod from being twisted when the carriage assembly and shaft turn in response to change in wind direction.

/It

It is desirable to keep the stroke of a crankshaft as small as possible in order to minimize turntable diameter. However with commonly available piston pumps it is desirable to make the stroke as long as possible. The apparent conflict between small crankshaft stroke and large piston stroke can be resolved by multiplying the stroke with a lever as shown in figure 7.

E. ORIENTATION MECHANISM

The orientation mechanism allows the rotor to be pointed into the wind. This can take the form of a classic tail vane for automatic orientation or, where changes in wind direction are not frequent, a manually operated tail rope as in Thai wooden blade windmills, (figure 15) or manually shifted 'A' frame axis supports as in the Dutch tjasker figure 33 and Chinese diagonal axis rotor figure 36.

The function of the turntable is to allow the rotor, mainshaft and carriage assembly to rotate only about a fixed point in a horizontal plane on top of the fixed tower and prevent any vertical or horizontal movement. Vertical power transfer usually passes through the centre of the turntable, however considerable savings in turntable construction cost may be achieved by having the power transfer outside the turntable as in Thai wind pumps.

Multiblade windpumps incorporate a ball bearing turntable but a simple greased circular steel ring has proved adequate for Greek wind pumps. The Thai wooden high speed rotor windpump uses simply a tapered wooden post inserted into a wooden hole with the power going down outside the post (figure 15).

F. HUB, MAINSHAFT, BEARINGS

Selection of hub, main shaft and bearings is most important because rotor load stresses are concentrated on these components.

1. The function of the hub is to connect the root end of the rotor spars firmly to the main shaft. The hub must withstand the centrifugal force of rotor, and bending loads of the rotor spar caused by wind pressure and rotor torque. By keeping the blade weight and tip speed ratio low the centrifugal forces on the hub will be considerably reduced. These forces indicated in figure 37 are quantified by the following formulae.

(a) Centrifugal force (kg) $= \dfrac{0.0283 \times W \times (U/V \times 0.2784 \times V)^2}{R}$

Where W = weight of the blade in kg

U/V = tip speed ratio at the centre of gravity of the blade

V = wind velocity in km/h

R = radius from centre of hub to centre of gravity of the blade.

/(b)

(b) Wind pressure P (kg) on a spinning rotor = $(0.0012\ (kV)^2) \times (1.42 \times R^2)$ Where P is in kg, K = constant 0.914, V = wind velocity in km/h, R = rotor radius in meters.

(c) The wind pressure on non-spinning rotor = 2 x P x solidity where P = wind pressure on spinning rotor, solidity = ratio of blade frontal area to total swept rotor area.

(d) Torque is the twisting force as a result of blade lift that is applied a certain radius from the centre of rotation. Torque (T) is calculated according to the following formula:

$$T = \frac{1210 \times D \times kW}{U/V \times 0.9134\ V}$$

Where T = foot-pounds torque, D = rotor diameter in meters, kW = power output of blades at V, U/V = tipspeed ratio at tip, V = wind velocity in km/h. These forces should be calculated for the highest wind velocity below that at which the control mechanism is actuated.

2. The main shaft must bear the weight of the rotor and withstand the torque and bending forces applied by the power transfer mechanism. The shaft may be made from wood, steel rod or steel pipe.

3. Simple wooden bearings or steel ball or thrust bearings may be used. If steel bearings are used adequate protection must be given against dust and rain. Wooden bearings should be easily replaceable. Provision must be made for lubrication.

G. TOWER

Determination of the type of tower is primarily a function of the materials and skills available. The Windworks octahedron module design (figure 10) has the highest strength to weight ratio of any non-guyed tower, however construction is complex and must be precise, steel truss towers (figure 6) are very strong and well proven but are quite expensive, single wood pole towers (figures 8, 15, 42) are the cheapest but can only be used when it is not necessary to have the power transfer down the centre of the tower. Multiple wood pole towers (figure 7) are cheap, strong, and easy to construct. They are limited primarily by their resistance to wood ants and termites. The use of guy wires when possible will significantly increase tower strength at little cost.

The minimum tower height should be at least rotor radius (R) + 1.8meters. Efforts to make the tower higher than this should be avoided because the increase in cost of additional tower height is greater than the increase in wind velocity with height except in locations with nearby wind obstructions.

/H.

H. CARRIAGE ASSEMBLY

The carriage assembly functions primarily to provide a firm foundation for the main shaft bearings. It may be built of wood or steel. It must be fastened to the turntable so that it may turn in response to changing wind direction. The tail is fastened to the carriage assembly.

I. STORAGE TANK

Maximum capacity of the storage tank is determined by multiplying the longest period of wind below starting velocity by the daily water demand. Storage above ground is uneconomical unless pressure supply is imperative. A ground level tank is most inexpensively constructed of stone masonry no greater than one meter height. Possible multiple use of the storage tank for bathing and fish culture should be taken into consideration.

J. WORKING DRAWINGS, MODEL

After preliminary sketches of each component have been prepared. The final working drawings should be made, showing the details of and connections between each component.

A 1/5 scale model should be made and tested in order to perfect the design and to gain familiarity with the construction process. Only after a model has been tested to satisfaction should construction of a full scale prototype proceed.

V. A HYBRID ASIAN WIND POWERED WATER PUMP

The following discussion will give an example of the design of a low cost wind powered water pump according to the sequential flow design process outlined above. An effort has been made to base the design on conditions common to many parts of Asia.

A. PRELIMINARY INVESTIGATION

1. Survey of local wind characteristics

The average wind velocity at Don Muang Airport, Bangkok, for 5 minutes of each half hour is routinely recorded by the Meteorological Department of Thailand. These data for the months of March, April, May 1975 have been summarized in figure 38. The data are further reduced for analysis in figure 39 (velocity frequency curve), figure 40 (power frequency curvey) and figure 41 (power duration curve). Data from Don Muang Airport were selected because of its exposed location in a rice growing area and its proximity to the Asian Institute of Technology and the proposed National Energy Administration (NEA) windmill test location.

2. Survey of local water pumping needs

March, April and May were chosen as the period when irrigation pumping is most required because the first crop of rice is already harvested by February and the fields are usually unused till the onset of the monsoon in June. Rainfall during this period is slight.

3. Classification of wind rotors and pumps

Lacking a complete classification of wind rotors and pumps, previous sections of this report will be referred to.

B. DATA ANALYSIS AND CRITICAL DECISIONS

1. Wind data anlysis

(a) A Study of velocity and power frequency curves indicates an optimum starting velocity of 6 km/hr and optimum rated velocity of 20 km/h in order to obtain maximum output.

(b) Study of raw wind data indicates that the longest period of wind below optimum starting velocity of 6 km/h is 6 hours.

(c) Study of the wind power rose (figure 35) indicates that an orientation mechanism would be useful but not necessary, however for the benefit of other areas with more variable wind direction it is assumed that there is a need for an orientation mechanism.

(d) Analysis of the power duration curve yields a load factor of 0.30.

2. Selection of rotor

Based on the widespread success, low cost and light weight of the Greek sail rotor, this configuration was selected (figure 38). An alternative configuration that may be used in areas of higher wind speeds is based on the Princeton sail wing (figure 39).

/3.

3. Selection of pump

For generalized design purposes a total head of 10 meters is assumed. Owing to its simplicity of construction and adaptability to variable low speed rotary motion the steel disc chain pump was selected (figure 29). The square pallet chain pump may however be best for areas where this pump is traditionally widely used and only a lowlift is required.

4. Determination of desired pump out rate

Assuming a daily requirement of 6.5 mm/day for rice cultivation and a desired irrigated area of 2 hectares the daily water demand is 130 m^3/day multiplication by the reciprocal of the load factor indicates that rated capacity of the pump should be 18 m^3/h.

$$\frac{1}{0.30} \times 130 \text{ m}^3 \div 24 = 18.06 \text{ m}^3/\text{h}.$$

5. Determination of rated energy requirement of the pump

Assuming 70% pump efficiency, the rated energy requirement of the pump is 0.703 kW.

$$E\,(\text{kW}) = \frac{0.00502}{0.70} \times 10 \times 9.807 = 0.703$$

C. <u>COMPONENT DESIGN AND MATCHING</u>

1. Control mechanism

Assuming frequent presence of the operator, furling of the sails will be the primary control mechanism. An emergency sail release mechanism similar to that used on Thai sail rotors will be incorporated (figure 38).

2. Size of rotor

$$0.703 \text{ kW} = (0.0000137 \times 3.14 \times R^2 \times 20 \text{ kph}^3) \times 0.5926 \times (.25 \times .50)$$

Where: 0.703 is the rated energy requirement of the pump.

20 km/h is the assumed rated velocity of rotor

0.25 and 0.50 are the assumed efficiency of the rotor and power transfer respectively.

Therefore : $0.703 = 0.02548\, R^2$

$R^2 = 27.59$; $R = 5.25$ m;

Rotor diameter = 10.5 meters.

This size is within the range of bamboo spars available in Thailand and most Asian places. Sail rotors have been operated successfully up to 10 m diameter so this size is acceptable.

3. Size of pump

Given the rated output of 18 m^3/h of a 70% efficiency chain pump the basis of calculation is 25.714 m^3/h. Assuming a rated rotor speed of 12 rpm with a 2:1 speed increase and a 0.5 m diameter pump drive wheel, the size of the pipe within which water is lifted by the washers on the chain should be 12.03 cm. The size of the pipe may be decreased by increasing the speed of the chain which may beeffected by greater drive speed ratio, or by increasing the diameter of the pump drive wheel. The optimum speed of chain pumps is unknown.

(a) 1.571 x 24 = 37.70 m/min chain travel, x 60 = 2262 m/h

25.714 m^3/h ÷ 2262 m/h = 0.01137 m^2 cross sectional area of pipe opening.

Therefore: inside diameter of pipe = 12.03 cm.

4. Orientation mechanism

Orientation of the main shaft by manual relocation of an "A" frame support structure (figure 42) supporting one end of an extended shaft is suggested because of its simplicity and proven feasibility on the Dutch tjasker (figure 33) and Chinese diagonal axis (figure 36) wind rotors. The opposite end of the shaft rotates about a fixed, guyed turn post (figure 41).

5. Power transfer mechanism

Because horizontal rotary motion is required to operate the chain pump only a simple direct pulley drive to ground level is required. Pulley wheels made of several laminations of wood boards are suggested (figure 40). Chain is suggested as a durable pulley belt. This method is widely used on both the Thai high speed and sail rotors.

6. Hub, main shaft and bearings

(a) A laminated wooden hub was selected (figure 44) because of its simplicity of construction and successful use on Thai sail rotors.

(b) An extended square wooden main shaft is successfully used on Thai sail rotors and has been selected for this hybrid design (figure 44). The shaft is rounded only at the points where it rests in the bearing (figures 40, 43).

(c) Simple wooden bearings have been well proven on Greek and Thai sail rotors and Australian "Comet" wind powered pumps. An improved version of Greek wood bearings with increased bearing surface and provision for lubrication has been designed for both main bearings (figures 40, 43).

7. Tower

The "tower" in this case consists only of the 2 legs of the movable "A" frame at one end of the shaft and the turn post at the other end. The turn post is guyed to the ground and the "A" frame is guyed to the base of the turnpost so that it is stabilized and still free to move.

8. Carriage assembly

In this hybrid design the large wooden bearings blocks function also as the carriage assembly.

9. Storage tank

Because the longest period of wind below starting velocity is only six hours a storage tank is not considered necessary though it would be useful for better irrigation control.

10. Final drawings

An overall sketch of this hybrid design (figure 45) is proposed as the basis for construction of models for testing only. For further development of this design, model test results should be evaluated and design modifications incorporated into final working drawings.

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(Knots) V	0	1	2	3	4	5	6	7	8	9
(km / hr) V	0	1.85	3.70	5.55	7.41	9.26	11.11	12.96	14.81	16.67
(Hours duration) T	291	32	619	331	857	387	604	219	517	92
(km/hr) $V^3 \times T$	0	202	31,354	56,585	348,687	307,287	828,281	476,714	1,679,402	426,180

(Knots) V	10	11	12	13	14	15	16	17	18	
(km / hr) V	18.52	20.37	22.22	24.07	25.93	27.78	29.63	31.48	33.33	
(Hours duration) T	293	23	104	25	14	5	1	0	2	
(km/hr) $V^3 \times T$	1,861,187	194,401	1,140,943	348,631	244,081	107,193	26,013	0	74,052	

Figure 2. Summary of .5 hourly wind velocity readings at Don Moung airport, Bangkok for March, April, May 1975

