Compendium in Sail Windmills

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Selected & Edited by John Furze 1993/95/97/02
Holme Bygade 12, 8400 Ebeltoft Denmark
Tel/Fax/Voice: + 45 86 10 07 86
E-mail: <furze@post.tele.dk>
University of Aarhus Faculty of Political Science,
Law & Economics

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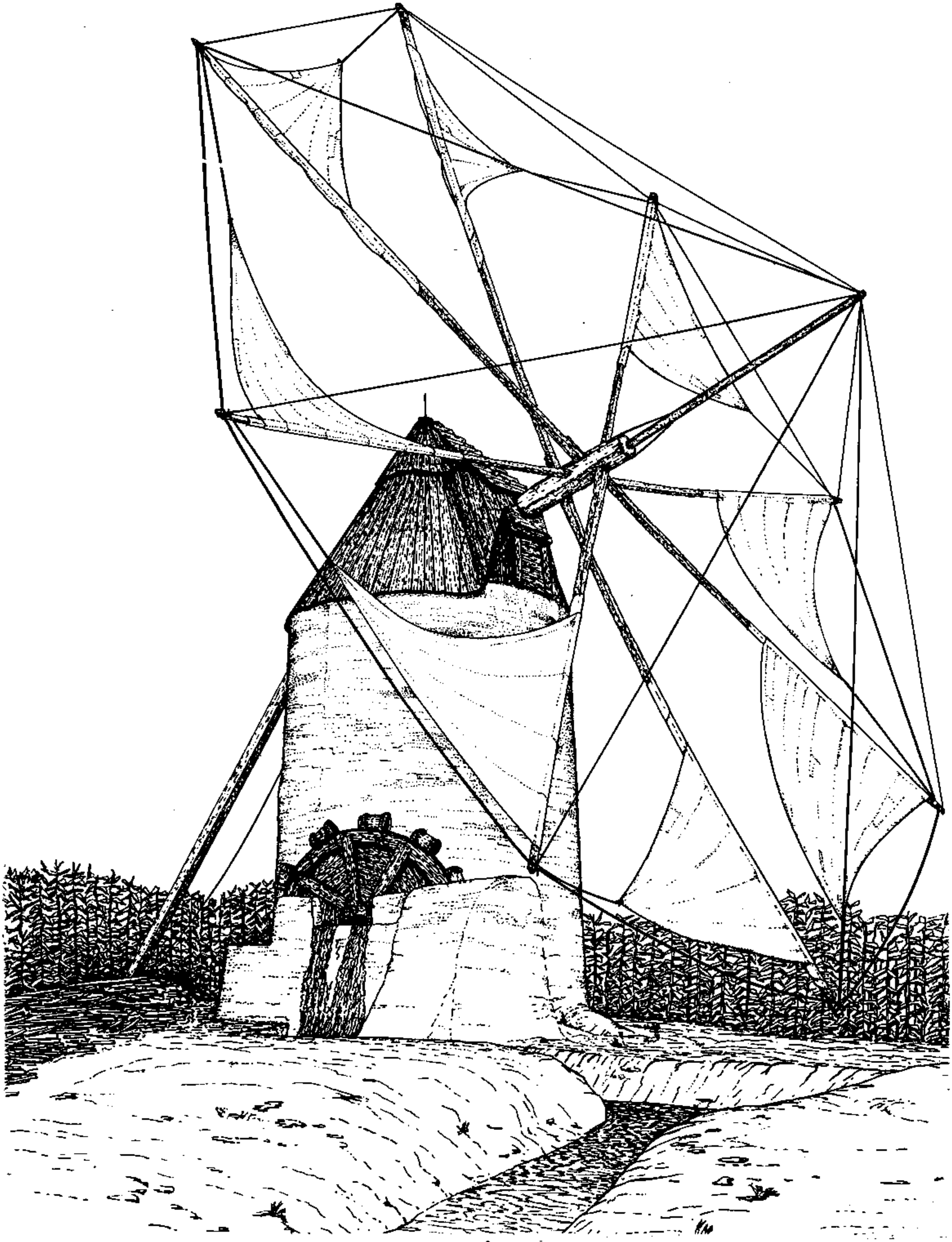
CONTENTS:



WINDMILLS OF MURCIA

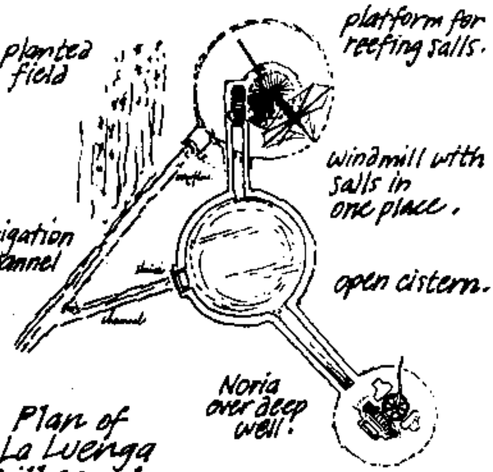
by Paul Oliver

When Don Quixote tilted at the windmills of La Mancha they were a new phenomenon in Spain. Llynn White, in his study of medieval technology has recorded that the windmill did not reach that area of Spain until Cervantes' time. La Mancha is in the north, and windmills probably developed independently further south. The mills in the north were generally of the post-mill type with the whole mill revolving on a single, central stem of tree-trunk proportions, and with sails of the type most common in the northern countries of Europe, with canvas stretched over a framework of laths attached to a whip or spar.

How windmills reached the south-east of Spain has been much debated and those to be seen still standing in the Campo de Cartagena region of Murcia are of a type which clearly hints at Arabic influence. This area lies just to the north of the important sea-port of Cartagena. Murcia isn't as romantic as the land of Andalucia a little further to the South; there's few hills of any size and it is mostly coastal plain with a few slight undulations in the ground. The wind blows off the sea and the coastal lake of Mar Menor, separated from the sea by the twelve-mile long strip of La Manga. It's ideal country for windmills, and only a few decades ago, before piped water was brought to the farms — and the developing hotels — the turning sails of the mills could be seen right across the plain. The farms are small and every farm had one or two mills. Some were used to grind corn, but the most prevalent type of mill still standing in the region is one that was used for irrigation purposes.

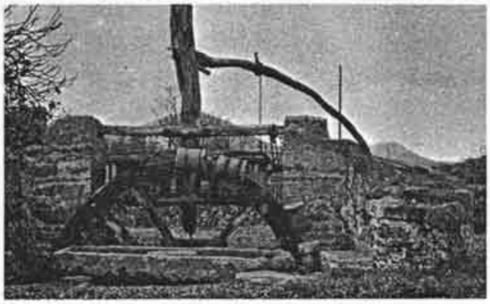
There is a good water table under the plain and the farms have small, well constructed cisterns and wells where water for domestic purposes can be drawn by hand. Generally the well-head sits right on top of the cistern, and the curved dome of the cistern has been built in fired bricks, strong enough to take a considerable weight. This method of building domes was probably brought by the Arabs, or at least influenced by them. Southern Spain came under Arab domination in the seventh century, and this continued until the "Reconquista" of the 14th century. The Arab heritage is still to be seen, most grandly in the Alhambra, but also in some aspects, in the folk vernacular.

One of these is the *noria*, an ancient system of drawing water for irrigation, which was observed by the Romans, and which still survives today in the Balearic islands. Only a few years ago you could see the blindfolded horses turning the great arm of the *noria* which brought up successive bucketfuls of water to discharge into the irrigation troughs. The *noria* worked on much the same principal as the Blue Ridge mountain sorghum press, or cane press; a horse, (or in North Africa, a camel) walked in a circle, turning a long timber arm which was attached to his harness. This revolved a central spindle which, in the case of the cane press, drove a pair of drums which crushed the cane. With the *noria* the central spindle turned a wooden cogwheel made of vertical bars of wood braced between two circular wooden plates. This primitive cog engaged with the teeth of a huge wheel, constructed by a similar method, with bars of wood making up its thickness. Over the wheel was looped a long, endless chain, to which was affixed leather, or sometimes pottery or wooden buckets. The buckets on the chain were lowered into the water of a cistern or well over which the *noria* was mounted, and as the wheel turned through the drive of the central spindle and cog and the walking animal, the buckets were raised to discharge into an irrigation channel. A small boy with a stick ensured that the horse or camel kept on walking and the endless chain of buckets maintained a continual flow of water.

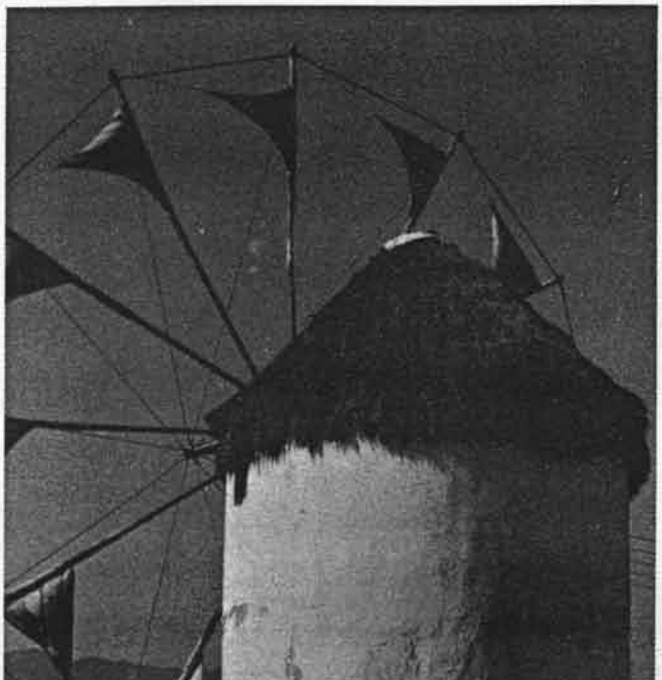


Plan of La Luenga mill complex.

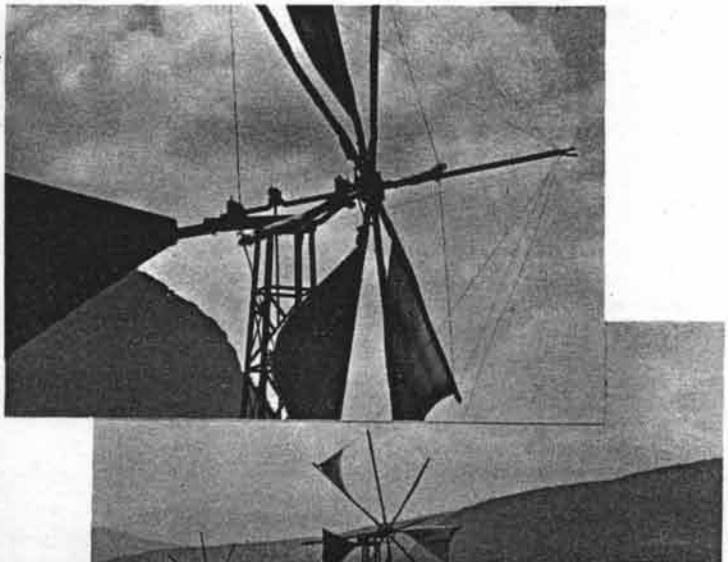
It was the inspiration of the unknown mill-wrights of Camp de Cartagena to adapt the *noria* to wind-power, so releasing the horses for farm-work. Whether this was an Arabic invention still remains a mystery. "One of the curiosities of Tarragona consists of mills built by the ancients: they turn when the wind blows and stop with it" wrote the Muslim author Ibn 'Abd al-Mun 'im al-Himyari, but his book, though probably of the thirteenth century, was known in translation only from the fifteenth century, and the mills to which he referred may date from that time. Until that time it is known that mills in the Iberian peninsula worked on the vertical axle principle, so it would appear that whatever the origin, the primitive form of the present mills arrived after this period. (Anyone wishing to pursue the references should trace them in Llynn White's *Mediaeval Technology and Social Change*, Oxford University Press, p. 161.)



Left: High irrigation mill at El Algar. Top right: Sail spars at wind shaft. Bottom right: Noria, a well mechanism of Arab origin, at Mallorca. Long arm turned by blindfolded donkey or mule.