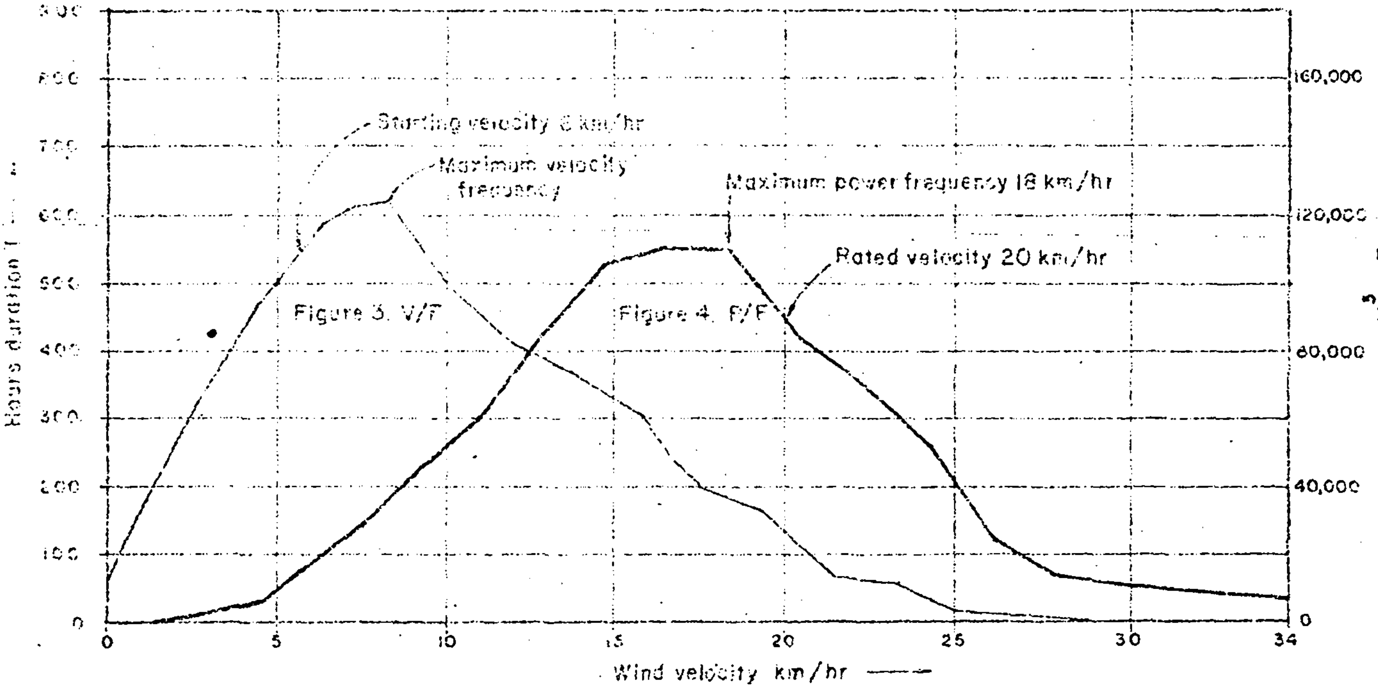


Figure 3. Velocity/Frequency curve, Figure 4. Power/Frequency curve

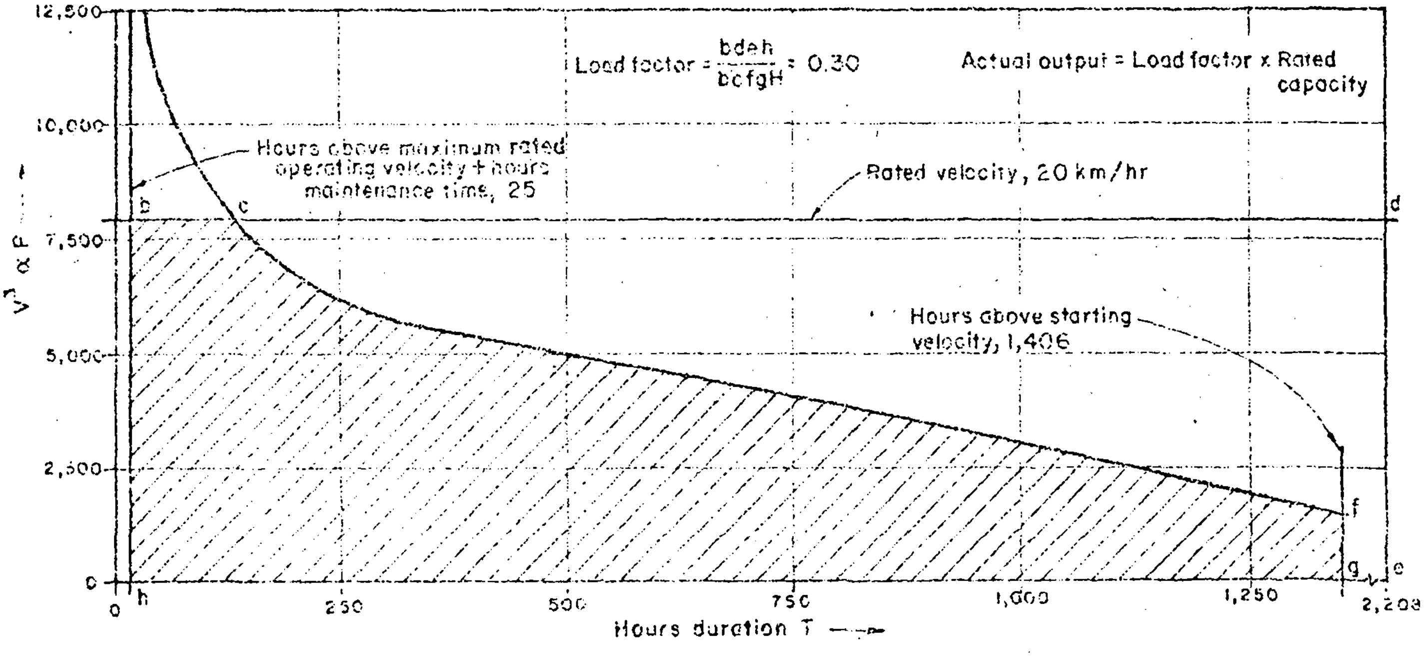


Figure 5. Power/duration curve

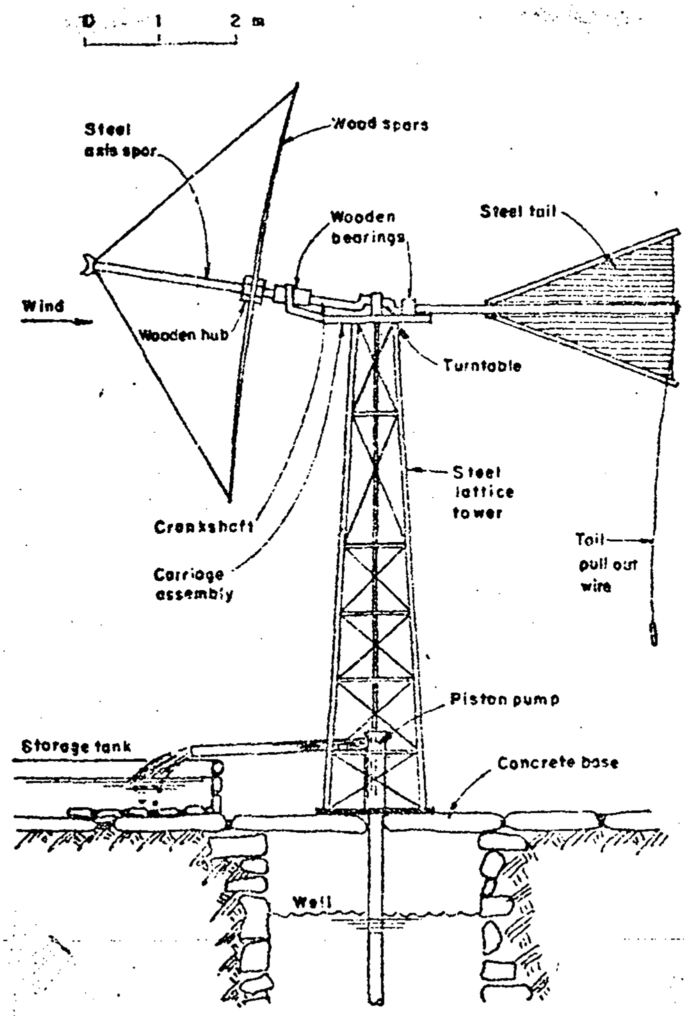


Figure 6. Greek sail rotor pump 1/

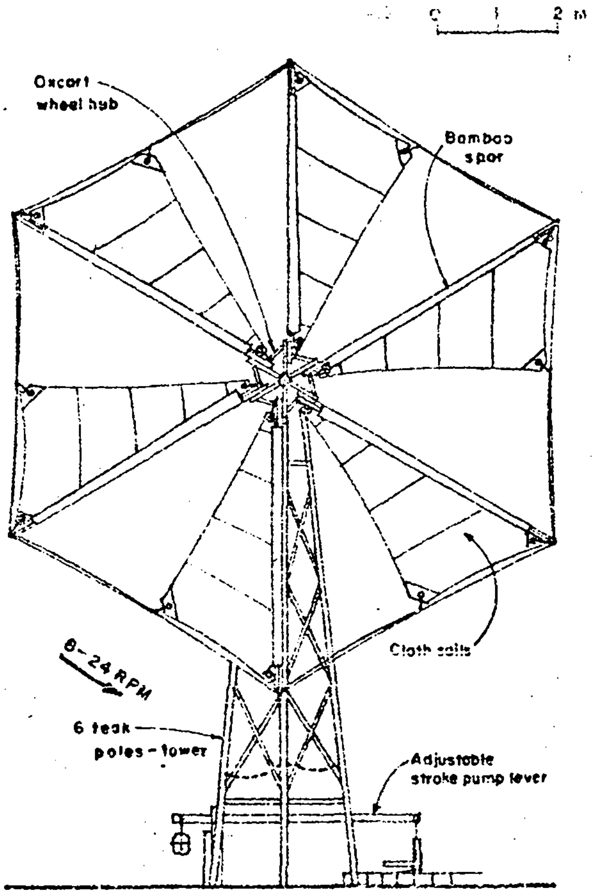


Figure 7. Madurai prototype sail rotor water pump 35/

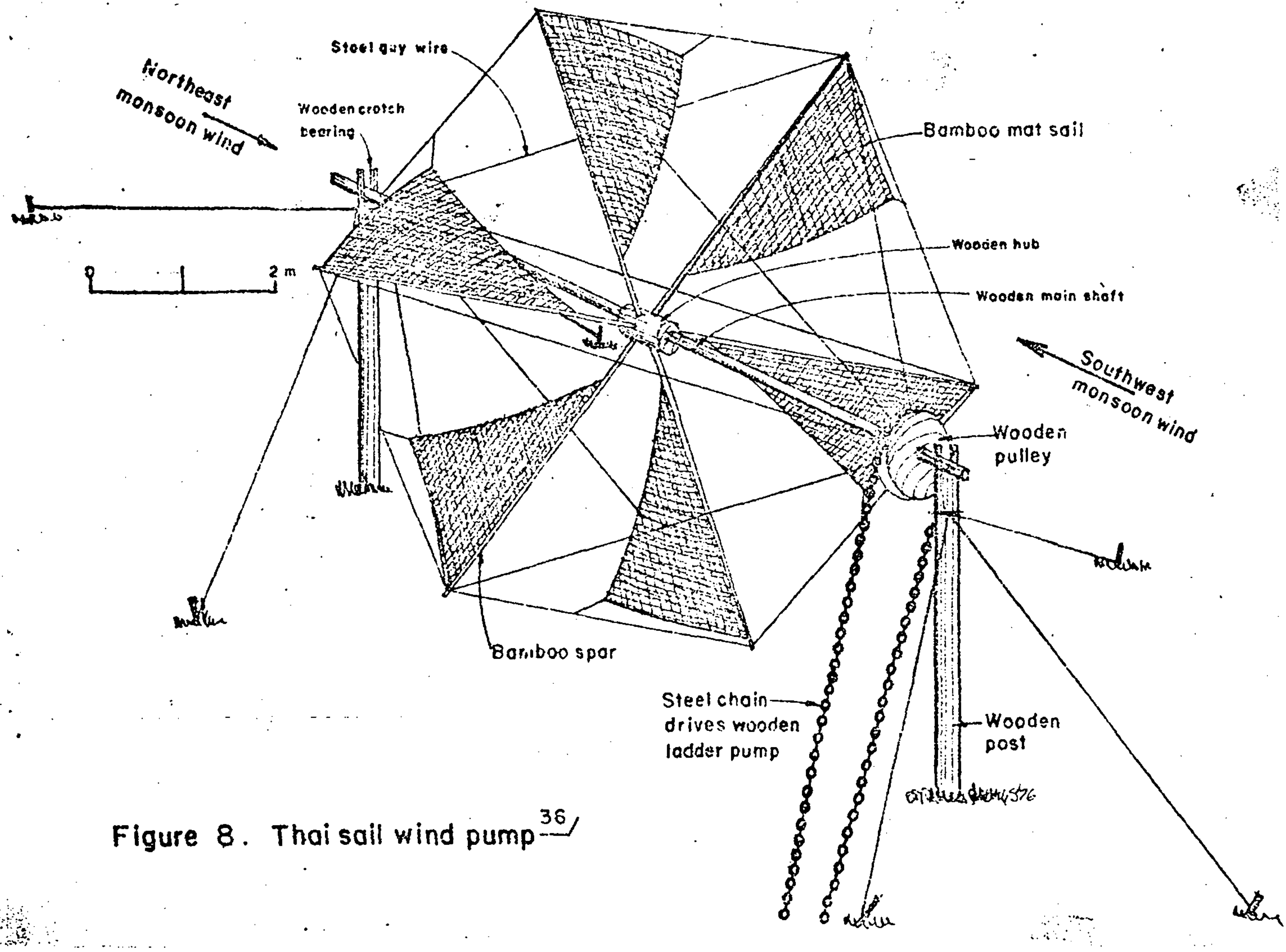


Figure 8. Thai sail wind pump 36/

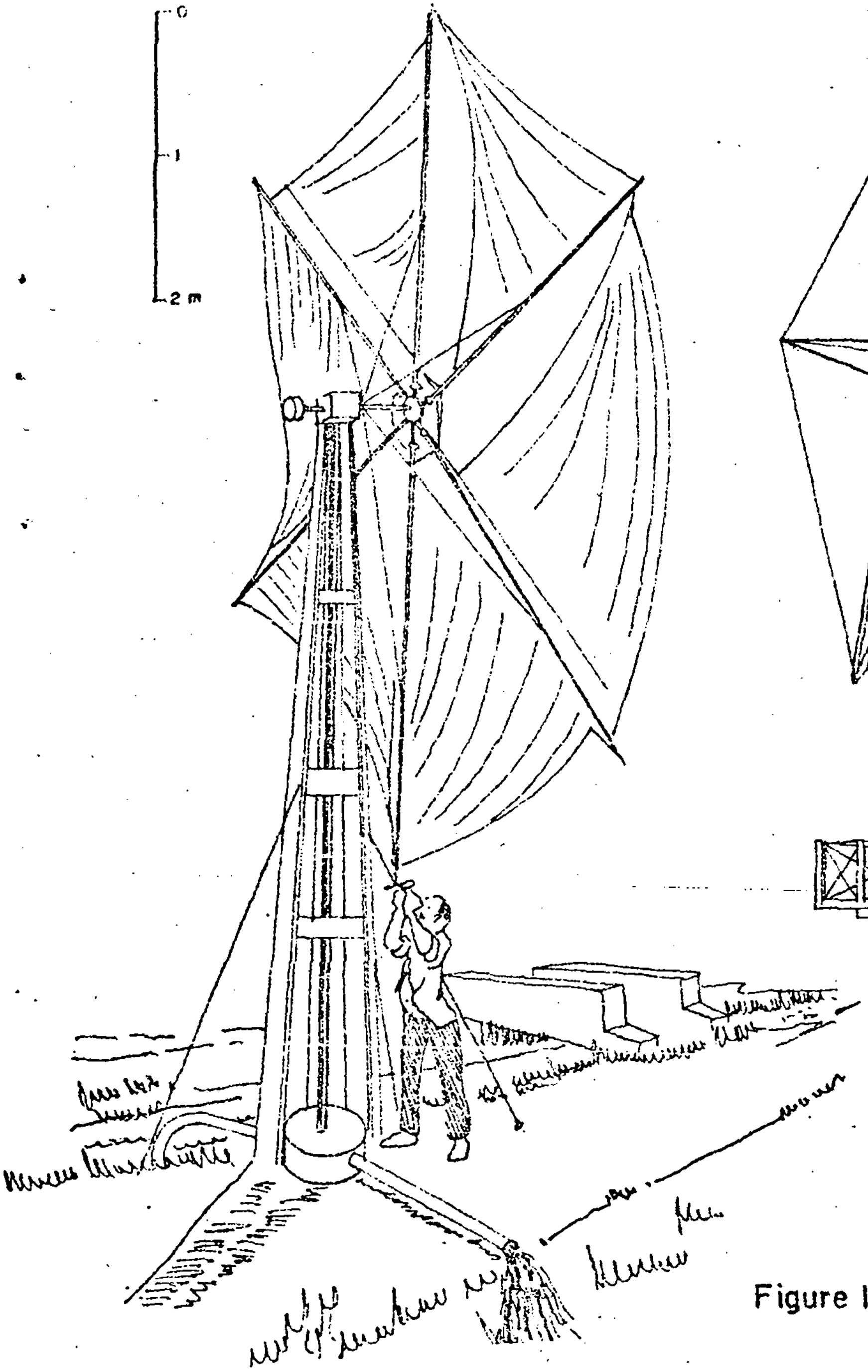


Figure 9. Malaysian Agricultural Research and Development Institute downwind sail rotor water pump 10/