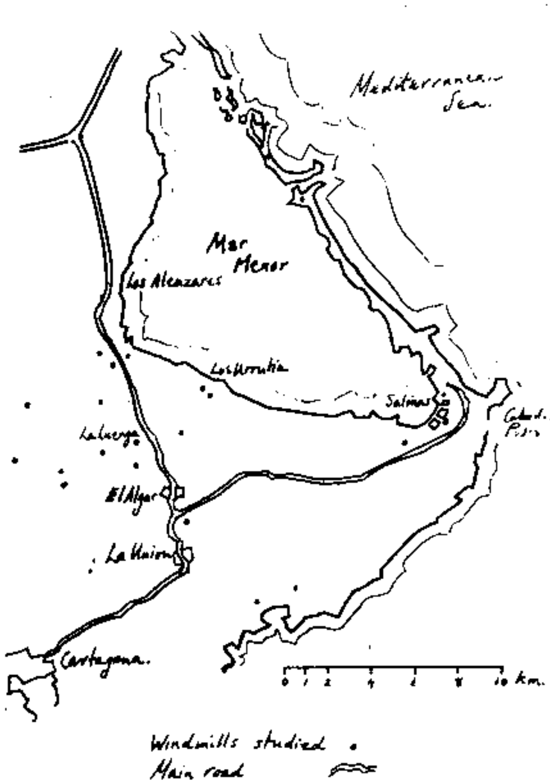


Thatched windmill on Mykonos.



Greek windmill for pumping water. Large rudder keeps mill facing into wind. Rod attached to hub is bent like crankshaft, attaches to vertical rod that goes into ground, pumps up and down.

Bill Bullis



Campo de Cartagena, Murcia, Spain

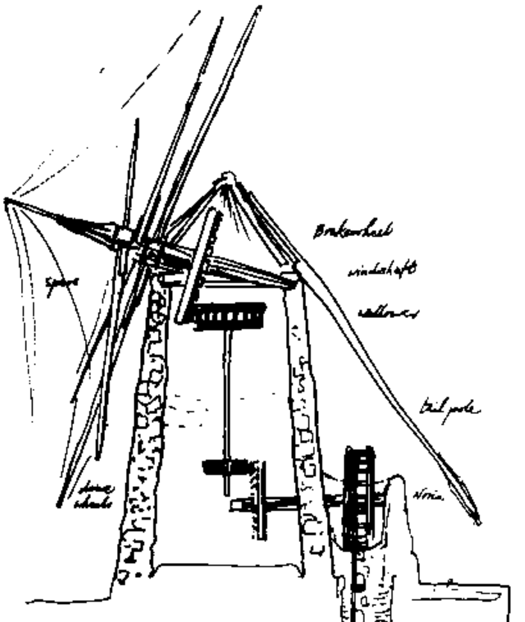
The construction is relatively simple, and the machinery far less complicated than that of a grinding mill. It's comparatively easy to build, given strength, materials and time. The mill tower is usually of rubble masonry, though more skillful mason's work can occasionally be seen. It stands about 30 feet; some are higher, and others are squat and rotund. There's no standard dimension but a higher mill allows a larger sweep of sail and scoops wind at the higher altitudes across the plain. A heavy timber windshaft is turned by the sails (discussed below), and this drives a massive wheel, which in English usage is commonly termed the "brakewheel." A large brakewheel also acts as a flywheel, while the more teeth it has around its perimeter the greater the efficiency of the mill. This brakewheel, inclined as is the windshaft, at a slight angle, drives a central cog or "wallower". Early wallowers were of a similar type to that of the *noria,* but during the nineteenth century cast-iron cogs seem to have been fitted in most mills. The "wallower" in turn revolves a central shaft, which turns another cog nearer the ground to drive another large wheel. This wheel in turn drives the exterior *noria* wheel of the mill and hence keeps the chain continually revolving.

As for the sails, these are of the Mediterranean island type. They take their technology, as might be expected among maritime peoples, from the small boats that ply between the islands and the mainland. The sails are literally *sails,* triangles of canvas which can be reefed to the whips or spars, and which can be opened up to provide a fair spread on each of the eight spars. As the spars, which are inserted into the end of the windshaft, require bracing, they need a superstructure of support. This cannot be behind the sails because the bulk of the mill tower is in the way; it has therefore to project beyond the sails, somewhat like an umbrella turned inside out. The superstructure is strong, but not rigid, and like a ship's mast, spars, rigging and sails, it creaks in the wind, and bends and gives to wind pressure. As the spar bends, the rigging tautens, and as the wheel of the sails turns, the tautened rope relaxes and another comes under tension. In this way the whole structure responds to the wind without, in normal circumstances, fracturing or breaking off. Ropes usually provide the rigging from the tapered tip of the windshaft extension to the outer perimeter of the wheel sail. The wheel was completed by ropes between the spars at the perimeter, but later, forged iron rods of narrow diameter were used instead. The rods did not break under strain, and lasted longer than the ropes, but they had one drawback in that they could not be shortened by the simple expedient of a thumb-knot or a sheepshank. Various alternatives were tried out, including an S-shaped link which could be removed from one or two of the rod lengths, and later, an iron box through which the threaded ends of the rods could be inserted and tightened by bolts.

As the slots to take the sail spars would weaken the windshaft if they were all inserted at the same point, they have to be fixed at intervals along its length. This creates slight problems of rigging and a somewhat unequal catchment of wind in the sail. Skilled millers could balance the reefing of the sails to take this into account, but a nineteenth century innovation was a star-shaped forged iron plate to which the spars were affixed, which was bolted to the end of the windshaft. This placed all the sails in the same plane. It seems however, to have been little used and probably the advantage gained was outweighed by the reduced three-dimensional strength of the total sail structure.

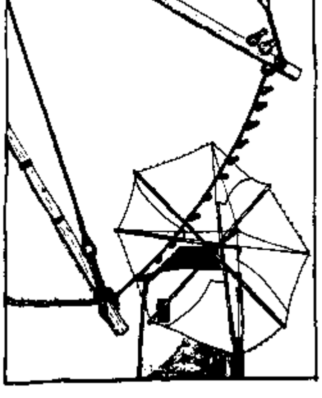
It is important that the sails are kept into the wind, and as the wind comes from more than one direction the sail structure had to be turned. As the mill was a fixed tower the apparatus was turned by revolving the cap which rested on the top of the tower. The cap gave support to the windshaft and brakewheel and could be turned manually by a long tail-spar which extended at an angle almost to the ground. Though it demanded considerable effort, the ring of the cap was well greased to facilitate its movement, while the structure was made as light as possible by using thatch or thin planks for the roofing material of the cap.

Some of the mills were quite small, like Molino los Alceitas at Los Urrutias on the coast. Others, like Molino de la Pichorra at El Algar were high, with the main *noria* wheel some fifteen feet above the ground providing water for an irrigation channel several hundred yards long. Perhaps the most interesting mill is La Luenga, a complex near El Algar which demonstrates very well the sequence of development of the Murcian mill. Nearby are to be seen several others, all within a few hundred yards and they must have presented a brave sight a half a century ago, when all were turning. About thirty yards



Section through Murcian mill. (supporting structure omitted to show mechanism.

away from the mill tower still stands the remains of an ancient *noria* , sited over a deep well. Its channel did not run straight to the field but to a large, fairly shallow, open cistern about thirty feet across. This cistern had a sluice which allowed the farmer to conserve water when he needed to, and to release a controlled flow from the cistern when it was required. It is surprising that this method of controlling irrigation wasn't used more frequently, but I've found few examples of it. However, the builder of the mill at La Luenga was clearly impressed and devised a two channel system which poured water into the reserve cistern when required, but which also had an overflow channel which fed directly to the fields when the water in the cistern was at a high level. La Luenga mill stands on a round plinth and it seems likely that part of the mill is built directly over the structure of the well. This complex, the most sophisticated I have found, seems to have evolved from the early *noria* over several centuries, and characteristically this well-kept farm used the star-shaped boss for the mill windshaft, when this innovation was introduced.

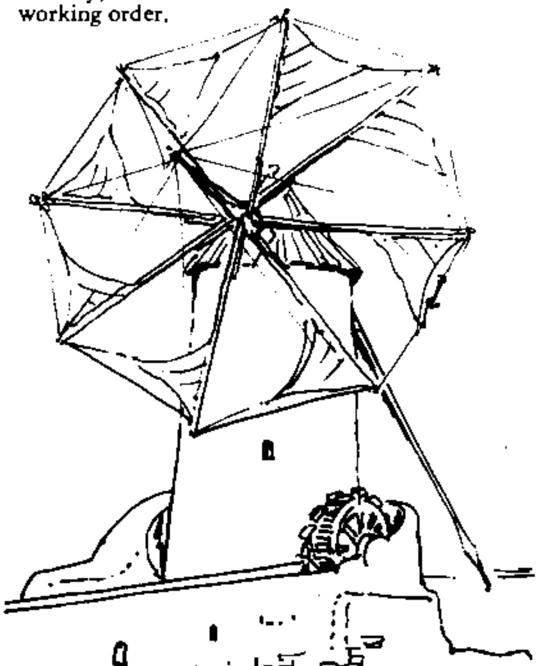


windmills in Torres Vedras, Portugal. Clay whistles on rigging signal farmers to reset sails when the wind changes.

A mill of the Cartagenan type would not present major problems to an inventive builder today. The tower need not be a solid structure but could be built on a sturdy frame of timber, or probably an old pylon or the framework of an American annular mill could be pressed into service. Only the brakewheel and wallower would present some problems but it seems likely that suitable parts could be adapted from nineteenth century machinery. The principle is so simple that it is open to innovation and improvisation.

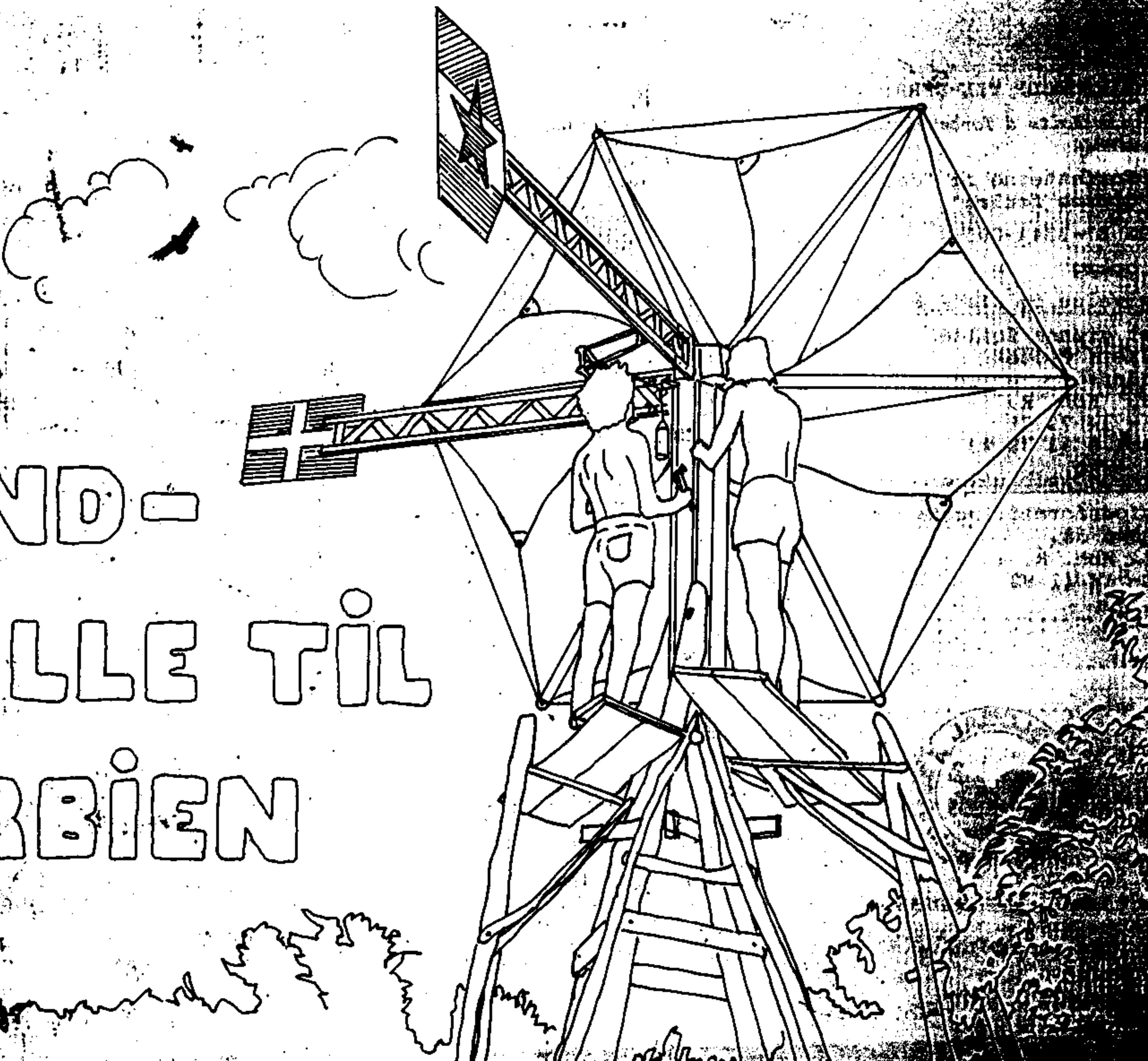
Though the mills were mainly used for irrigation, some grinding mills for grain were also built and a few were used for grinding salt at the salinas which are to be found near La Manga and Mar Menor. Today however, all that remains of the majority of these are the slowly deteriorating towers and the heavy windshafts and brakewheels which have been inconvenient to remove.