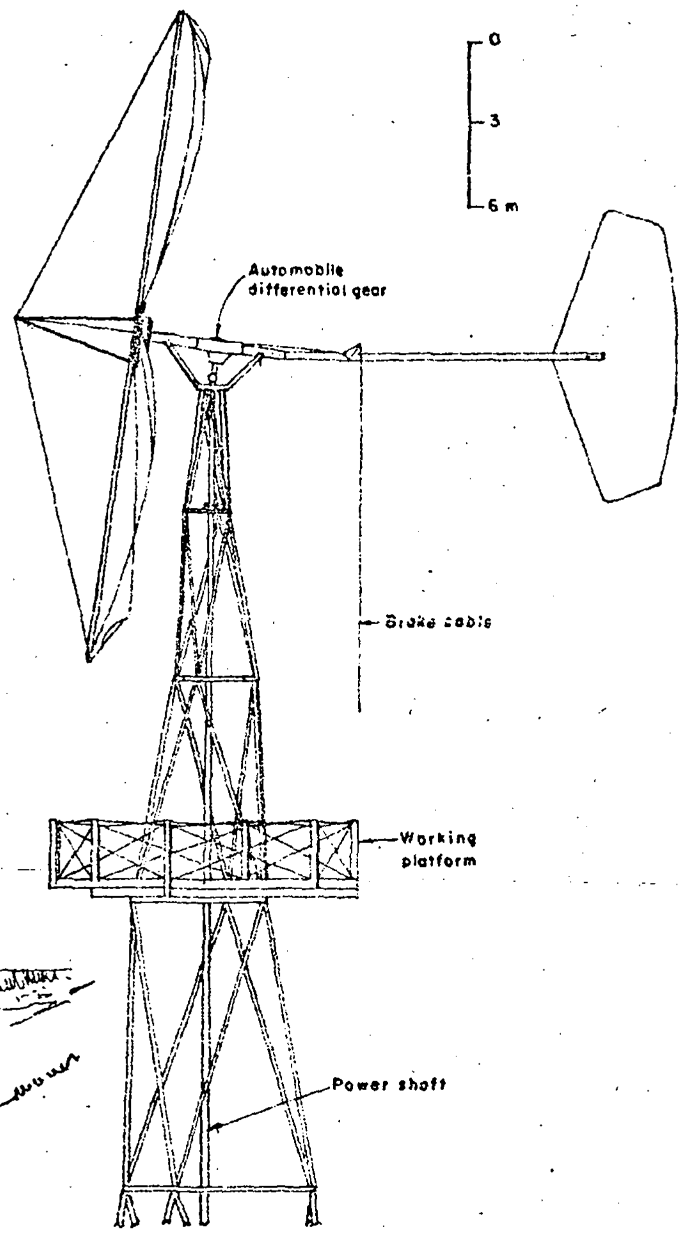


Figure 10. Brace Institute-Windworks sail rotor with Octahedron module tower 7/

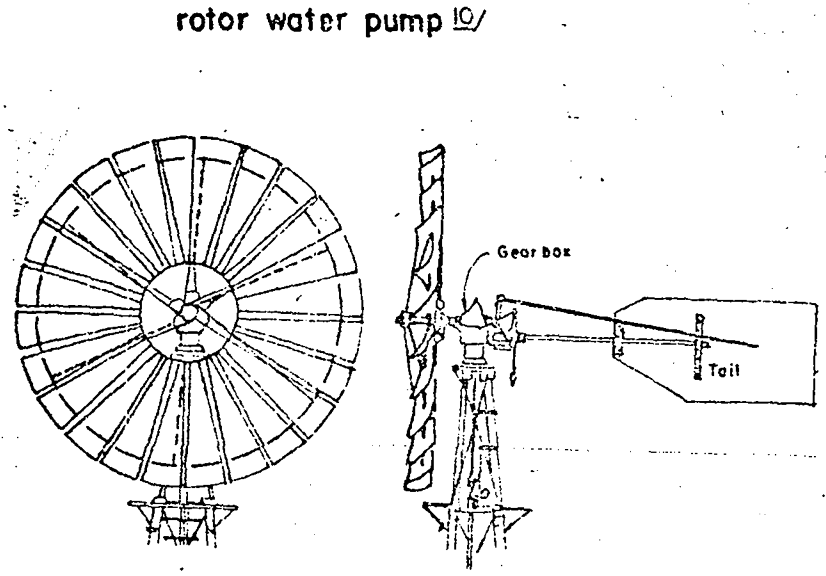


Figure 11. Multiblade metal rotor 36/

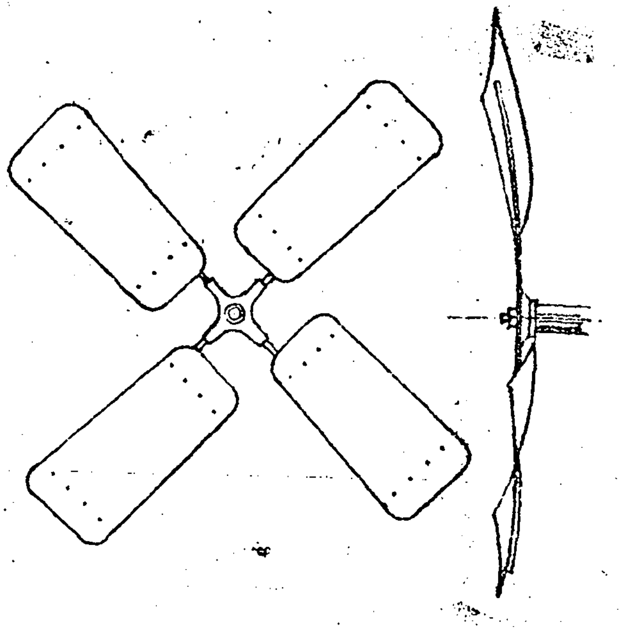


Figure 12. 4 Blade metal rotor 36/

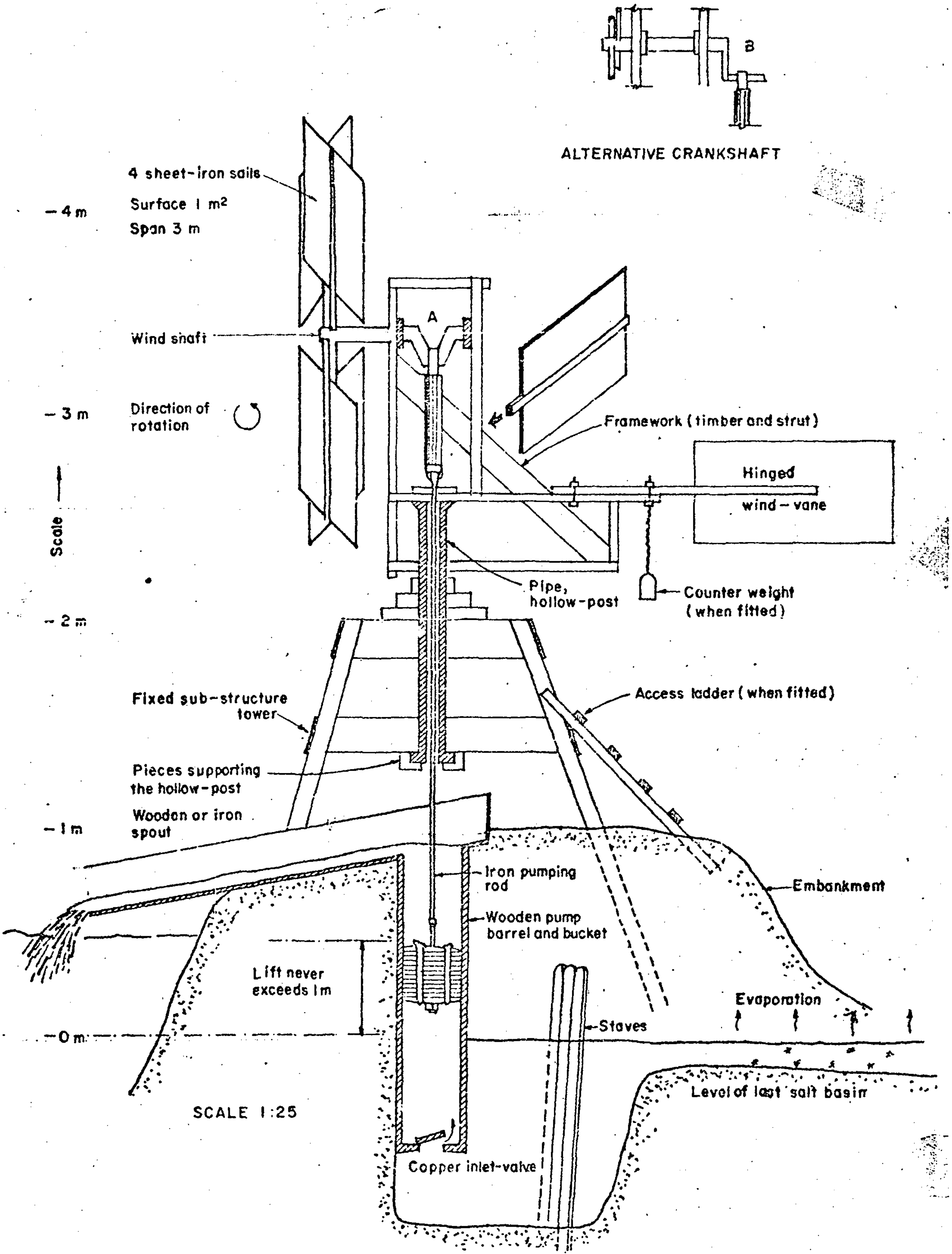


Figure 13. 4 Blade metal rotor salt makers wind powered water pump at Ile de Noirmoutier, France 38/

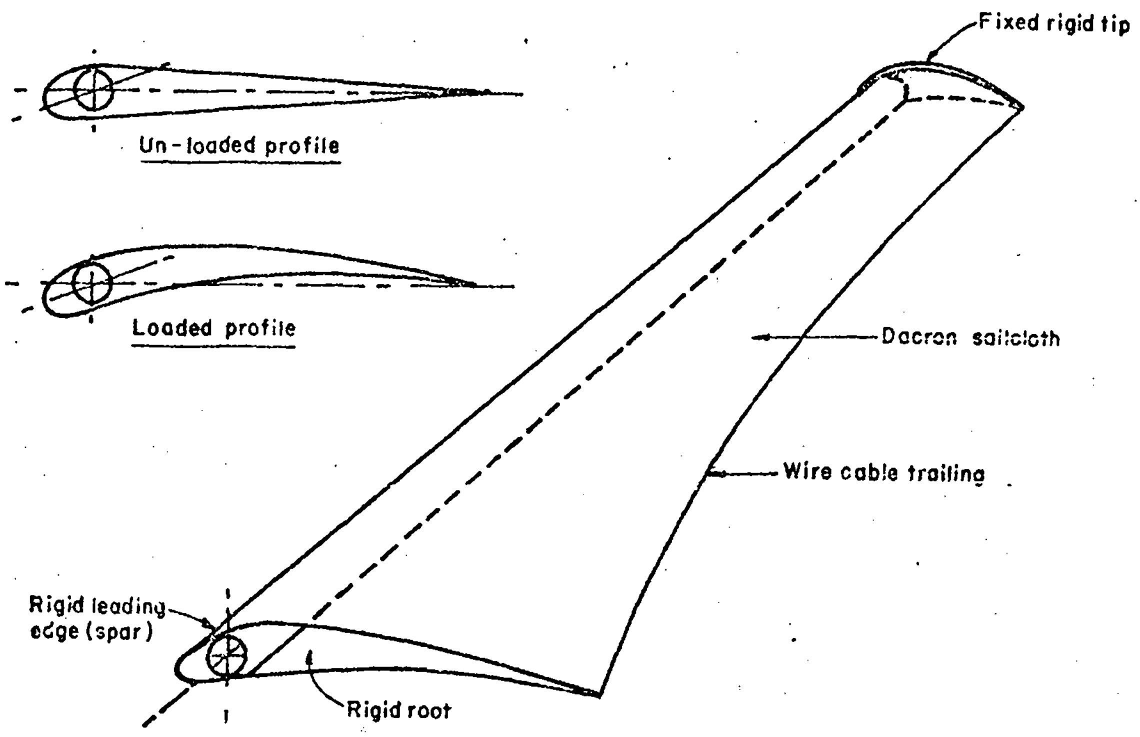


Figure 14. Princeton sail wing rotor blade [38]

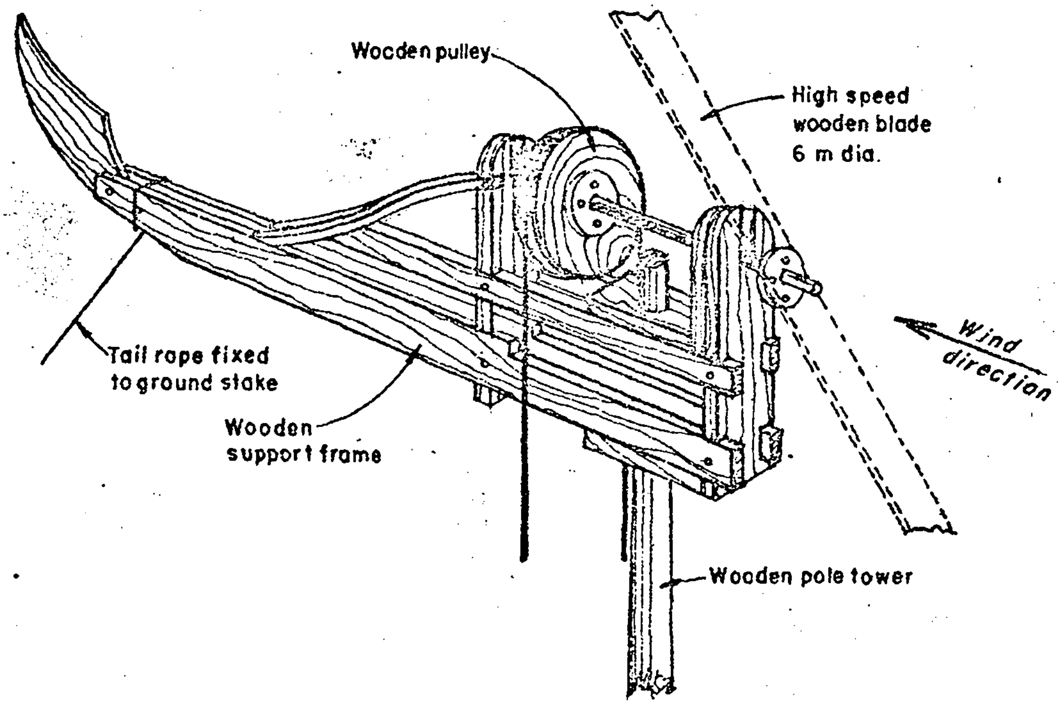


Figure 15. Thai highspeed rotor wind powered water pump wooden mounting assembly

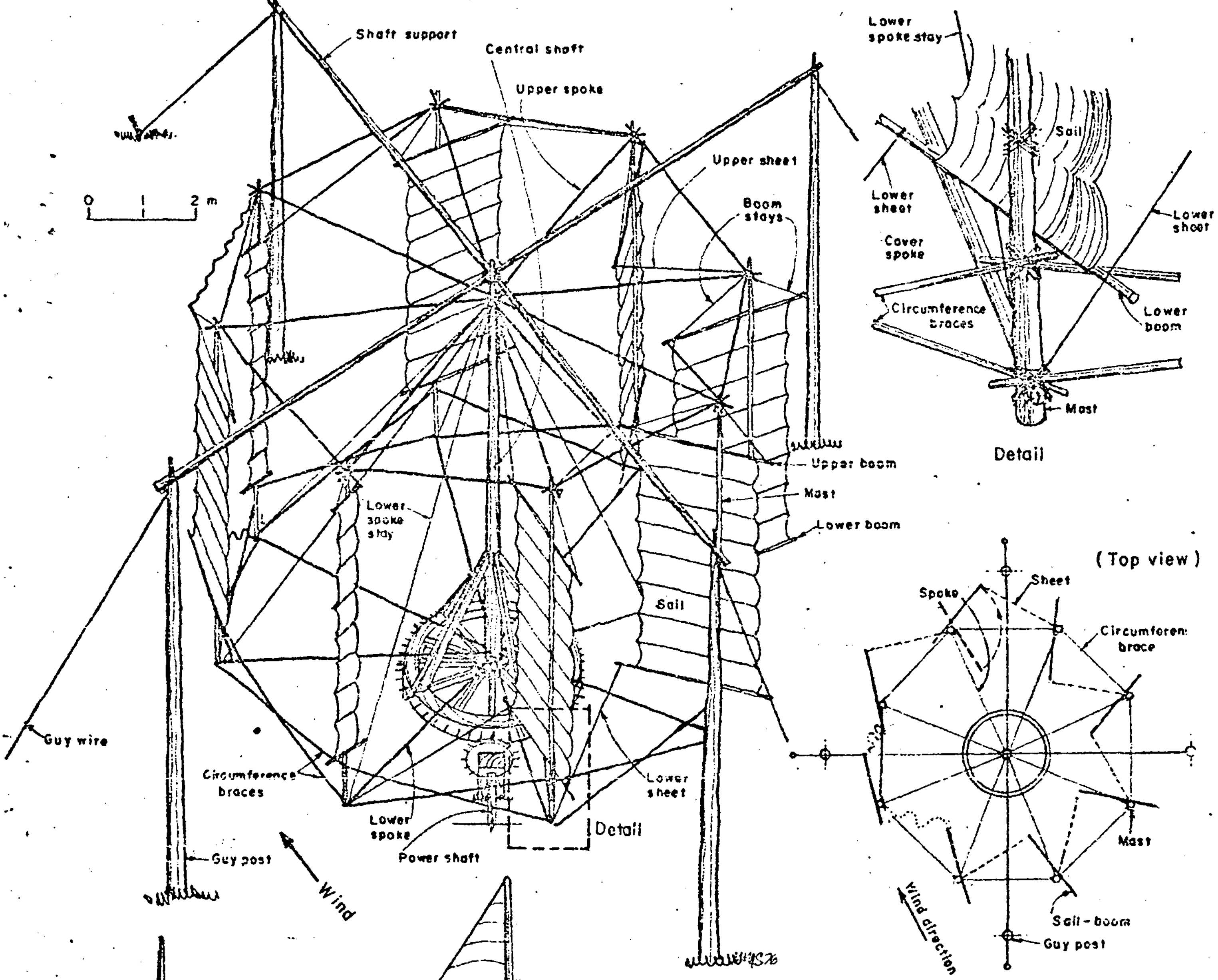


Figure 16. Chinese vertical axis roter (and supporting system) 5/

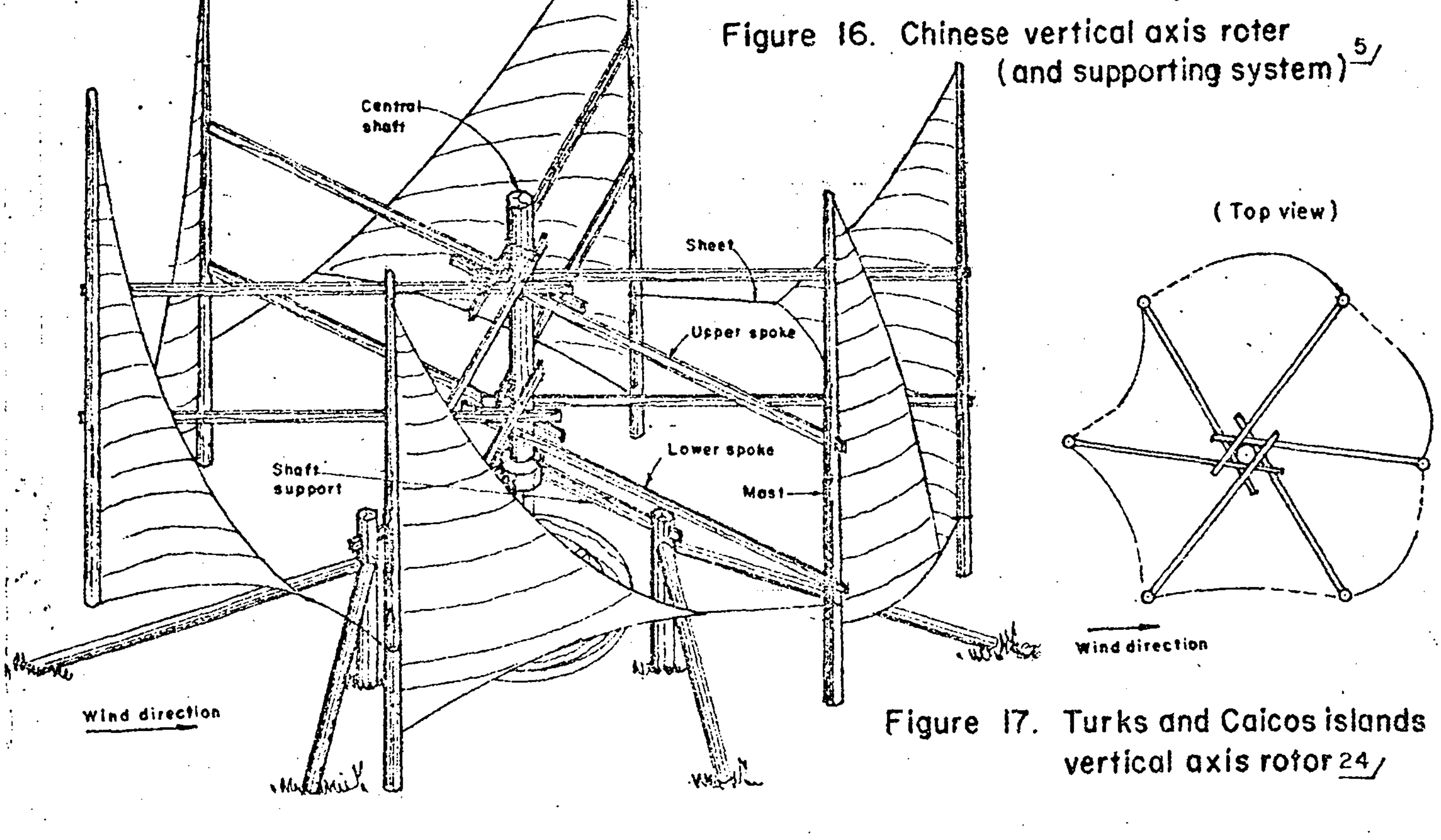


Figure 17. Turks and Caicos islands vertical axis rotor 24/

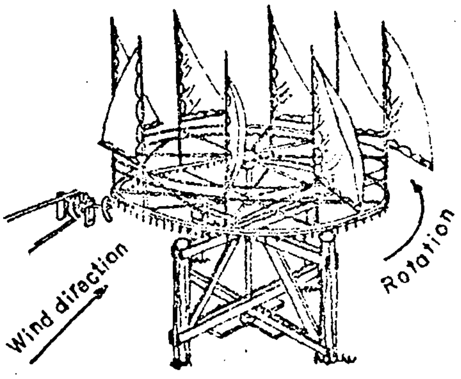


Figure 18. Thai jib sail rotor 3/

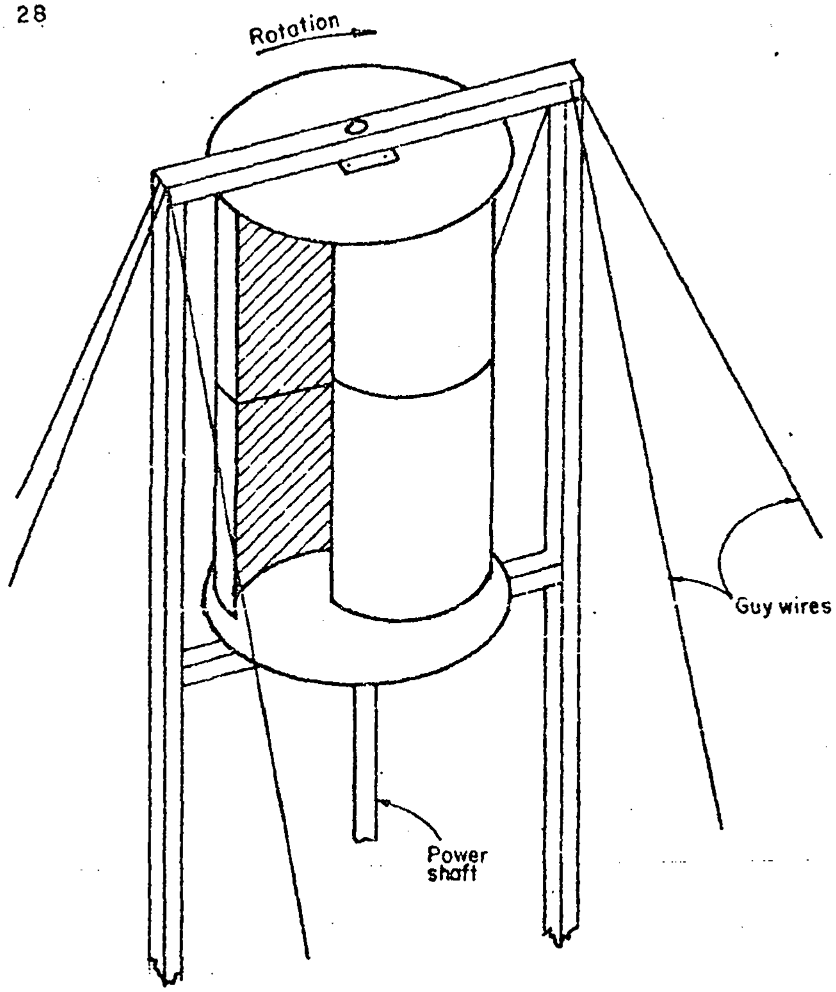


Figure 19. Savonius rotor 33/

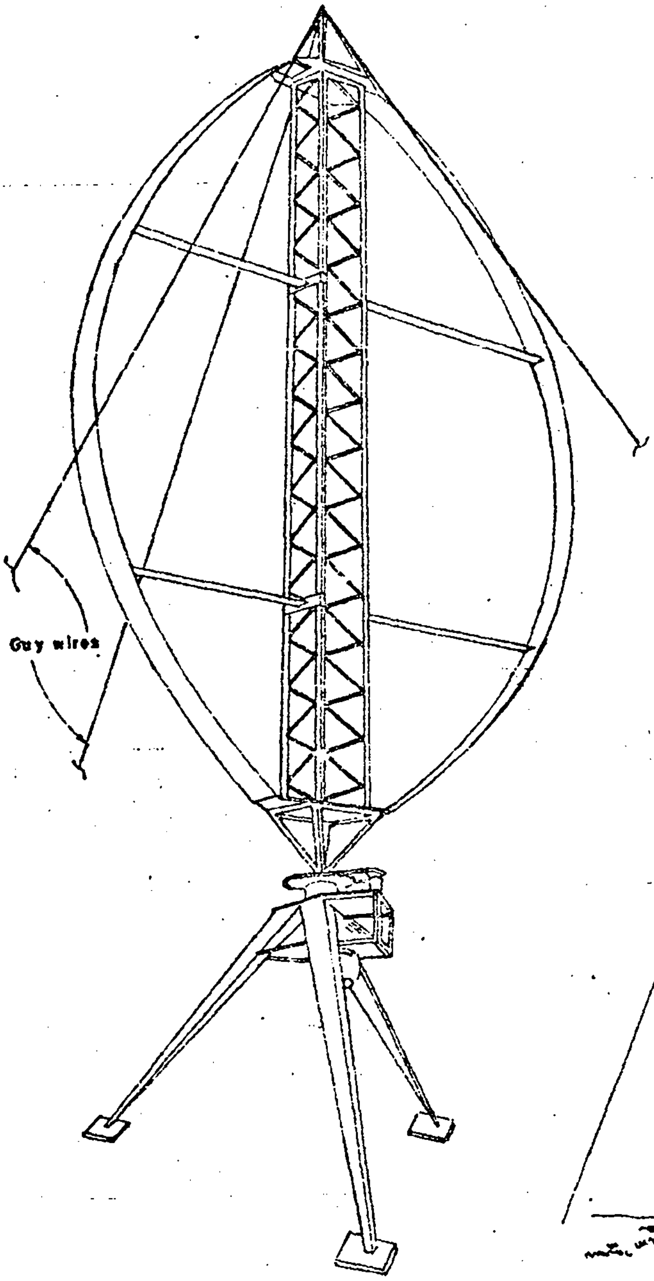
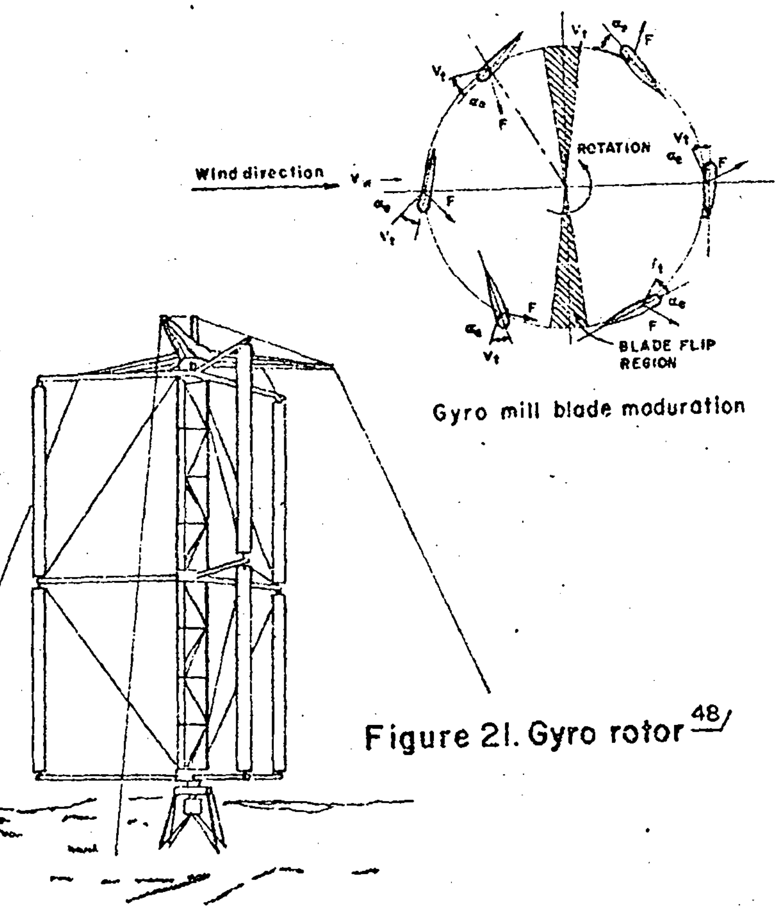