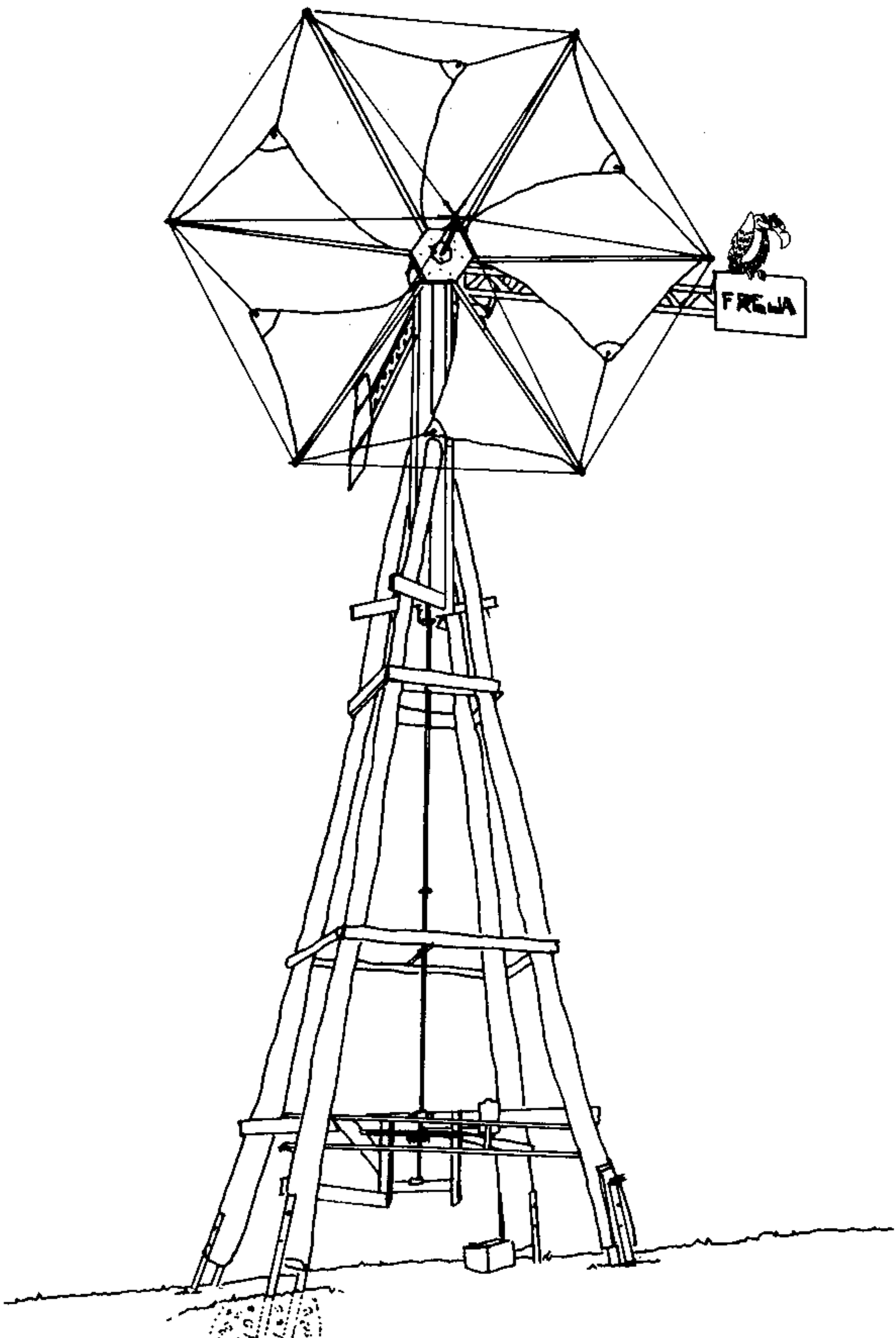
Generally the mills would seem to date from the eighteenth and early nineteenth centuries, but restoration and rebuilding obscures the evidence in most cases, and some bear traces of seventeenth century consttuction. Now they are falling into ruins but very recently an organization, Amigos de Los Molinos Viente de Campo de Cartagena, has been formed. Their conservation methods extend hardly beyond a coat of whitewash and bitumin paint on the roofs, but hopefully, with support in this not very conservation-minded country, some of the mills could be restored to working order.



Rigging of Murcian mill. This one has a ramp for reefing sails.

EN VIND-MØLLE TIL SERBIEN




FREJA

Sail Windmill Project

In February 1978 - a group of students from Institute 3A - The School of Architecture - in Copenhagen Denmark were invited to visit the native village of one of their fellow students - Milorad Karadiz from Serbia in Yugoslavia.

The students designed and built a sail windmill to bring with them as a gift and as a demonstration project for the village inhabitants and as a contribution towards the introduction of Renewable Energy technology.

The village of Novi Durevac has no access to electricity and the nearest grid connection is 8 kms away in the larger village of Zitni Potok.

For lighting - the Karadiz family have installed 6 units of 12 volt fluorescent lights in their house and barn. Power is supplied from old car batteries - transported every 14 days by ox-cart to Zitni Potok for re-charging.

The windmill would be erected on a small mound in the garden for charging the lighting system's discharged or flat batteries. A direct electrical connection to the house would result in too high a power loss.

The windmill should be based on recycled materials and have a technological level equivlant to what local village inhabitants and the local blacksmith could be expected to reproduce.
It was the intention to demonstrate to the other villagers how one could produce electricity from the wind, as an intelligent alternative to centralized electrical power stations that are not only resource-intensive but also discriminate against distant rural areas resulting in emigration from the countryside to the towns.

The windmill should also be able to charge batteries belonging to neighbours - in addition to providing mechanical power for water pumping, sawing wood, etc.

Our first step was to ask Claus Nybroe to assist us in getting started. He acted as our source of inspiration and technical consultant and together we were able to choose the blade-design and to estimate the expected production.

The most important detail - information on the available wind was sparse, inaccurate and disappointing. Wind data from two larger towns - about 150 kms distant from Novi Durevac showed an average wind speed of about 1½ - 2 meters pr. second.

However mountains and hills are different from larger towns and Milorad informed us that the wind was stronger in the mountains with often strong gusts. However as the average yearly wind-speeds are rather low, - we had to consider some form of multi-blade farm-type windmill that could utilize the available low wind speeds.

The actual construction was done in the School of Architecture's workshop - where we received assistance with welding and machining etc. During the final construction period we were visited by Jacob Bugge from the Danish Technical University who pointed out some errors, - assisted us with different calculations and suggested practical alternative solutions for such things as "turning out of wind". He informed us- that he thought that the windmill looked "good-enough"- but that we would first know whether theory also agreed with praxis after the windmill had been in operation for a while - this last information was later shown to be very true.

Progress in the workshop was very slow - we were only 2 - 3 persons and our task was a mix of both design and construction.- we were finally able to finish the task with a great effort and with the assistance of friends - only 14 days before the windmill was due to be transported to Yugoslavia.

The slow rotational speed of this blade design requires a high gearing to produce sufficiently high dynamo rotational speeds. We also had to consider the possibilities of the powerful gusts of wind and provide the windmill with a tail-construction to turn the windmill out of the wind so as not to overload either the blades or the dynamo.

The requirement for the use of re-cycled materials - gave us many deliberations as to just what we could expect to find in a Serbian junk-yard - Milorad thought that used car parts were more abundant than used bicycles. These deliberations had to be combined with what we in the concrete situation could find back home in Denmark. This resulted in many unusual choices. [Outside observers often pointed-out easier and more efficient solutions which did not however take fully into account our absolute requirements of low-technology and re-cycling of resources].

This was a very important parameter for us - as the windmill should fit into the already existing technological level and at the same time fall inside the framework of the local practical-technological capability - which can be of course limited by the resource base of existing on-site tools and machines.

During the final 14 days we built and erected a tower and carried-out a preliminary trial-run, where we did not have time to try-out the gear and electrical equipment. This was an unfortunate omission as these particular components gave us several problems later.

However we were all in good spirits when Milorad drove off for home in his 4-wheel drive Unimog with the loaded - disassembled windmill.

Blades

The blade type that we used are similar to those used for centuries by the Greeks in Crete. Six wooden poles - covered with canvas - radiating out from a wooden hub and all joined and connected together with steel wire to stiffen the construction.

To keep the rotor away from the tower - the poles, spars or masts are set at an angle of **7° - [7 degrees]** - away from the vertical position by wooden wedges placed in the hub and by the use of steel wires running from each mast-tip or cap to an extended axle or bowsprit.

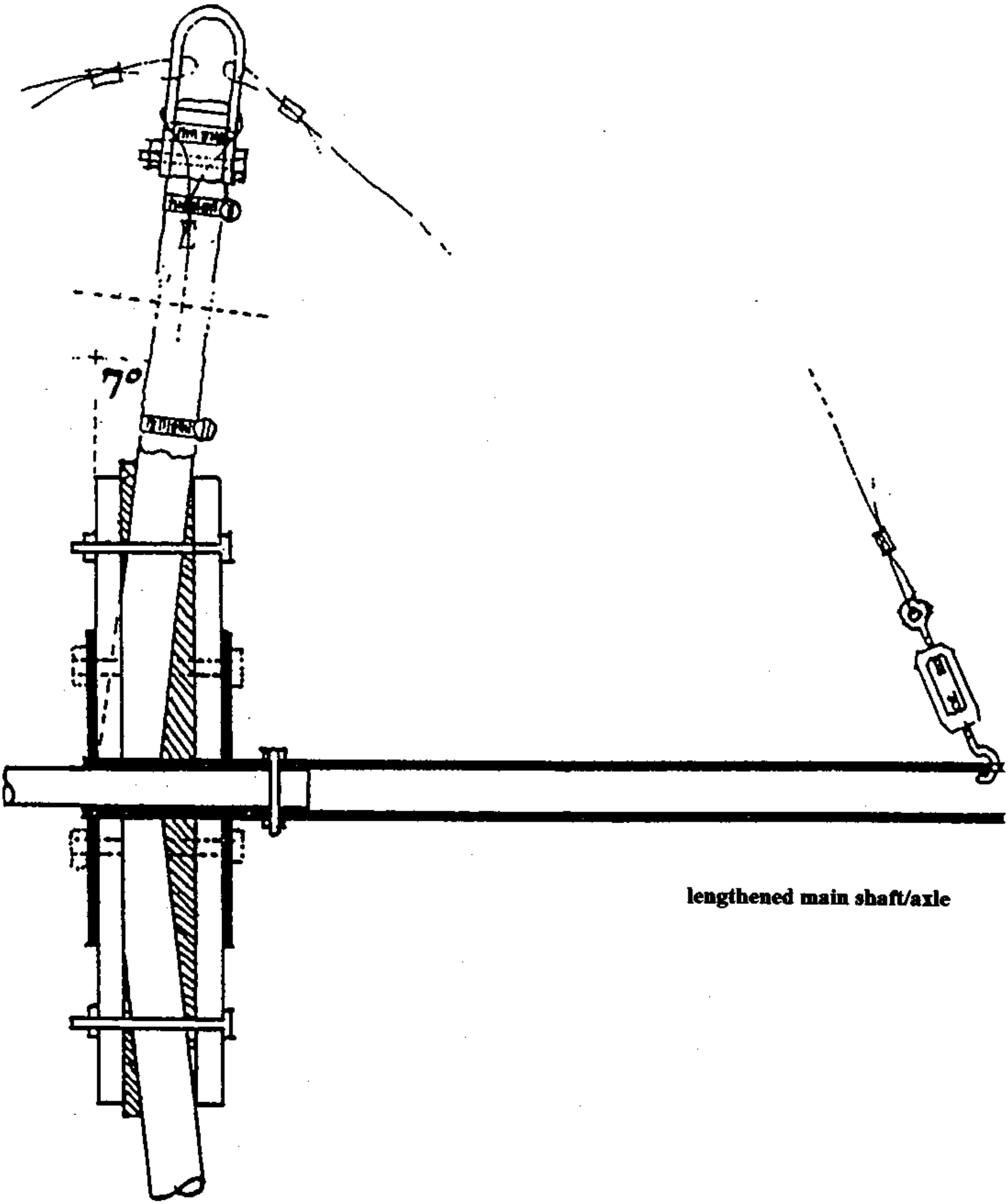
The hub is made of 2 pieces of waterproof plywood. - wooden spacers are placed between the poles to maintain the correct distance between the two sides. The completed unit is bolted onto an iron pipe with a welded flange and a loose plate.