Figure 20. Darrius rotor 41/



Gyro mill blade moduration

Figure 21. Gyro rotor 48/

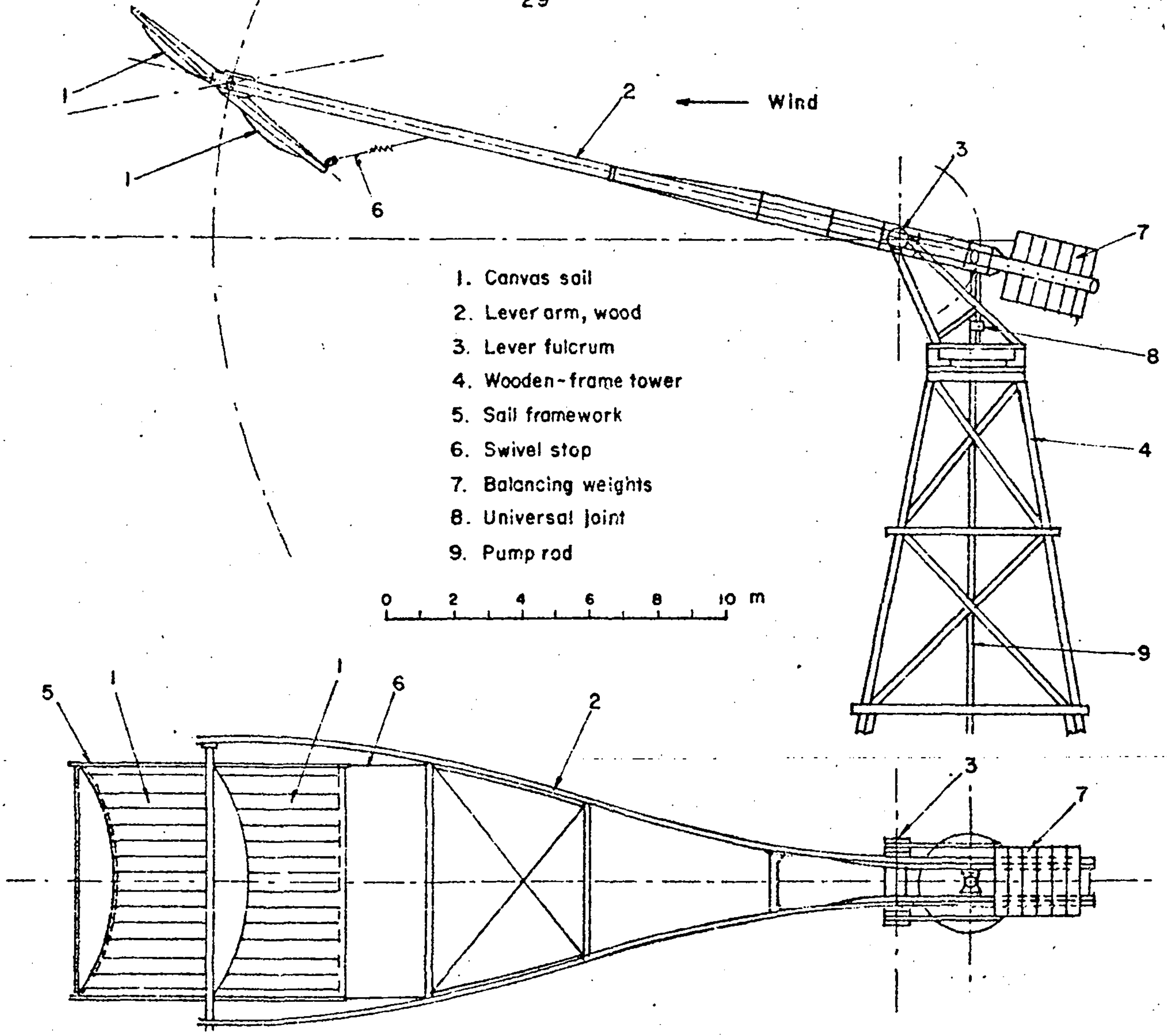


Figure 22. Flaping-vane pump 29/

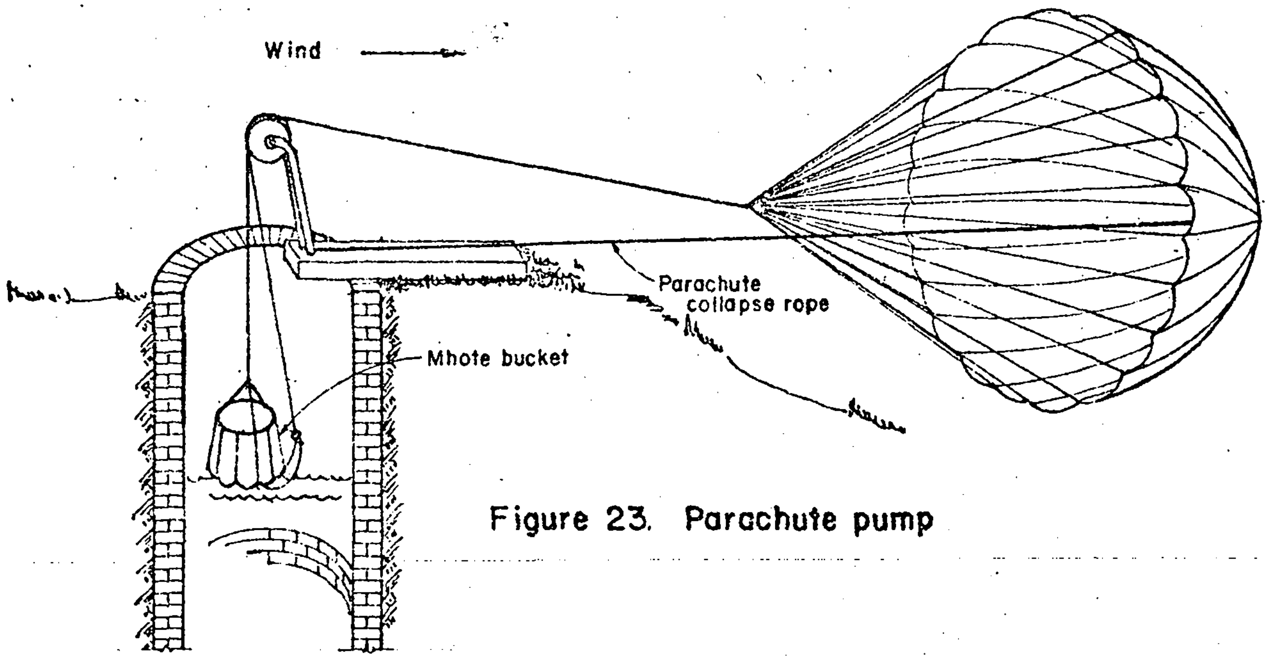


Figure 23. Parachute pump

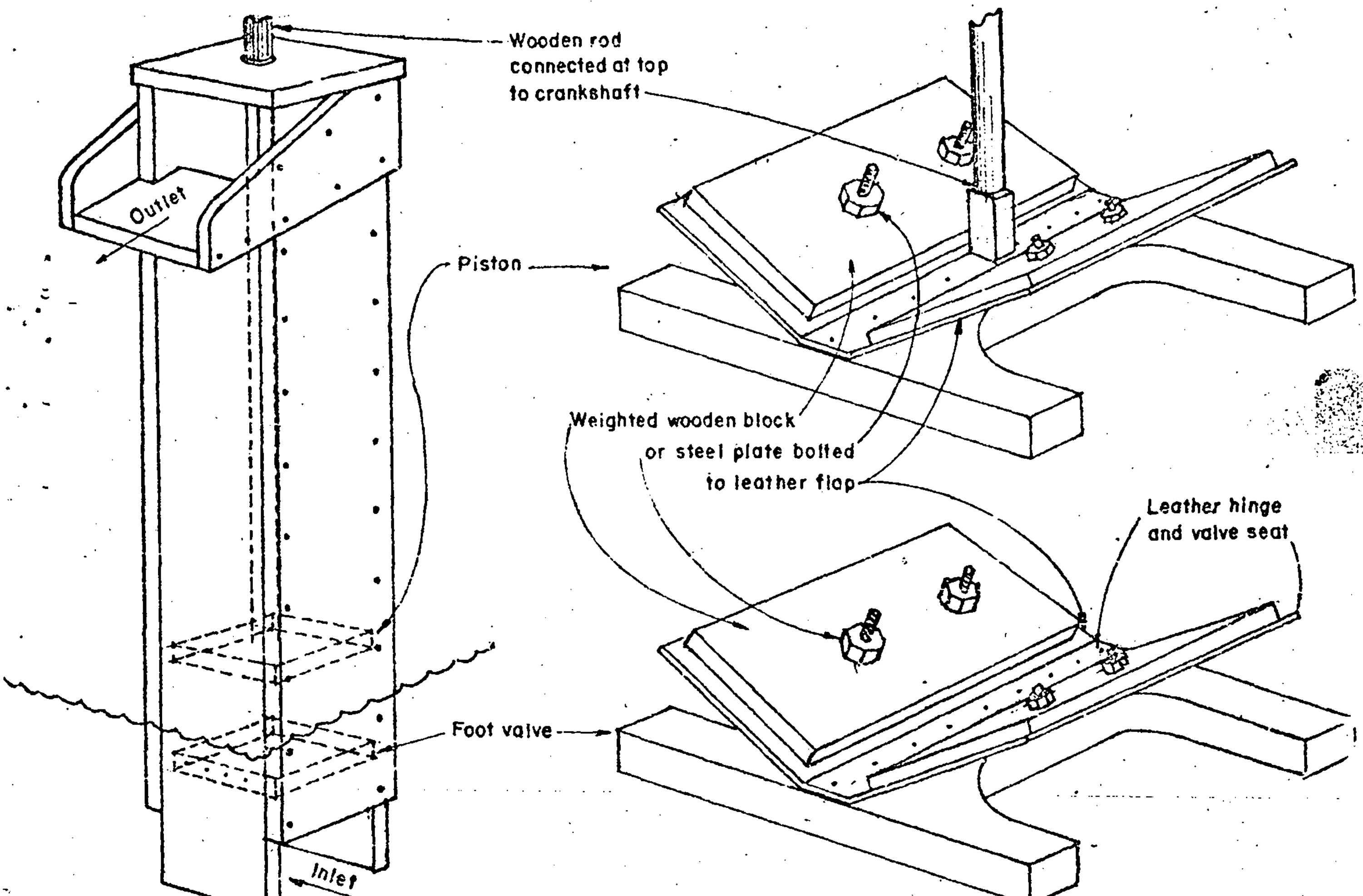


Figure 24. Square wooden piston pump

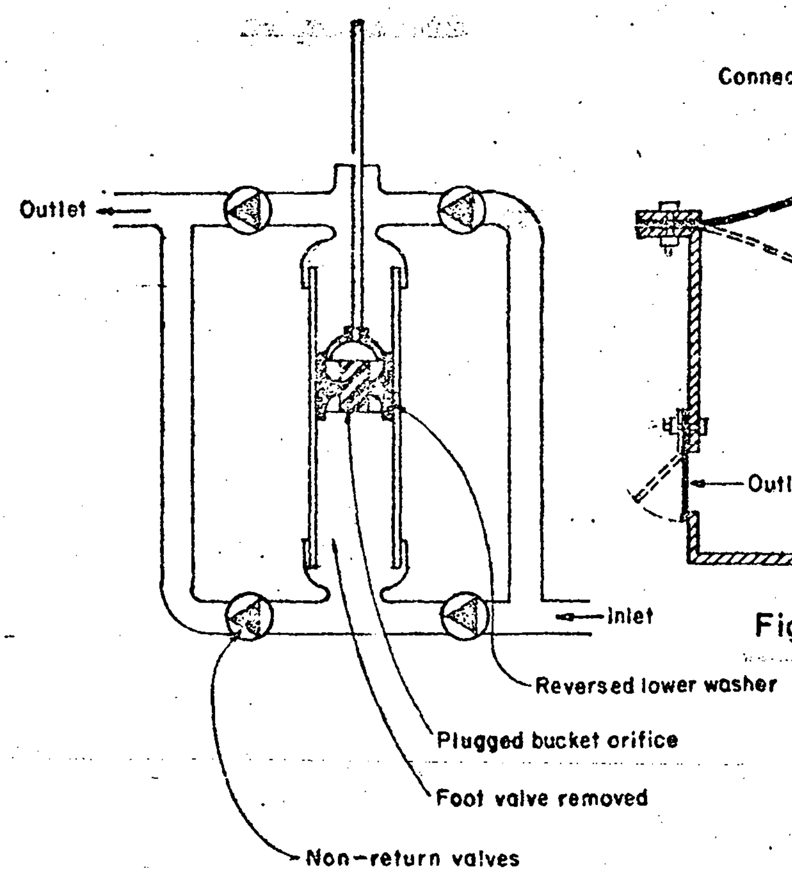


Figure 25. Double acting piston pump[11]

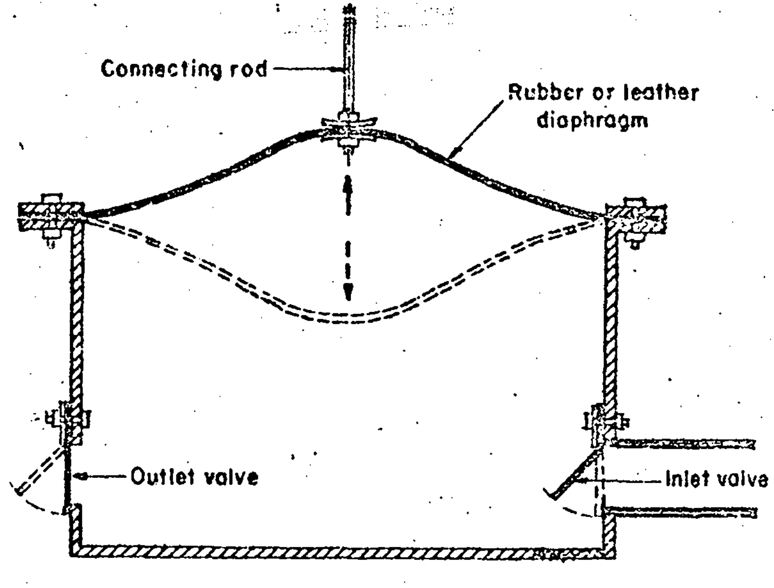


Figure 26. Diaphragm pump

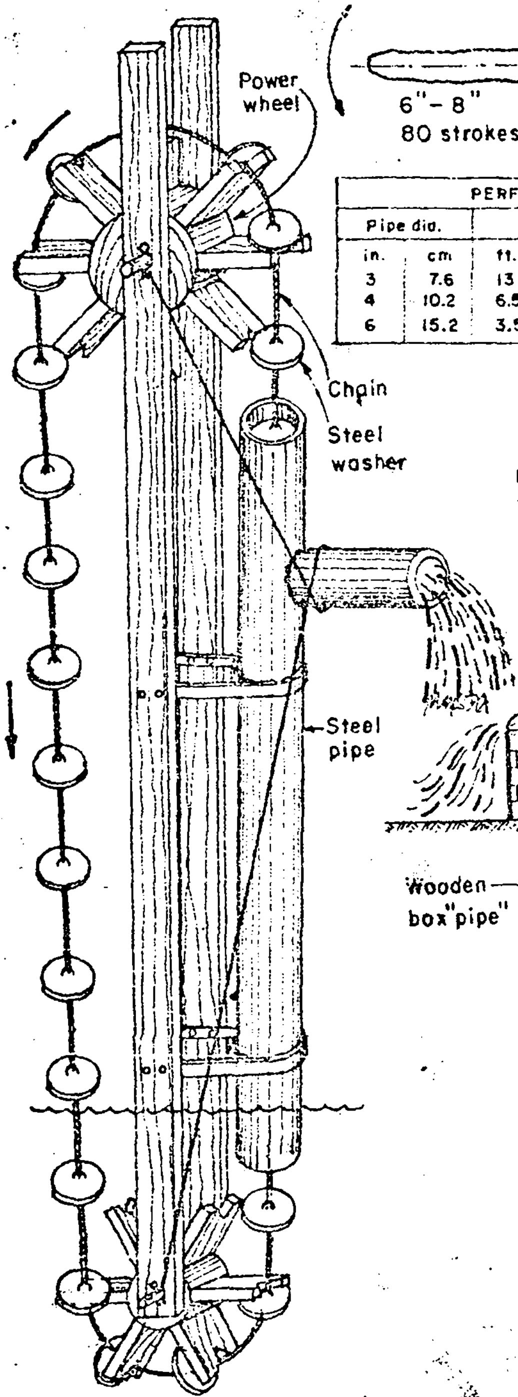
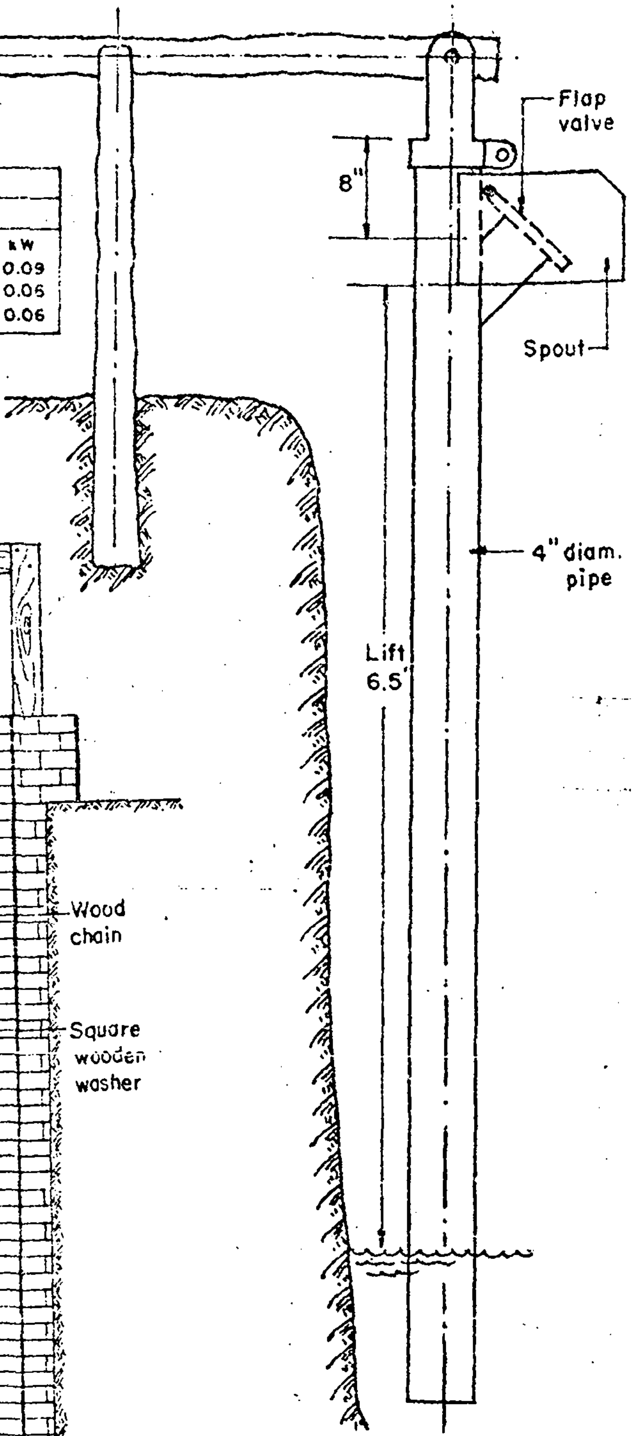


Figure 29. Steel washer chain pump



PERFORMANCE OF INERTIA PUMP							
Pipe dia.		Lift		Output			
in.	cm	ft.	m	gal/hr	L/h	HP	kW
3	7.6	13	4	1,800	6,840	0.12	0.09
4	10.2	6.5	2	2,400	9,060	0.08	0.06
6	15.2	3.5	1	4,500	1,704	0.08	0.06

Figure 27. Inertia pump

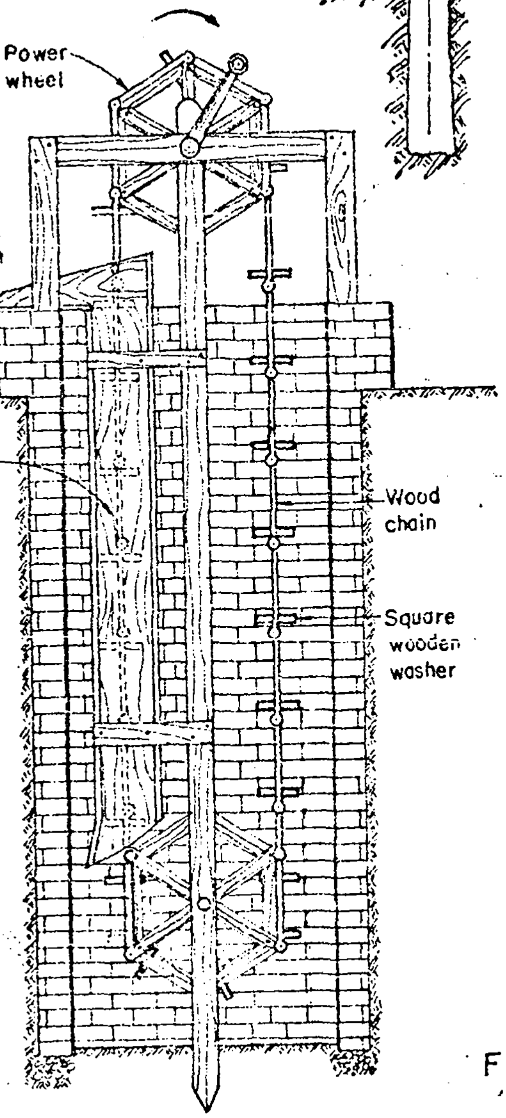


Figure 30. Square wooden enclosed chain pump

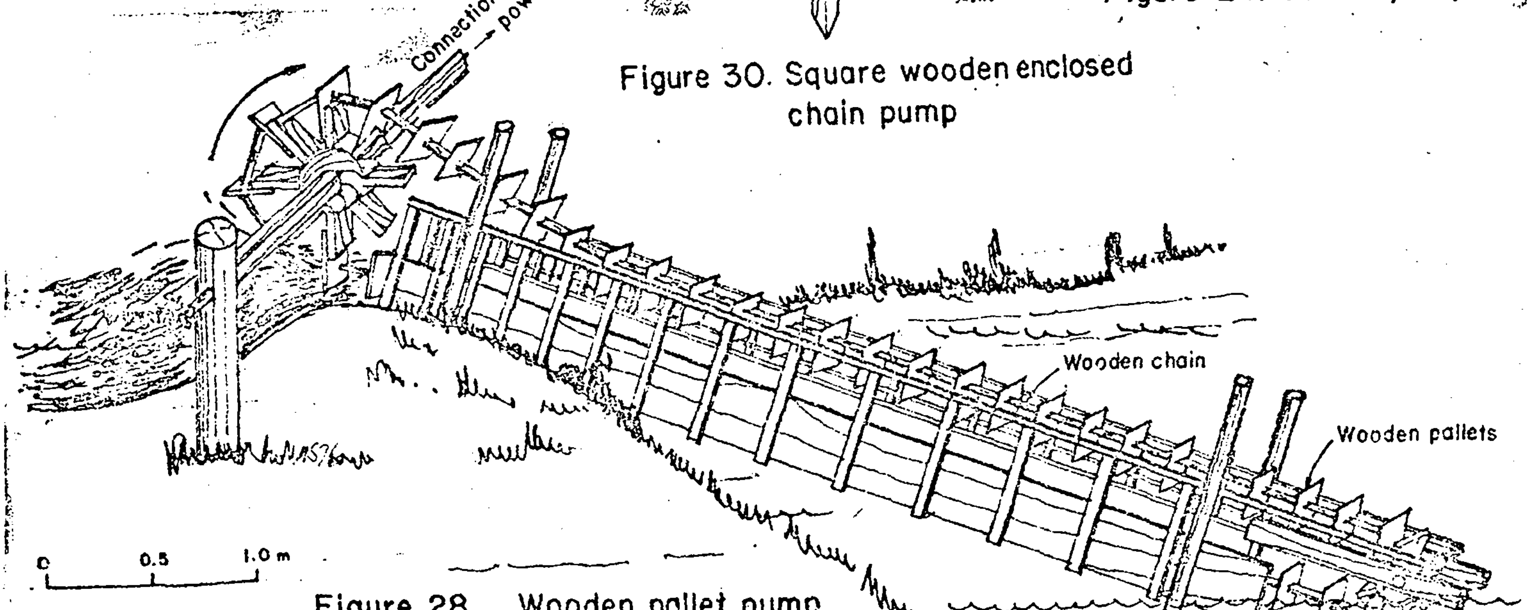


Figure 28. Wooden pallet pump

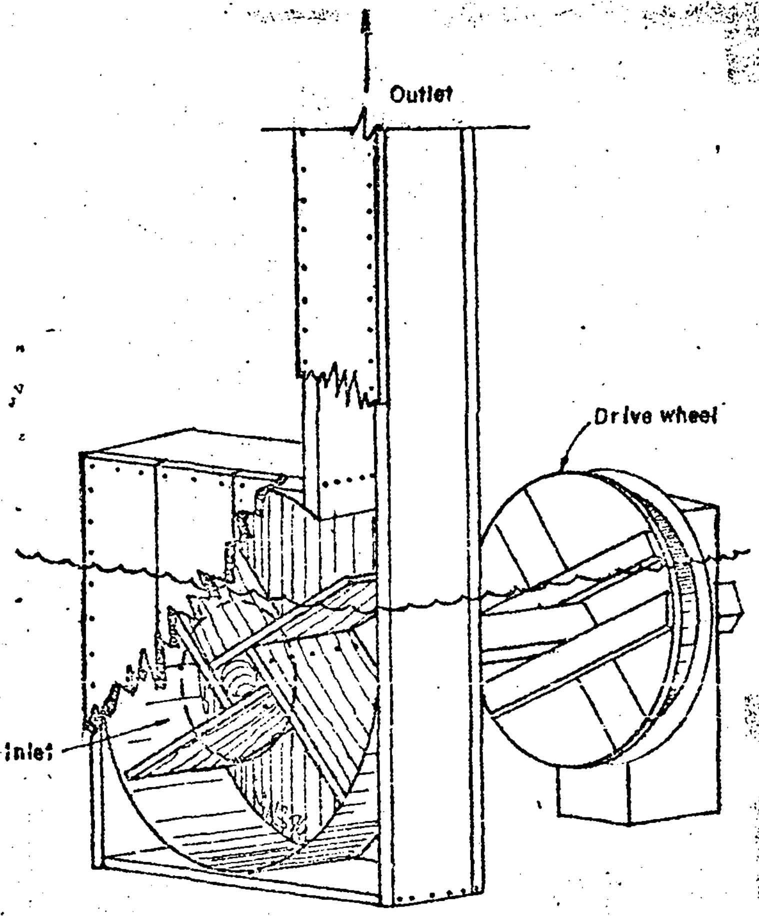


Figure 31. Large diameter slow speed centrifugal pump

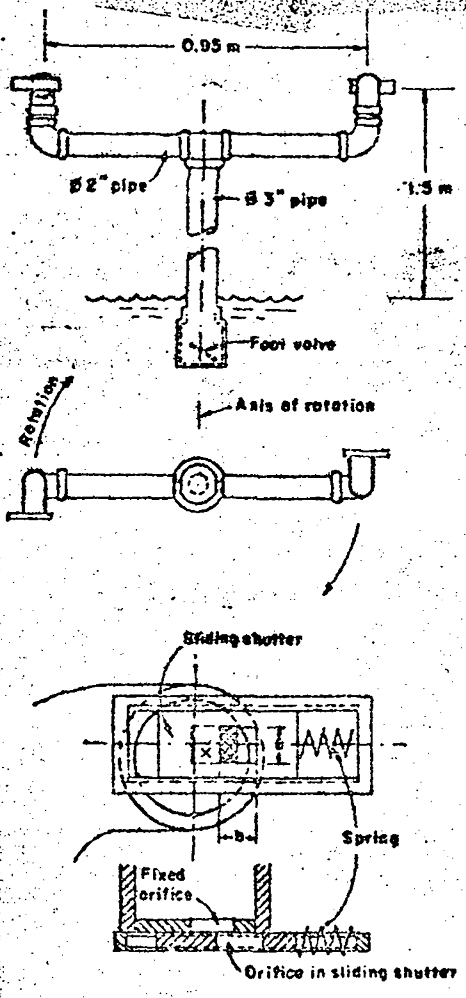


Figure 32. Centrifugal reaction pump[32]