The canvas sails are sewn with extra reinforcement pieces at attachment points and the sails are treated with sheep's-tallow [fat] to prevent soaking.

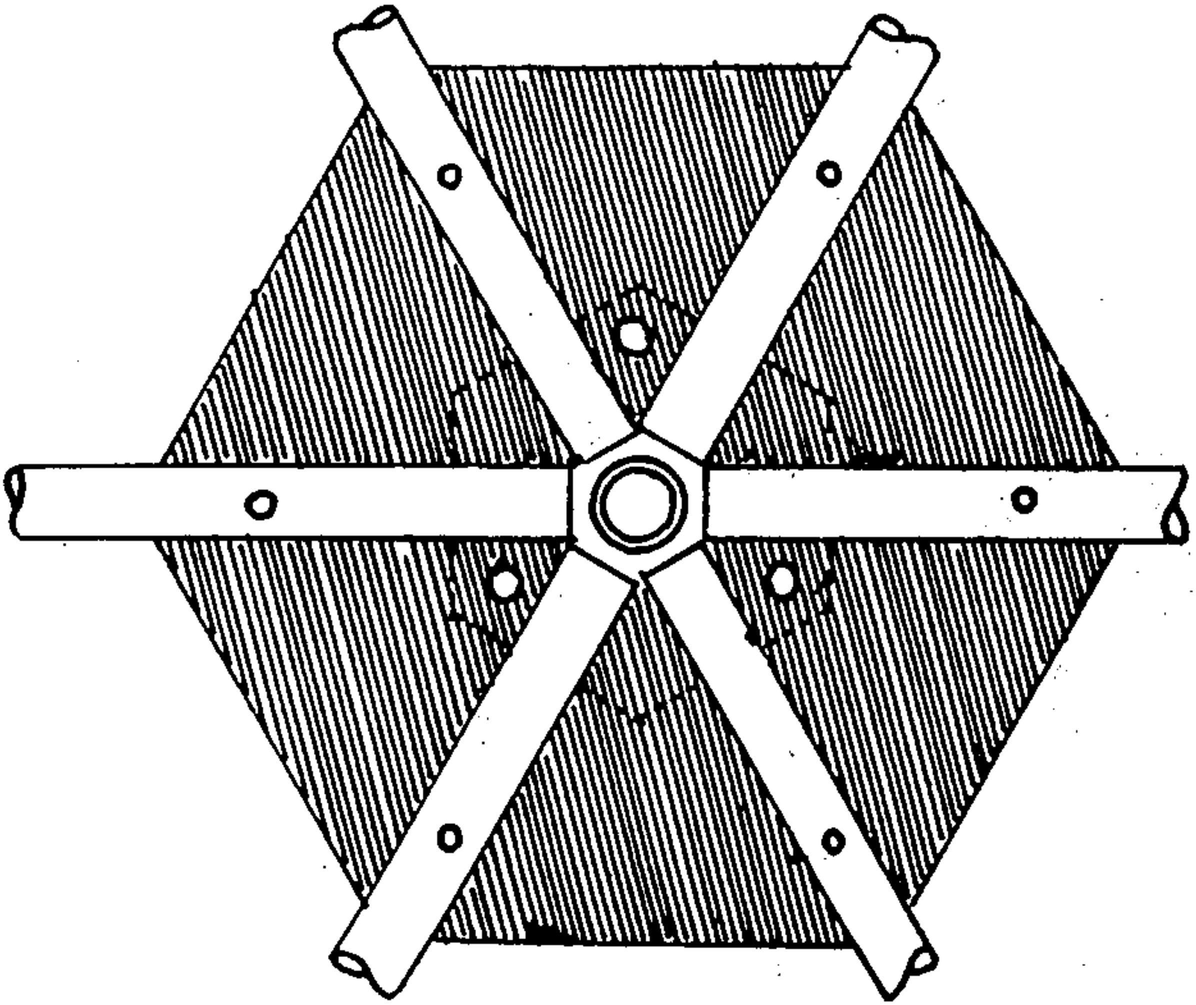
During periods of high wind speeds the sails will stall - and will therefore not increase their rotational speed above a certain level. As an additional safety factor - the rope that holds the sail in position will rupture - if the force of the wind threatens to tear the sails or break the spars.

The rotor diameter is **3.20 m.** and the swept area is **app. 3.5 m^2.**

sail masthead cap with wire stay rigging



lengthened main shaft/axle



hub with front plate removed

Nacelle and Turntable.

The rotor requires a high gearing and as we did not wish to use a gearbox - this could be difficult or expensive to find in Serbia - the power was transmitted down through a vertical shaft.

The gearing system using several wheels and a V-belt pulley-drive took up so much space that there was not sufficient room on the nacelle upper bed plate.

A bearing construction is placed on a 5 mm iron bed plate. A bevil drive gear or crown-wheel on the horizontal steel axle inter-meshes with a shaft drive pinion fastened to the upper end of the vertical shaft.

To enable the windmill to turn into the wind - the upper section is mounted on top of another iron plate. A thick layer of grease prevents friction between the two plates.

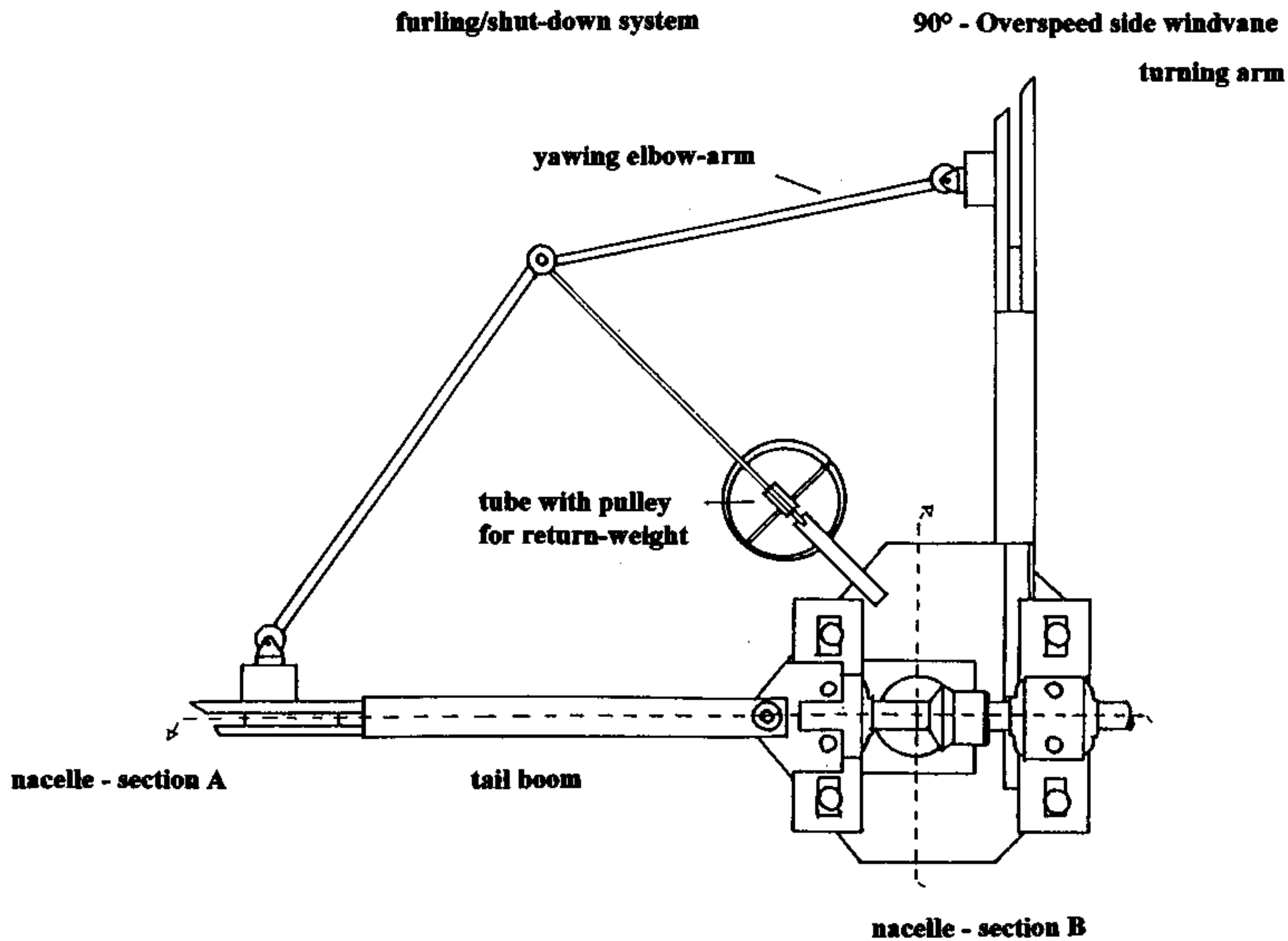
4 iron strips or “flaps” are fastened to a pipe welded to the bottom plate. These strips are to bolt the whole construction to the upper vertical wooden tower section.

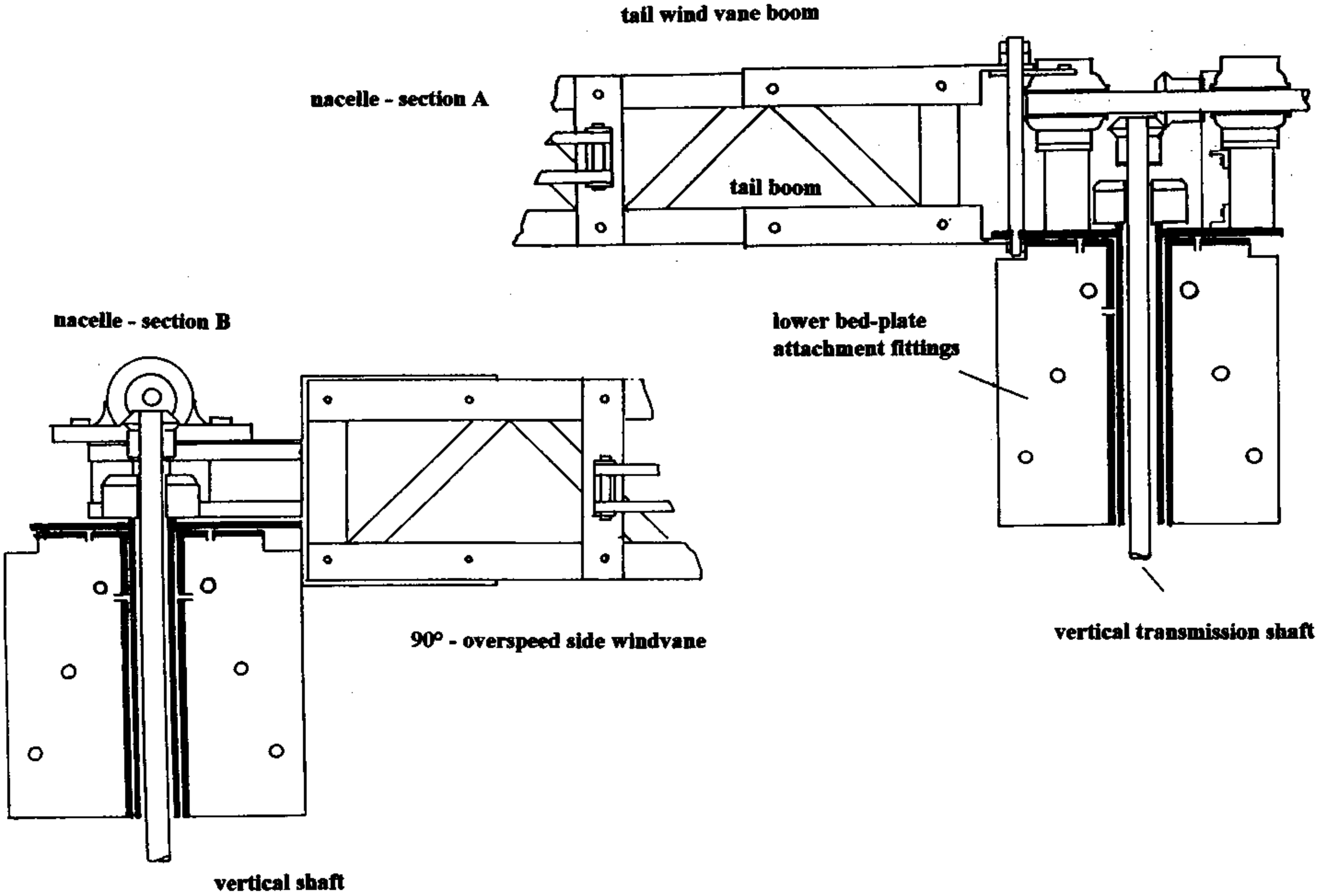
The rear tail boom assembly is bolteded to the rear end of the upper rotating section - positioned on top of the bottom fixed plate. The wooden vane is fastened to the tail assembly with a piece of angle-iron. The side-mounted tail boom in a similar fashion - is bolted to the front end of the upper rotating bearing section.