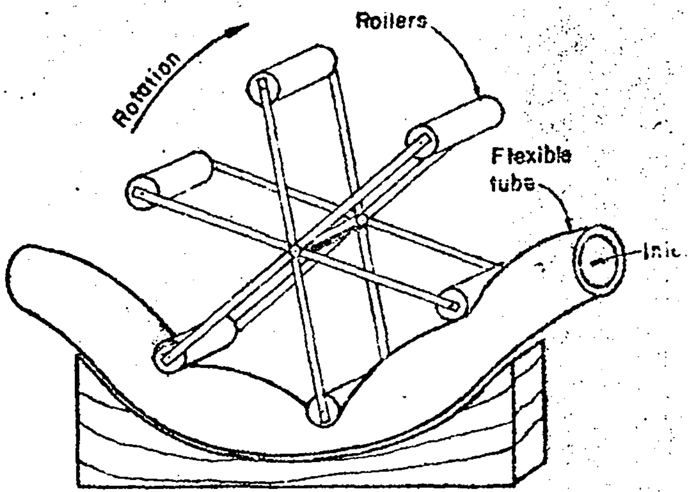


Figure 34. Peristaltic pump

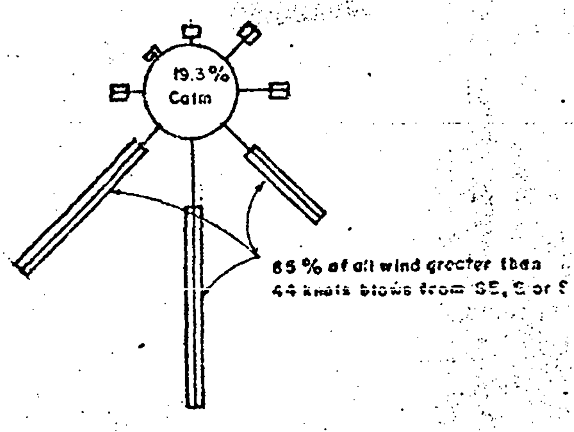


Figure 35. Wind power rose, Bangko
March, April, May

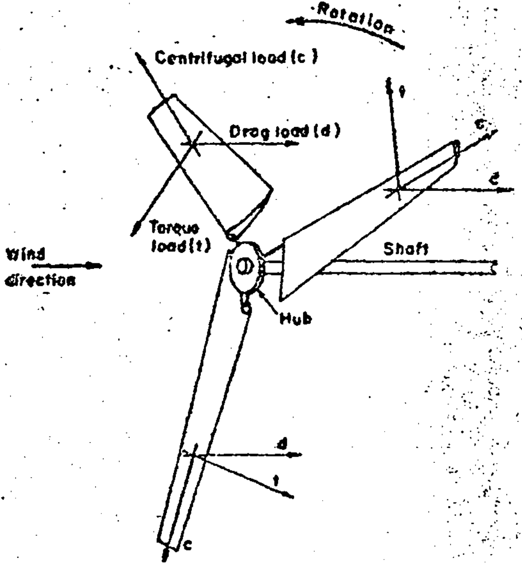


Figure 37. Force loads on rotor

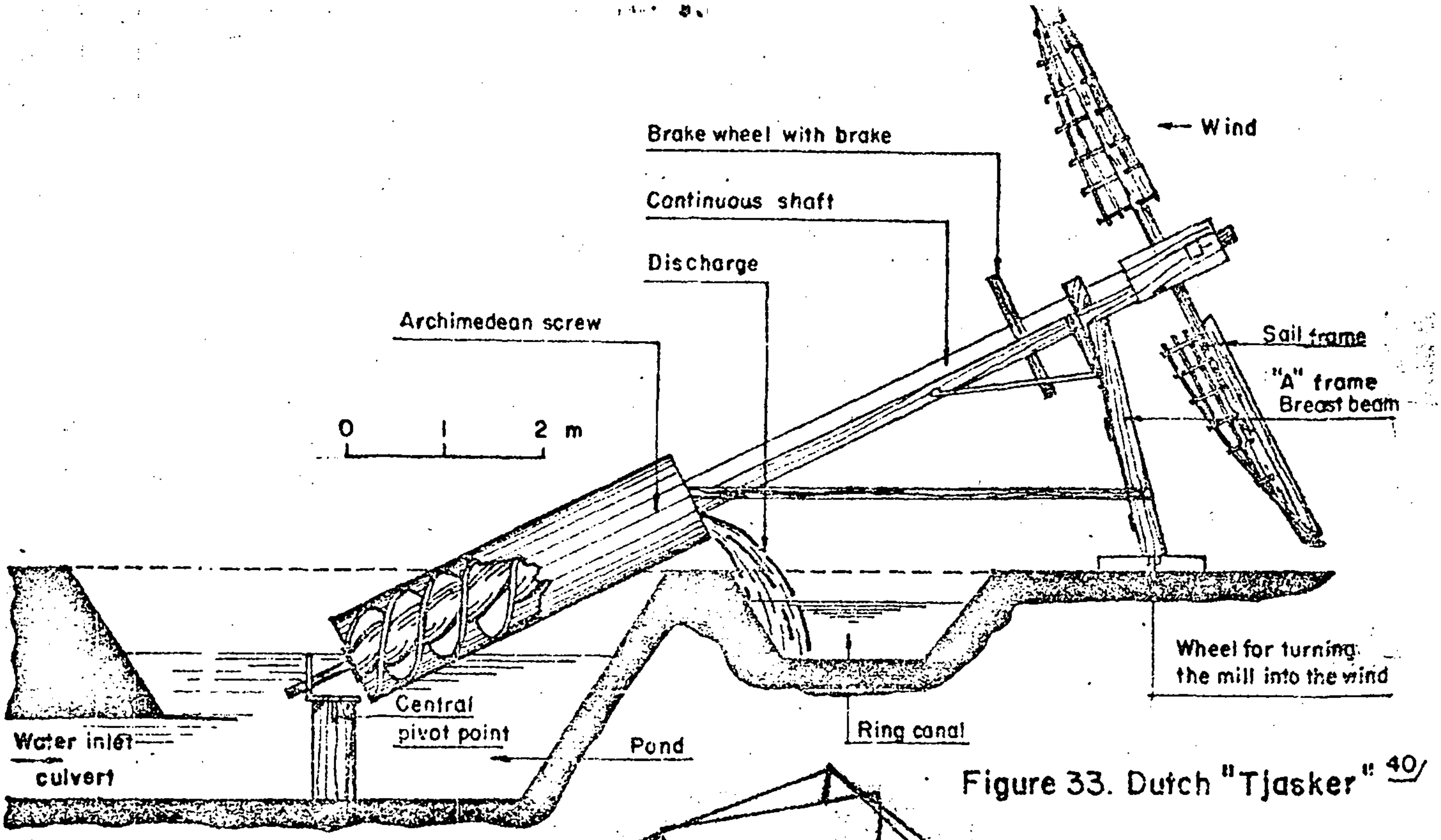


Figure 33. Dutch "Tjasker" [40]

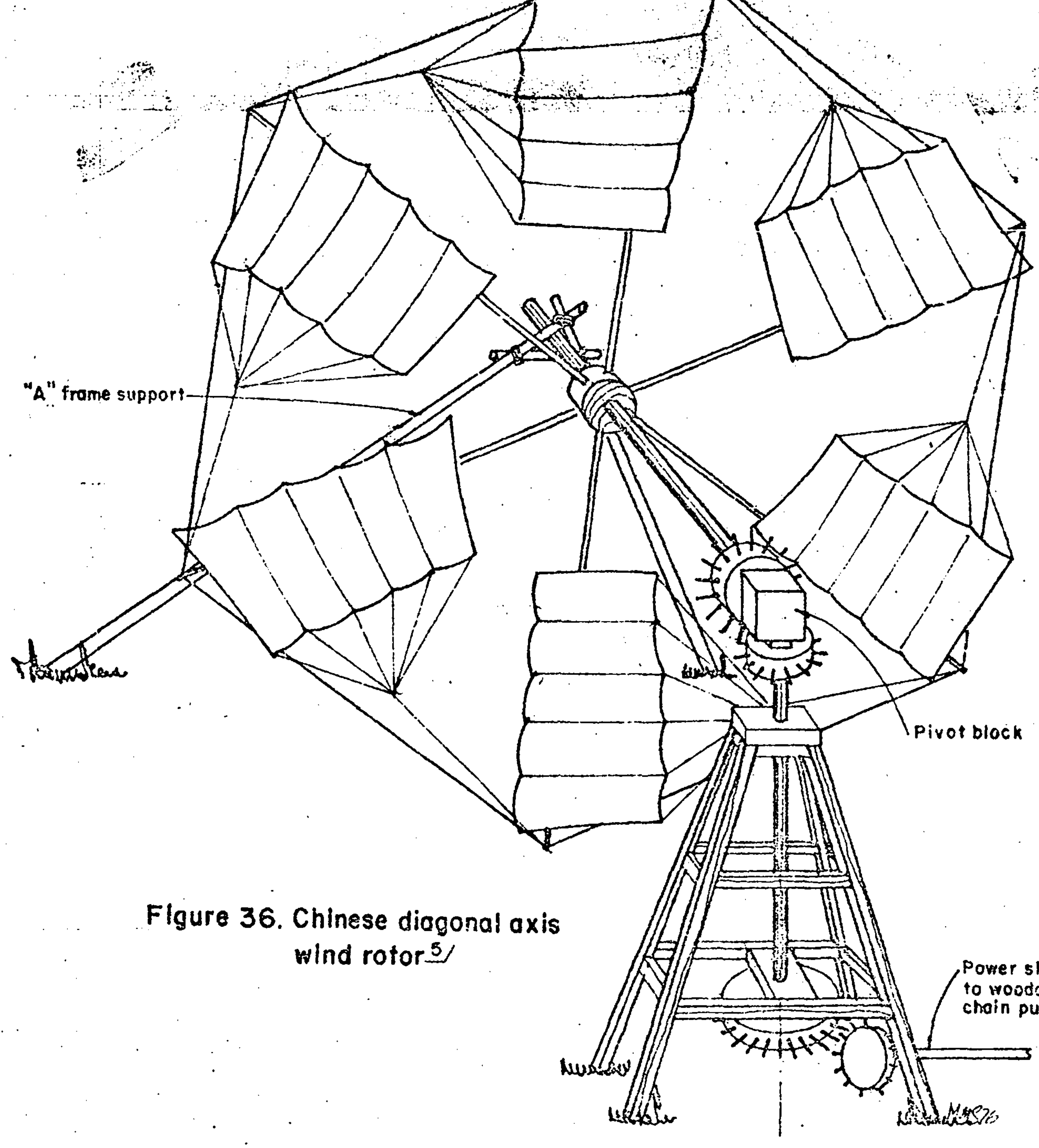


Figure 36. Chinese diagonal axis wind rotor[5]

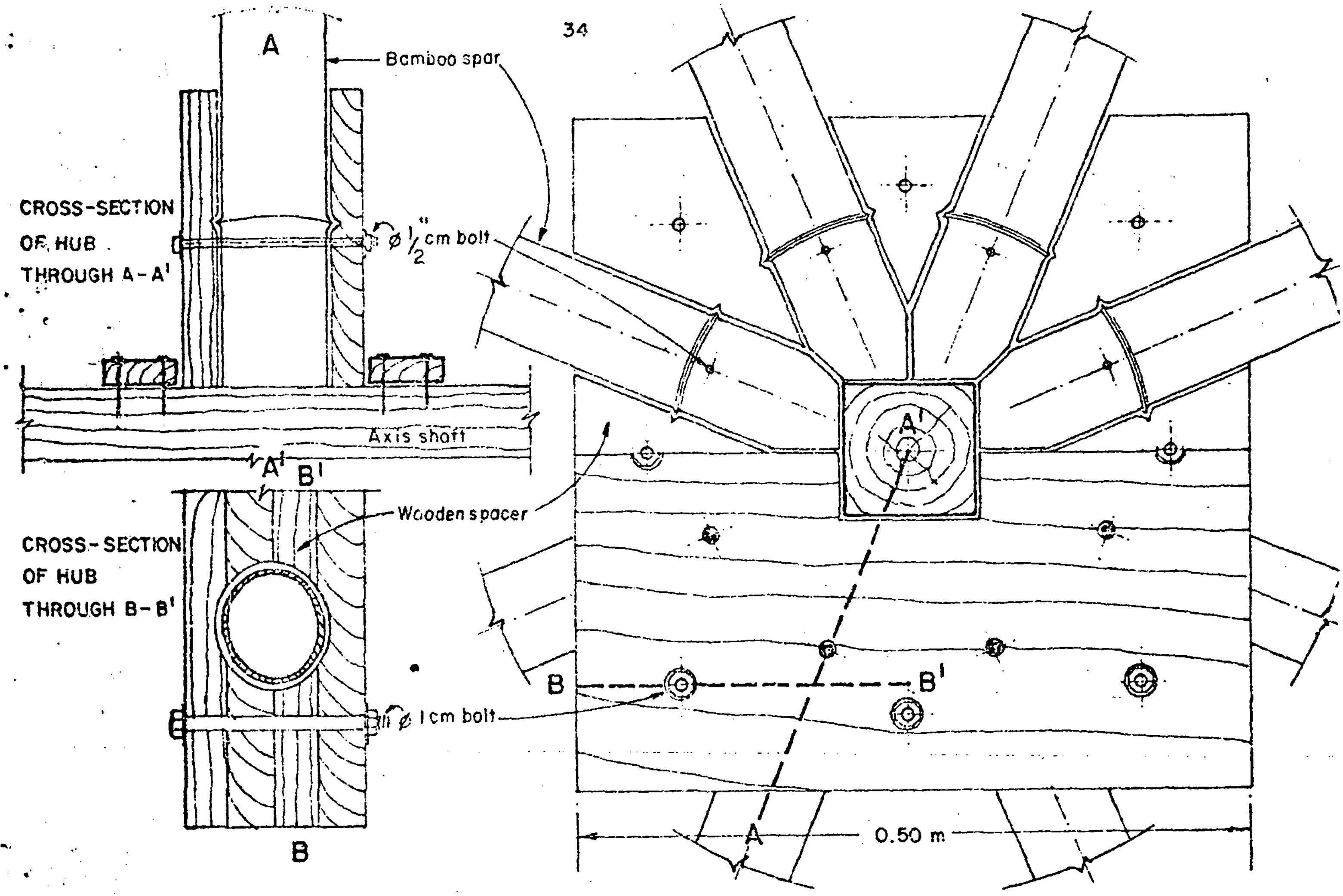


Figure 44. Side views of hub, half assembly (top), full assembly (bottom)