Due to the flimsy construction the nacelle had several weak points. The force from the blades bent the 5 mm. thick iron bed plate. This resulted in unsatisfactory inter-meshing of the bevel gear teeth due to displacement of the bearing case.

We were unable to construct a satisfactory cover for the nacelle at the workshop in Copenhagen. This was a task for Zitni Potok’s skilled and effective tin-smith who supplied the local surroundings with buckets and containers. Inside an hour - he bent, hammered and riveted a suitable “hat-cover”. We had made a small drawing , but he had no use for that. He just took a large cardboard-box - cut it with a pair of scissors and then asked us - “Does it look like this ?”.

The shaft drive pinion gear wheel’s mounting on the transmission shaft with a keyway or slot and a locking ring was a further weak point. The locking ring slipped off when the machined mounting track on the shaft became worn. We had neglected to have the transmission shaft hardened.


furling/shut-down system
90° - Overspeed side windvane
turning arm
yawing elbow-arm
tube with pulley
for return-weight
nacelle - section A
tail boom
nacelle - section B


tail wind vane boom
nacelle - section A
tail boom
lower bed-plate
attachment fittings
vertical transmission shaft
nacelle - section B
90° - overspeed side windvane
vertical shaft

tinsmith making the nacelle cover

Gearing

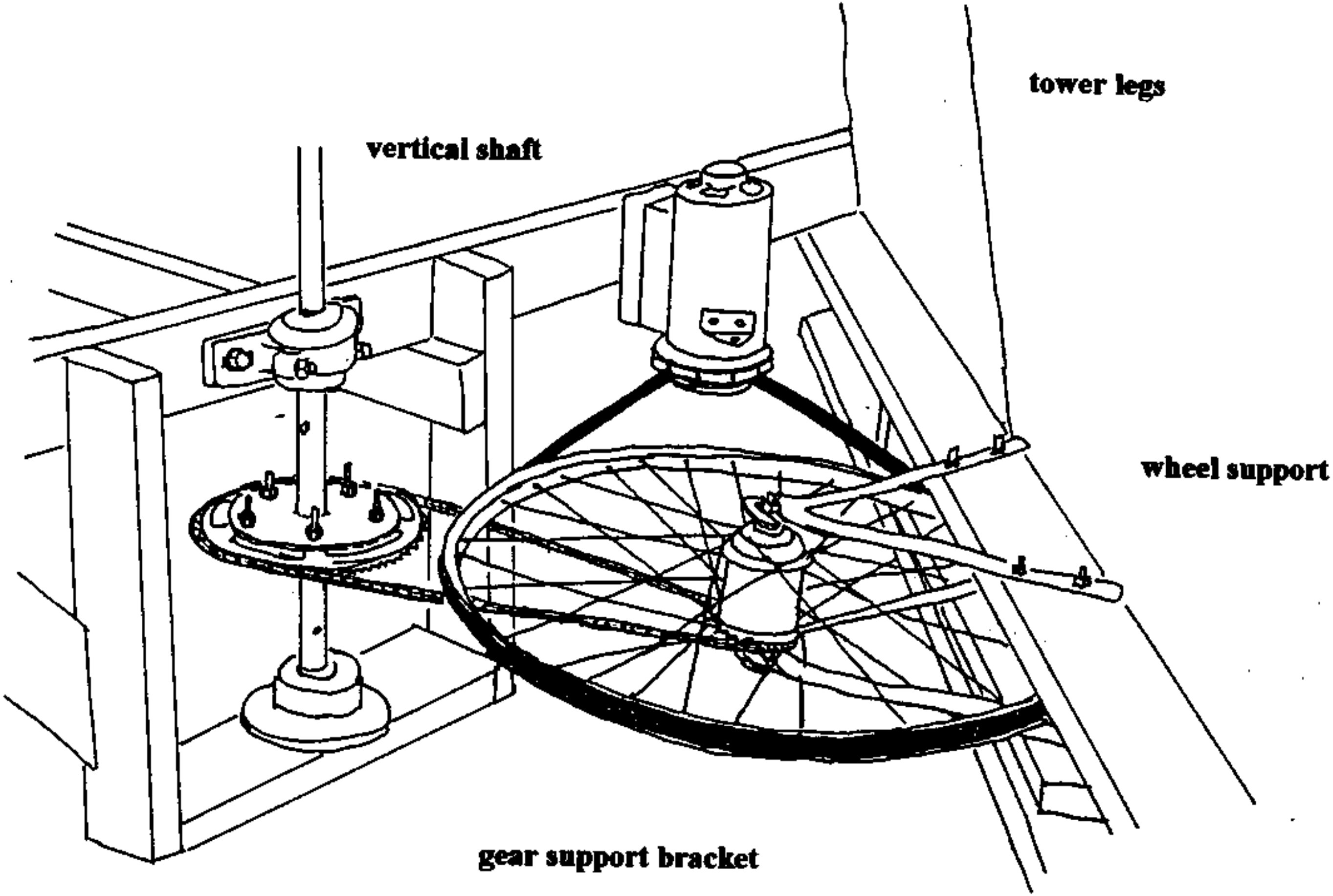
We had difficulty in calculating the gear ratio as we could find no exact formula concerning the blade-tip speed and the effect of our chosen blade type. With the assistance of Claus Nybroe - we approximately estimated - a maximum dynamo effect at **2400 rpm.** - the gearing should therefore be **app. 1 : 28** - as the rotational speed of the blades was estimated to be about **87 rpm.**

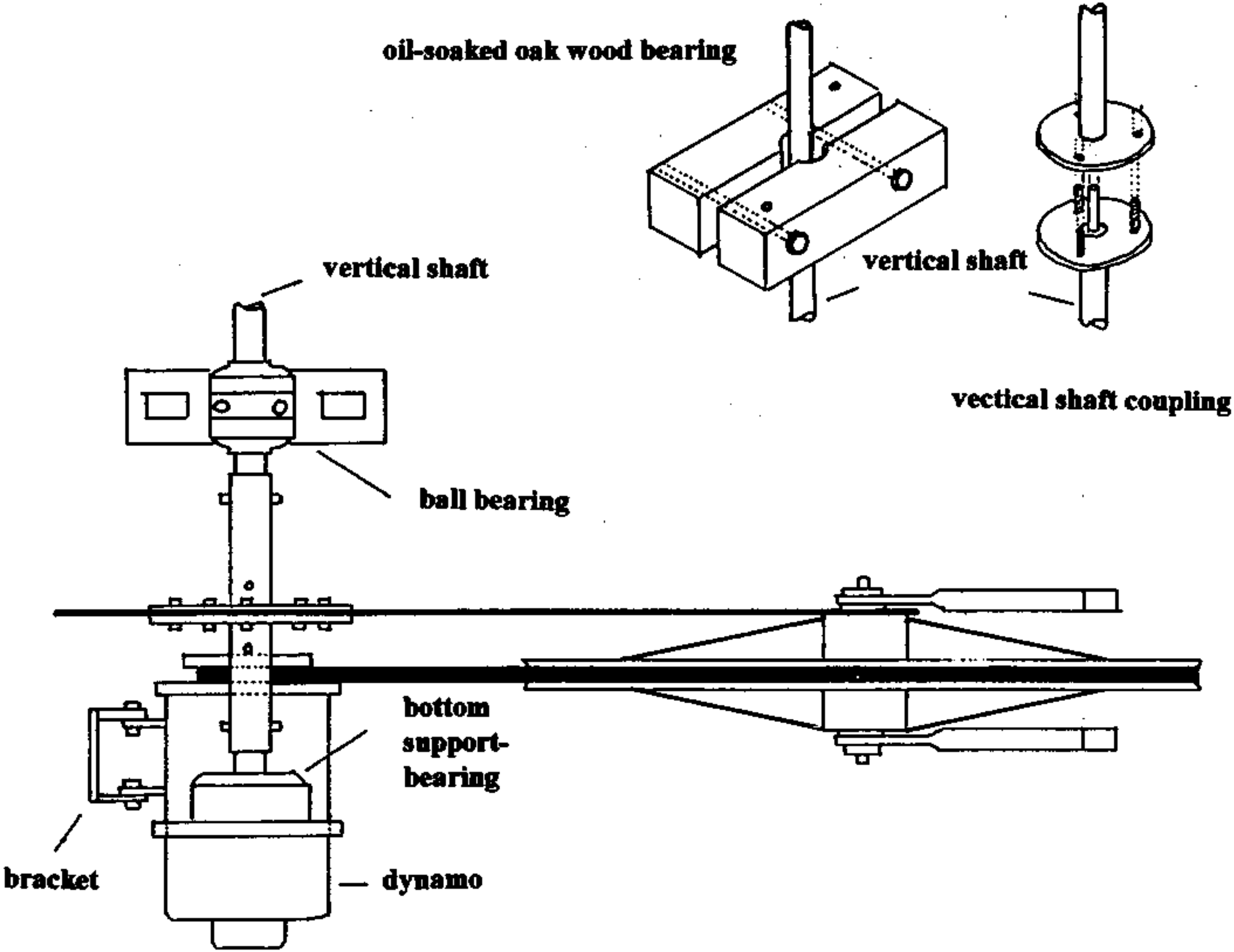
The main gear is placed at the foot of the long **5.5 m.** vertical transmission shaft. This shaft is supported by **3** wooden oak block bearings. These bearings are each made from two blocks of oak boiled in linseed oil. The bearings are then fixed around the shaft as seen in the drawing -and will absorb the radial thrust and prevent unwanted sideways movement and vibration in the shaft.

The shaft is made of three lengths with welded flanges to enable coupling [thick rubber washers should perhaps be placed between the flanges - note by JF.]. The power take-off - a **52-teeth** bicycle crank-wheel - is positioned between the fixed ball bearing and the lower bearing support.

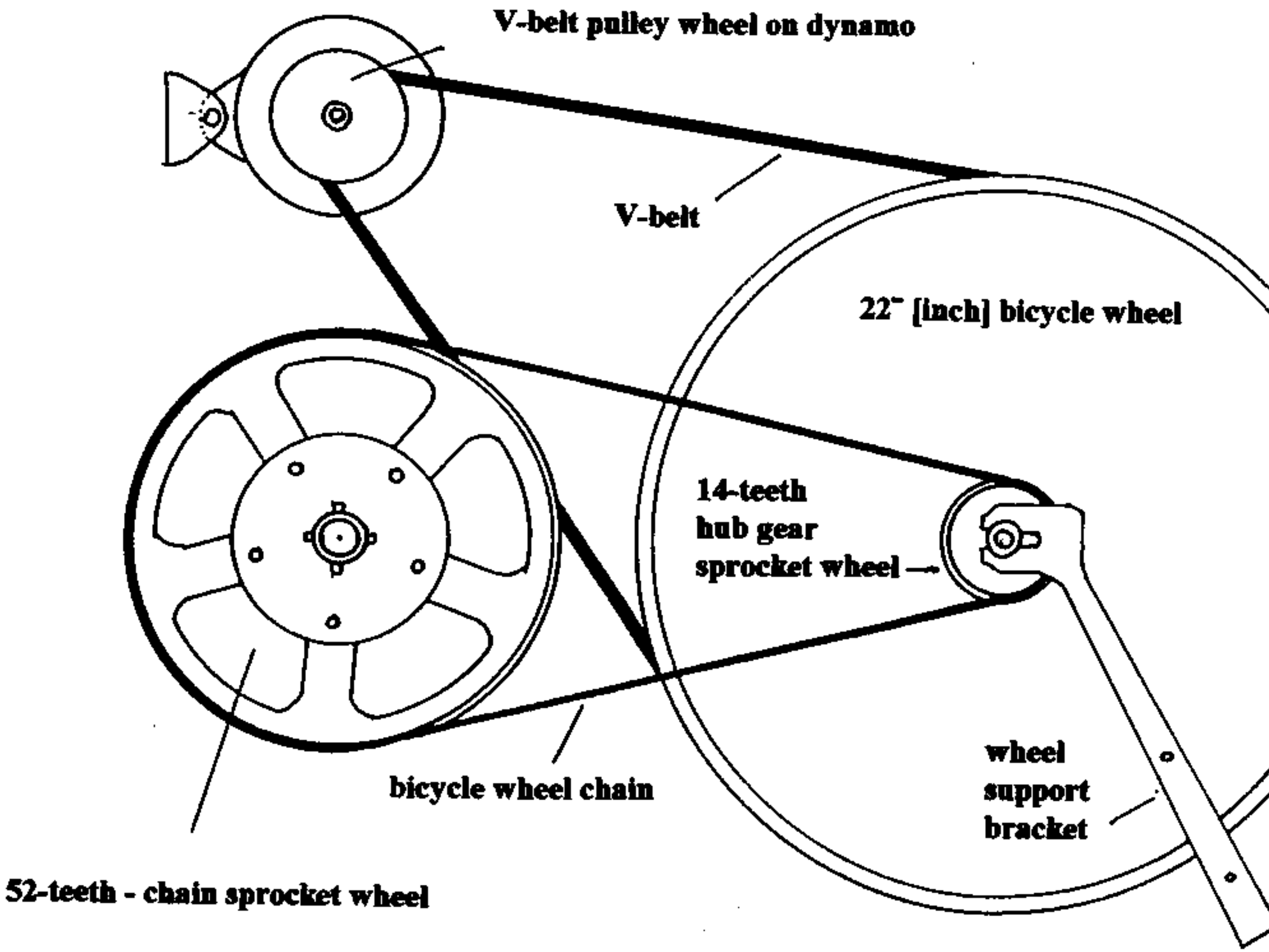
A bicycle chain goes from here over to a **22" [22 inch]** bicycle rear-wheel equipped with a
14-teeth gear wheel. A V-belt goes from the inside rim over to the dynamo's V-pulley wheel.
This construction gives the required 1 : 28 gearing. There is also the possibility of a gear-shift to a lower gearing as the wheel hub is equipped with a 3 speed - Sturmey Archer hub gear. This allows the possibility of compensating for possible calculation errors concerning the windmill gear ratio.

The wheel, dynamo and bearings are supported by brackets and fittings on the tower-leg horizontal cross pieces. These cross pieces are subject to strong vibrations during periods of strong wind - resulting in a risk of the V-belt falling-off. A much stronger reinforcement of the cross pieces is necessary.


tower legs
vertical shaft
wheel support
gear support bracket



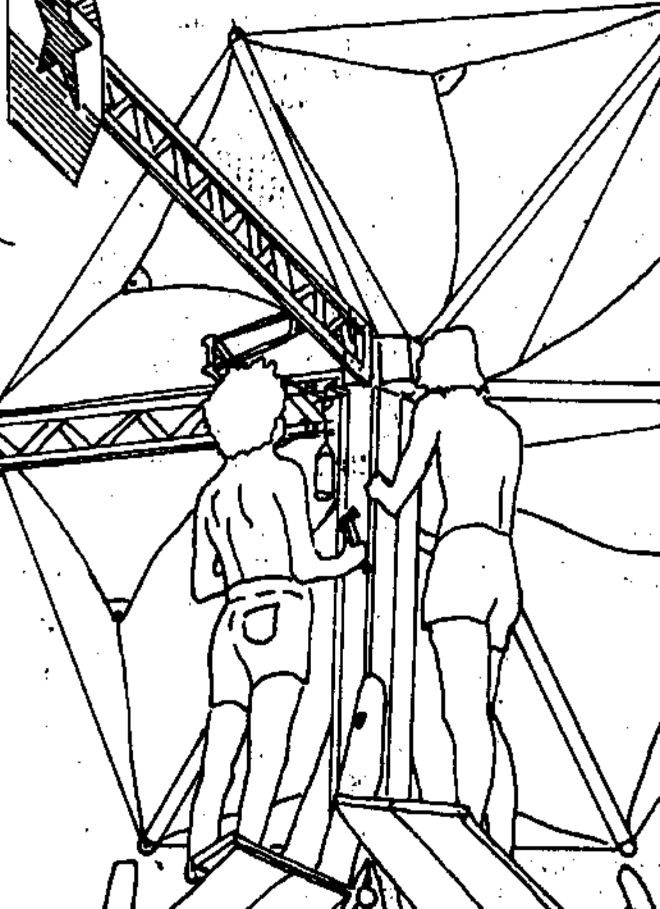
oil-soaked oak wood bearing
vertical shaft
vertical shaft
vectical shaft coupling
ball bearing
bottom support-bearing
bracket
dynamo

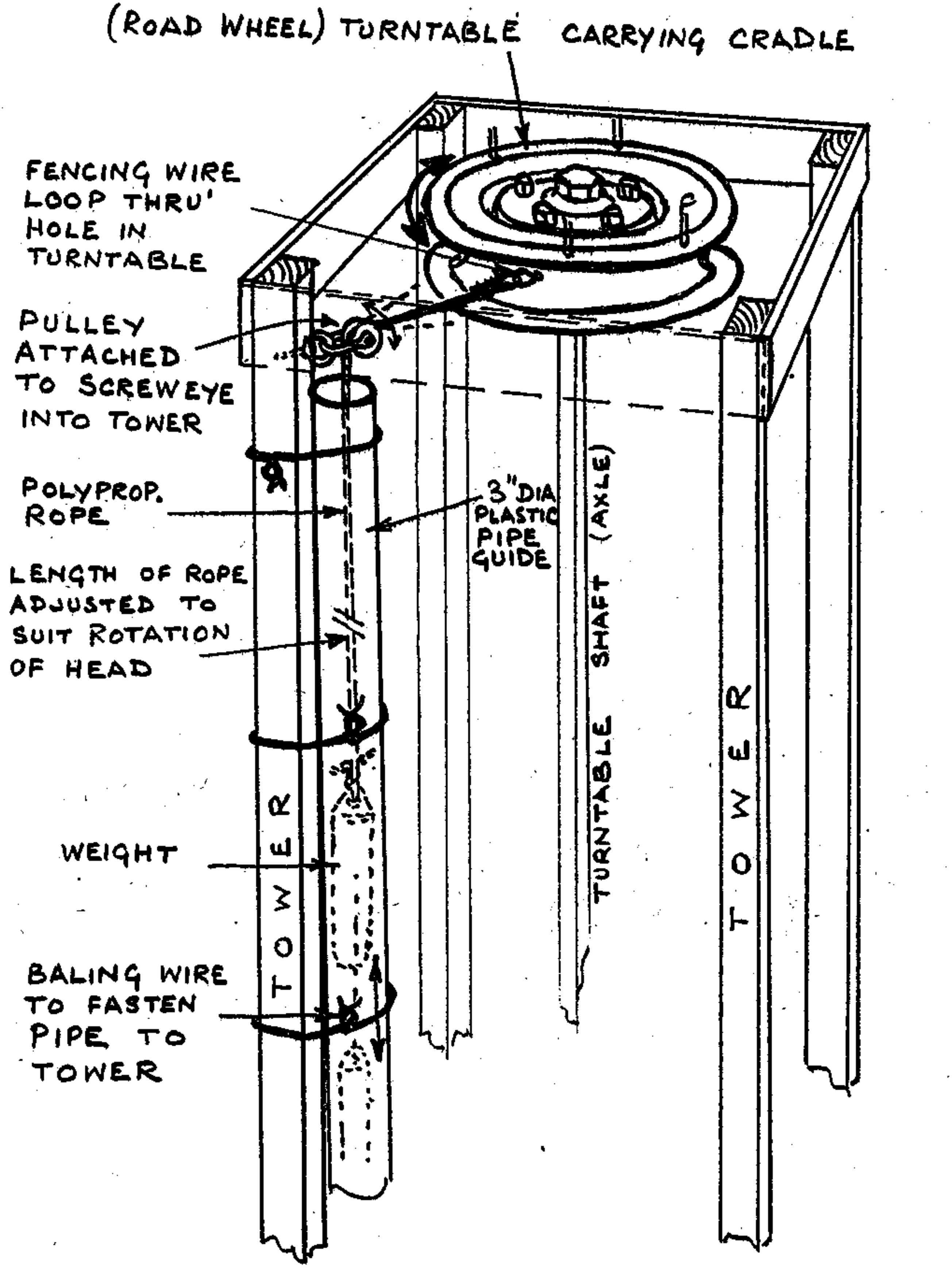

V-belt pulley wheel on dynamo
V-belt
22" [inch] bicycle wheel
14-teeth
hub gear
sprocket wheel
wheel
support
bracket
bicycle wheel chain
52-teeth - chain sprocket wheel

Tail and Side Wind-Vane

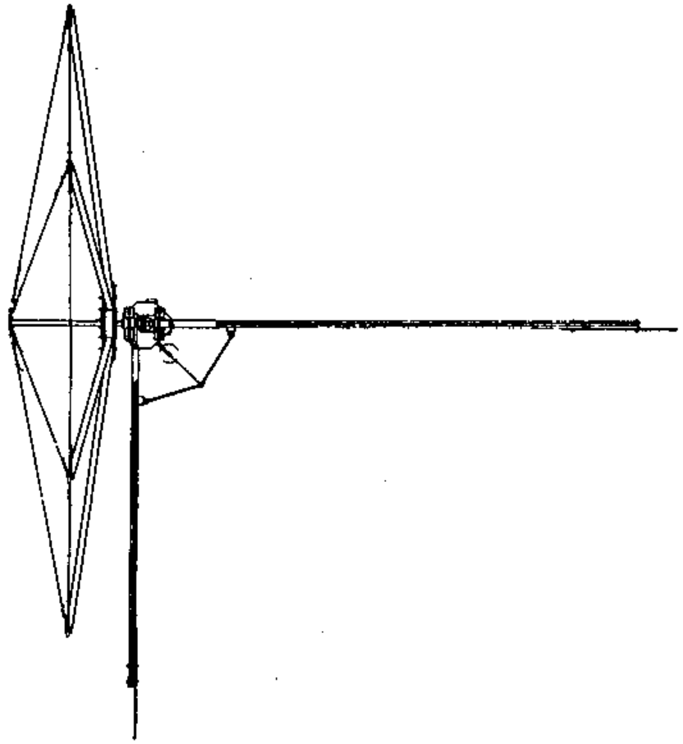
The very strong girder construction of the tail and side wind-vanes was made of **1.5 cm.** thick - wooden laths - to reduce the weight.

A spring mechanism was first used to return the side vane and the rotor back to an operative position. This was later abandoned in favour of a "Falling-weight" - [this principle is clearly shown in a following diagram taken from another project]. When the windmill turns out and away from the wind - the falling-weight is pulled up. The weight's "return-force" is therefore able to return the windmill to the start position as soon as the force from the excess wind speed has lowered.