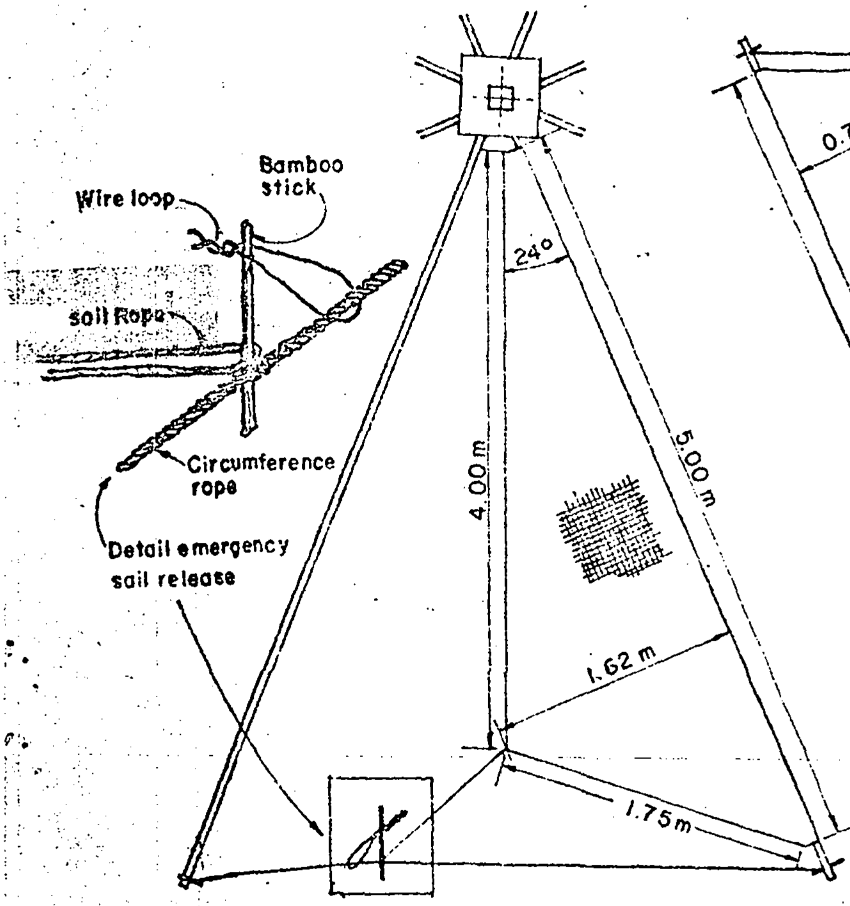


Figure 38. Cloth sail rotors: Greek sail wind rotor configuration

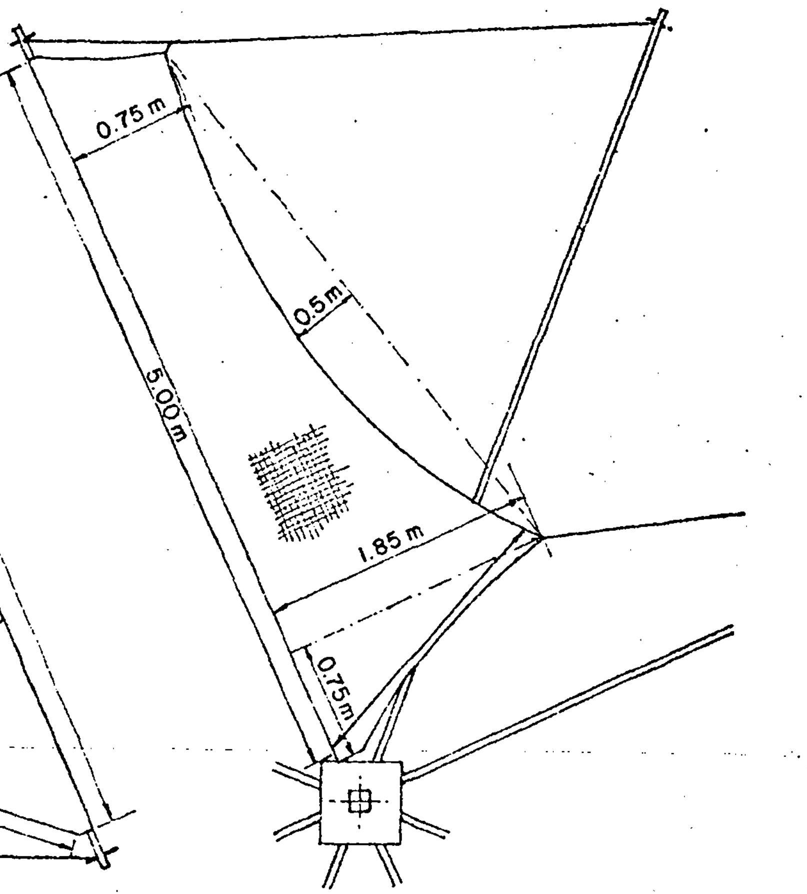


Figure 39. Hybrid Princeton- Greek sail wind rotor configuration

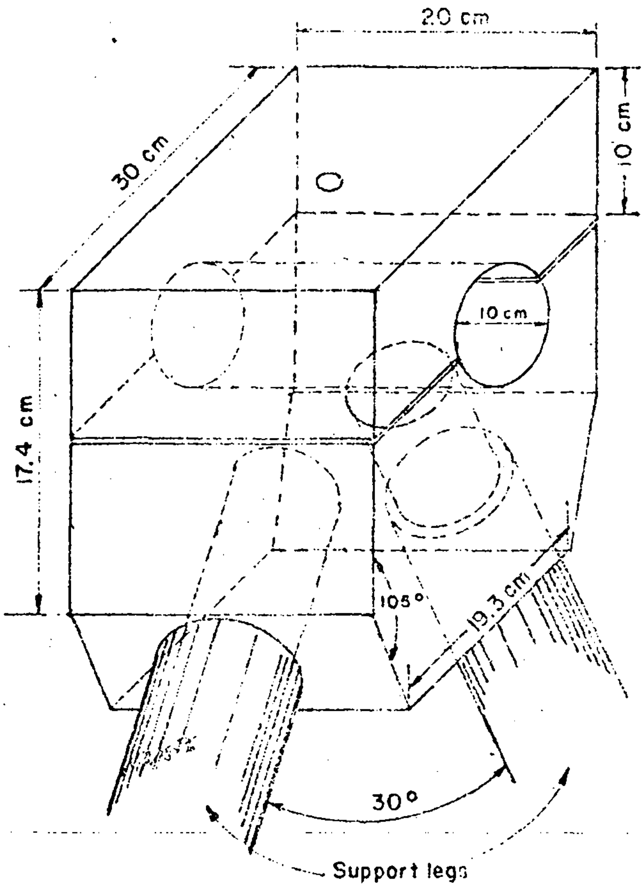


Figure 42. Double leg support/axis bearing block

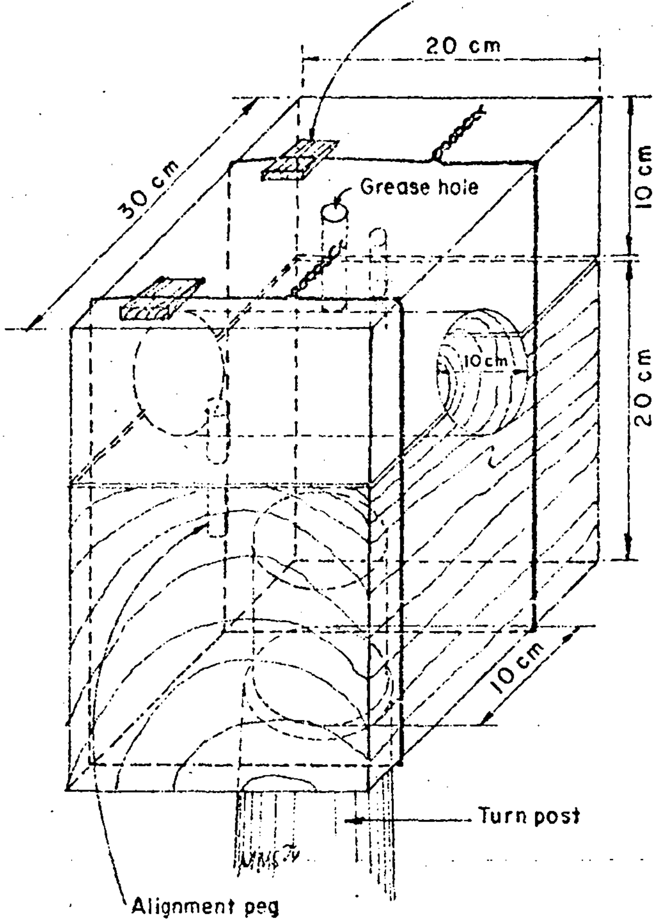


Figure 41. Turn post/axis bearing block

SCALE 1:5

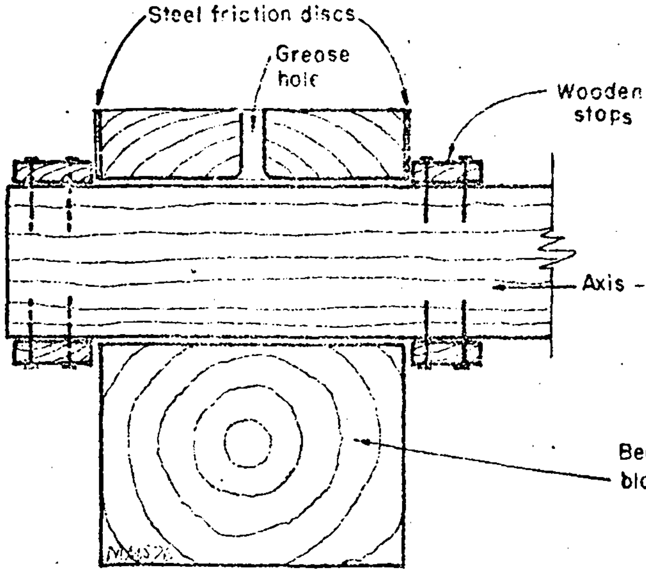


Figure 43. Vertical cross-section through leg support/axis bearing block

SCALE 1:5

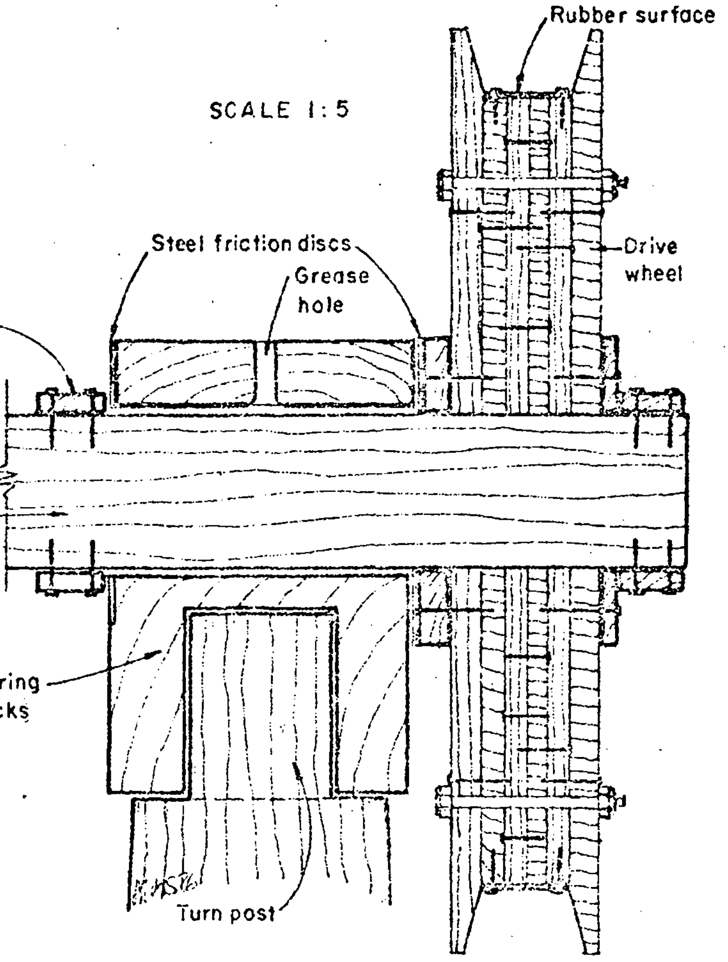


Figure 40. Vertical cross-section through turntable post axis bearing and drive wheel

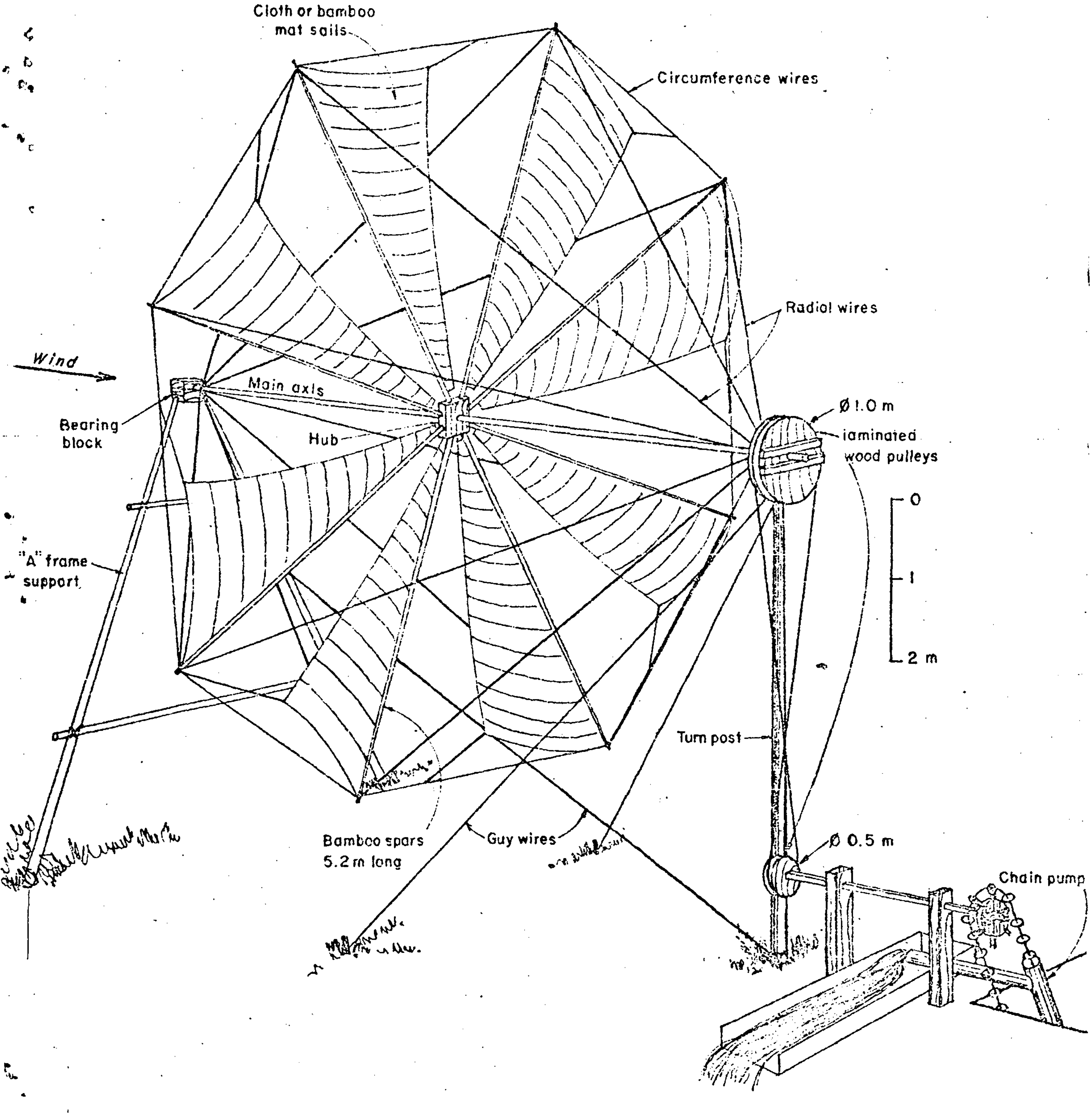


Figure 45. Hybrid Asian wind powered water pumping system