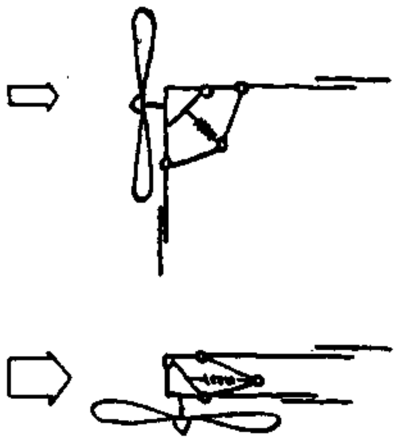




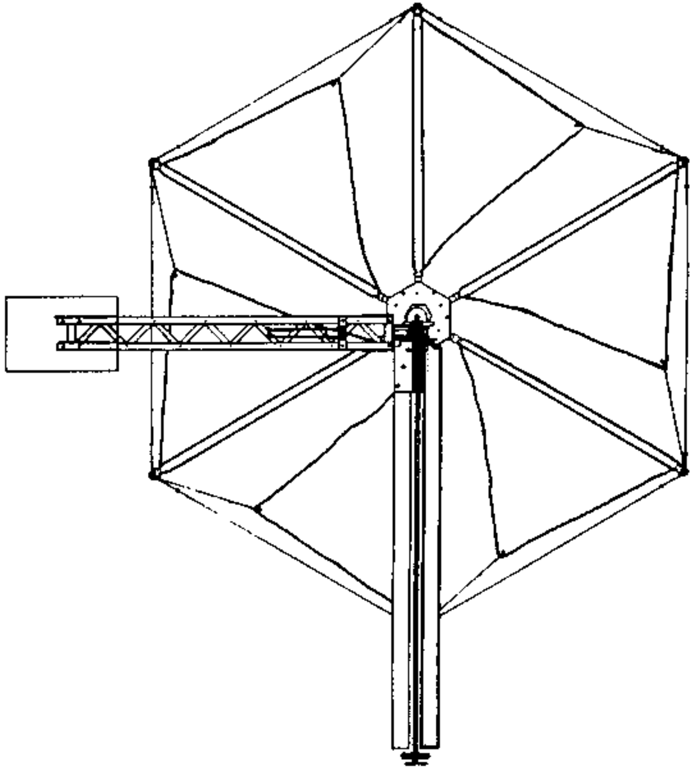
(ROAD WHEEL) TURNTABLE
CARRYING CRADLE
FENCING WIRE LOOP THRU' HOLE IN TURNTABLE
PULLEY ATTACHED TO SCREWEYE INTO TOWER
POLYPROP. ROPE
3" DIA PLASTIC PIPE GUIDE
LENGTH OF ROPE ADJUSTED TO SUIT ROTATION OF HEAD
TURNTABLE SHAFT (AXLE)
TOWER
TOWER
WEIGHT
BALING WIRE TO FASTEN PIPE TO TOWER



turning/yawing arm



yawing system



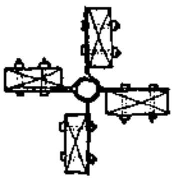
Tower

The experimental tower - built in Denmark - was too big to be transported to Serbia, - and a new one was constructed on site.

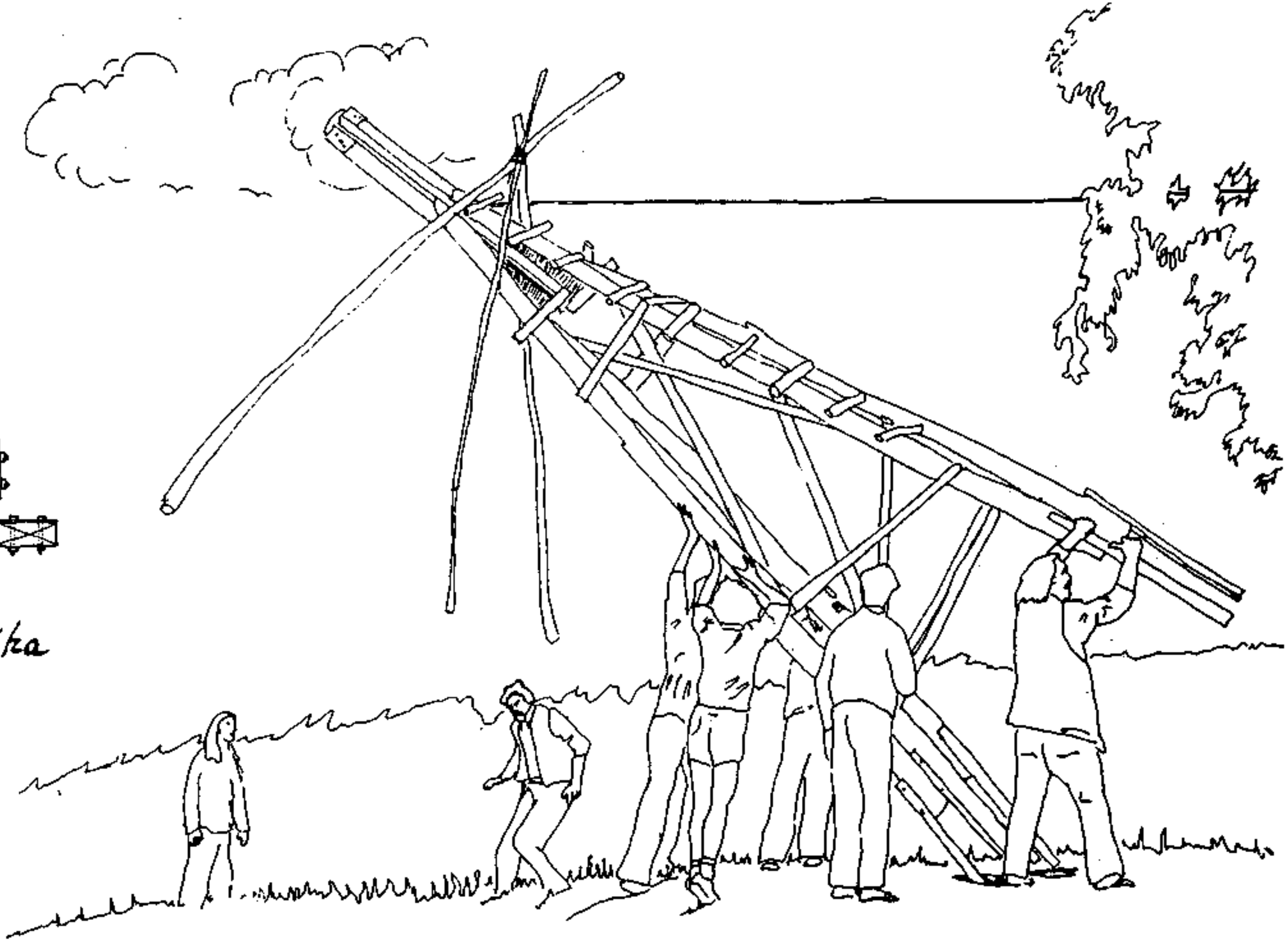
The upper **2 m.** vertical wooden tower section - was assembled in the form of a svastika - bolted onto the lower nacelle bottom plate “flaps”. This section was then bolted onto the angled tower legs. Wooden cross pieces were then fixed to provide additional constructional stiffnesss.

The rough and uneven tower oak poles gave many problems. This was erected with the assistance of the 4-wheel drive Unimog truck. Four foundation holes were excavated **70 cms.** down into the solid rock. Each leg was fitted with two bolted-on lengths of angle iron - to provide a good join with the concrete poured into the foundation holes and to raise the wooden legs app. **- 15 cms**. above ground level.

Following the tower erection - a home-made scaffolding was built to enable the nacelle, top covering and the rotor to be mounted in place.



Svastika



The Electrical System

Dynamo
Most newer cars use an effective AC-generator called an alternator. Alternators however require a starting current from a battery to energise the system [magnetise the stator]. This means that during periods of no-wind - this requirement could discharge the battery.

A dynamo will start to charge at about 1000 rpm - it will have a maximum effect at about 2400 rpm and highest rotational speed at about 7000 rpm.

NB: - If the dynamo has been unused for a long time - or if it has been run in reverse. There is a possibility that the remanence or residual magnetism has been lost. [that is - the iron core has lost it's magnetism and must therefore be re-magnetized].

The dynamo is connected to a battery [both a 6 V or a 12 V - battery can be used] - and run as a motor for an instant. The dynamo is re-magnetized and is therefore now able to produce electricity and charge batteries. This method is also a good test of of a dynamo - if these are purchased second-hand. If a dynamo cannot run as a motor - it is fairly certain that it is defect.

Relay
The function of the relay is to regulate the current and voltage produced by the dynamo. A relay is an iron core wrapped with a copper wire winding [a spool]. When current is sent through the spool - the iron core is magnetized - and is able to attract an loose iron plate [the relay armature]. The relay armature is connected to one or more electrical contacts - which are then opened or closed.

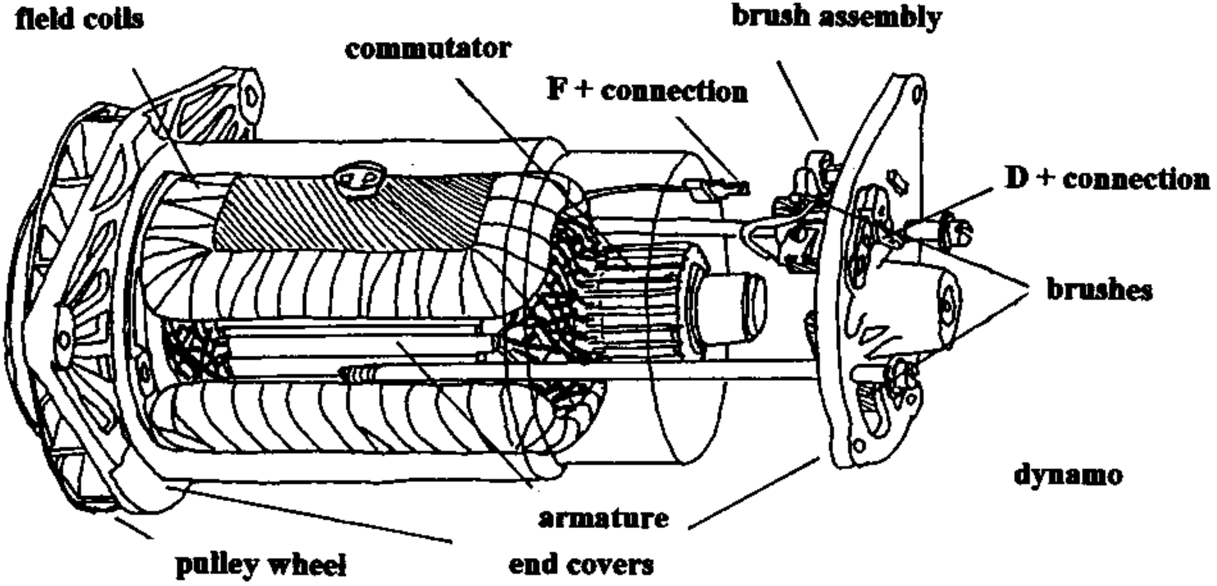
There are several different manufacturers and many different types of relay's available on the market - differing in numbers of spools and armatures. It is important when purchasing a relay to ensure that the dynamo and relay can function satisfactorly together. And to ensure that the they both have **plus [+] or minus [-] to earth [ground]**.

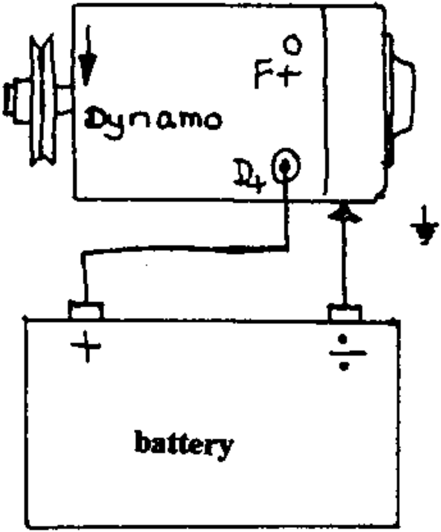
Electrical Wiring
Current-loss in a low-voltage system is quite considerable. This means that one must place the windmill in the near vicinity of the power consumption if one does not wish to use arm-thick power cables. We chose to place the batteries at the foot of the tower, enabling us to use normal household electrical wiring. Every week or so - the discharged battery from the house must be exchanged with the now fully charged battery from the windmill. If we had chosen to lead the current 20 meters - directly into the house - we would have required a cable with a thickness of **10 mm cross-section** - as can be seen in the nomogram.

Battery
A car battery is not the most efficient for windmill use - as it is constructed for many small charges and discharges - and is not very suitable for deep discharging. We were fortunate in obtaining a battery from a fork-lift truck - nearly an ideal type - built for hard daily use with a night-time re-charge.
The battery size must also roughly correspond with the dynamo's electrical production capacity or effect - as can be seen from the following table.

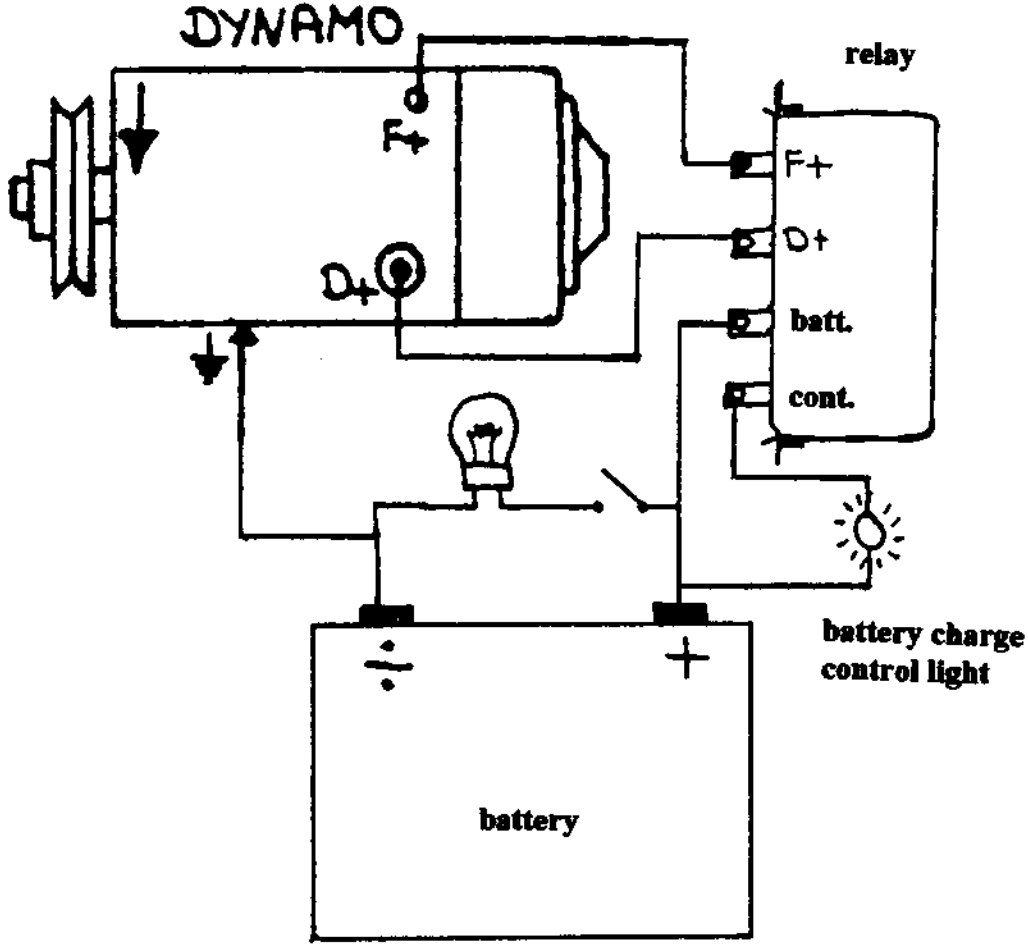
Batt. - Amp/hours	**105**	**150**	**300**
Dynamo	**130**	**200**	**500**

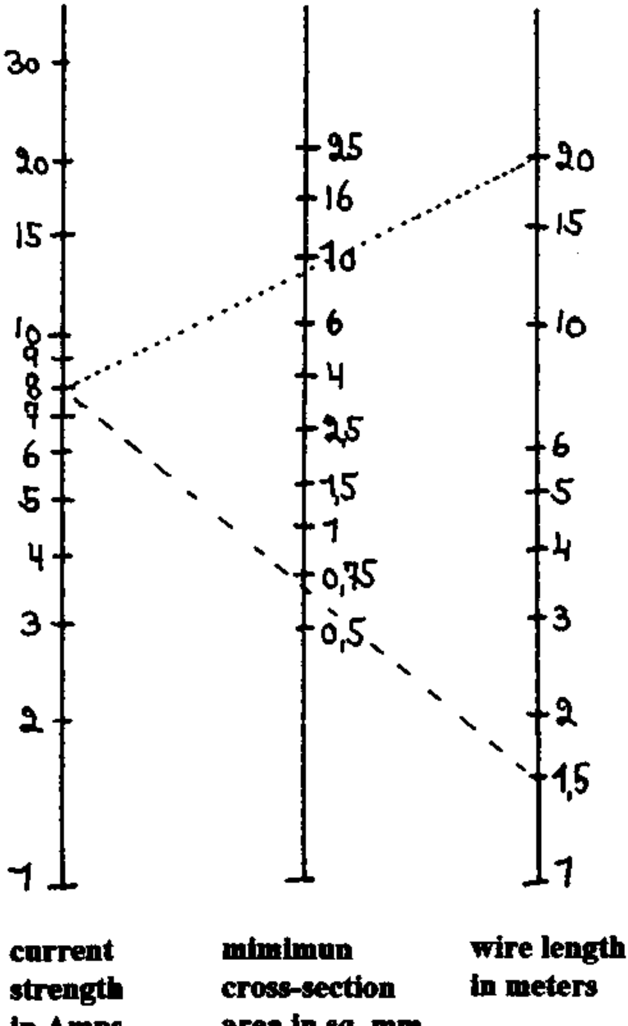
Batteries that are not often used - will suffer a chemical discharge and over a longer period of time the cells are destroyed. If a battery is left unused for a longer period - it must therefore be charged from time to time and distilled water must be added to the cells. [self-discharge is roughly about **0.7%** of the battery capacity pr.day]


field coils
commutator
F + connection
brush assembly
D + connection
brushes
dynamo
armature
pulley wheel
end covers



F+
Dynamo
D+
+
battery


DYNAMO
F+
D+
relay
F+
D+
batt.
cont.
battery charge
control light
+
battery


30
20
15
10
9
8
7
6
5
4
3
2
1
25
16
10
6
4
2,5
1,5
1
0,75
0,5
20
15
10
6
5
4
3
2
1,5
1
current strength in Amps
mimimun cross-section area in sq. mm.
wire length in meters

Total Costs

If one has time to look through junk-yards and if material is bought through scrap-merchants etc. - a windmill can be made at very low-cost.
Our cost list from 1978 - does not include the the expense of the tower.

Bearings including housing	------------------------------	App $ 35.00 USD
Top bevel gears	------------------------------	5.00
Spars - etc.	------------------------------	26.00
Iron sheet/plate	------------------------------	17.00
Angle-iron	------------------------------	3.00
Wood and plywood sheets	------------------------------	23.00
Various bicycle components	------------------------------	35.00
Dynamo with V-belt and relay	------------------------------	27.00
Nuts - Bolts, screws etc	------------------------------	131.00
Battery	------------------------------	43.00
Extras	------------------------------	10.00

Total app: $ 355.00 USD.

EN VINDMØLLE TIL SERBIEN

af *Kim Høite & Torben Eriksen*
FREJA

ISBN 87-7344-005-1

1. oplag

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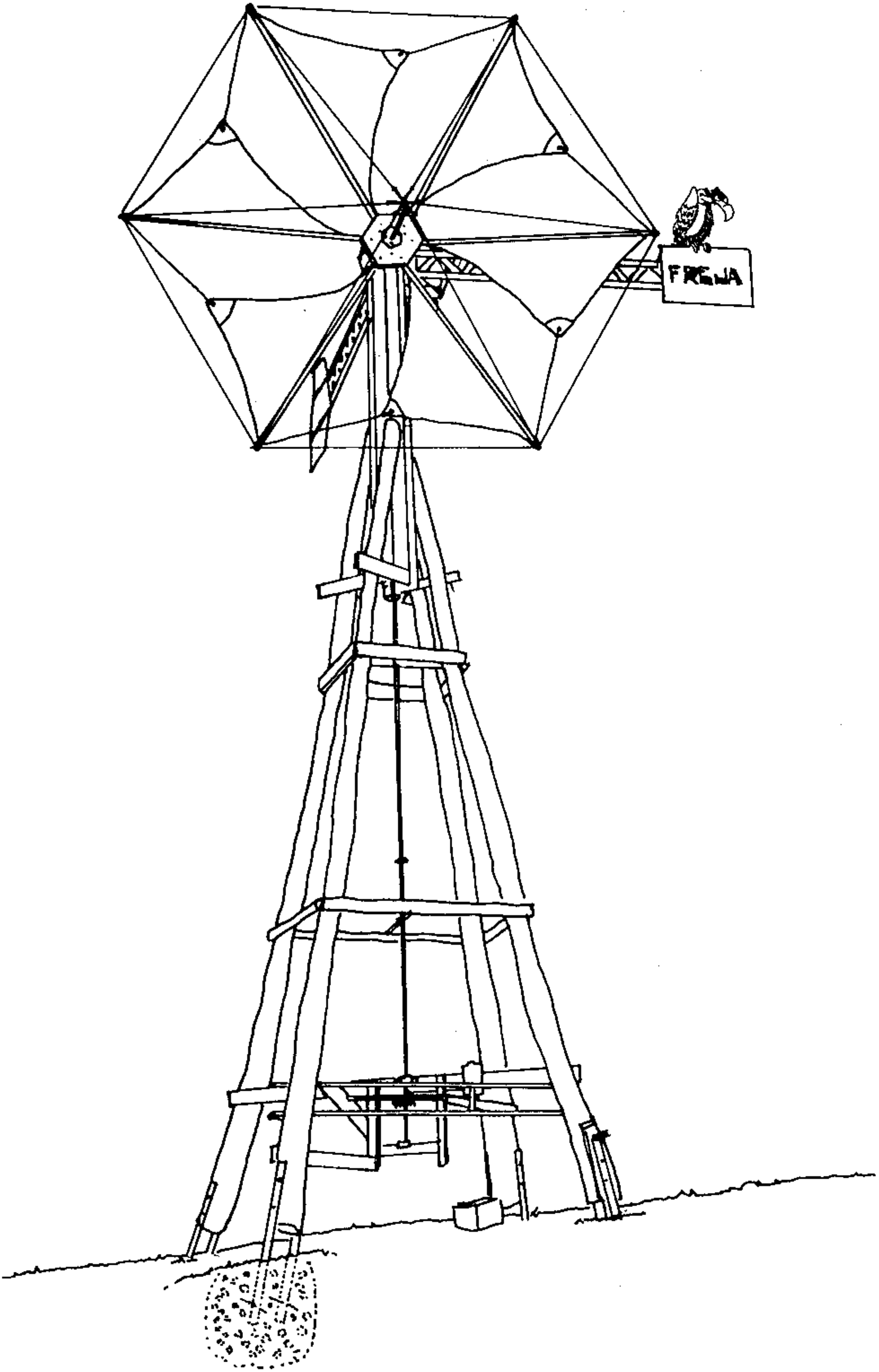
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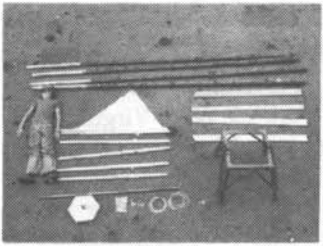
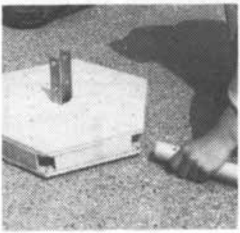
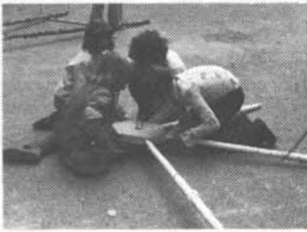
En god begyndelse

fra Bagsværd Ny Lilleskole







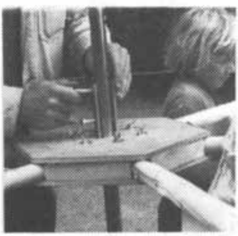


PLATE NO. 48

The sail windmill can be the most efficient of all wind machines if proper modern airfoil cut sails are used. A great deal of development money has been spent to perfect such sail designs for world class yacht races, like the Americas Cup.

It might even be a good idea to tailor your mast lengths to the size of the sails you can buy.

Home made sails will work, they just do not work as well.

If you use "store bought" sails, you should also use the masts that are designed to go with them. Tailor the hub thickness accordingly.

The disadvantage of the sail windmill is that the sails have to be taken down, or furled, (fig. 3), in foul weather. They are, therefore, not ideal for northern hemisphere winters.

The theory, or principle, is that the windmill sail operates in the same way as the jib sail on a yacht, (see 1, 2, 3 and 4). The jib sail in fig. 4 looks just like the windmill sail in fig. 1.

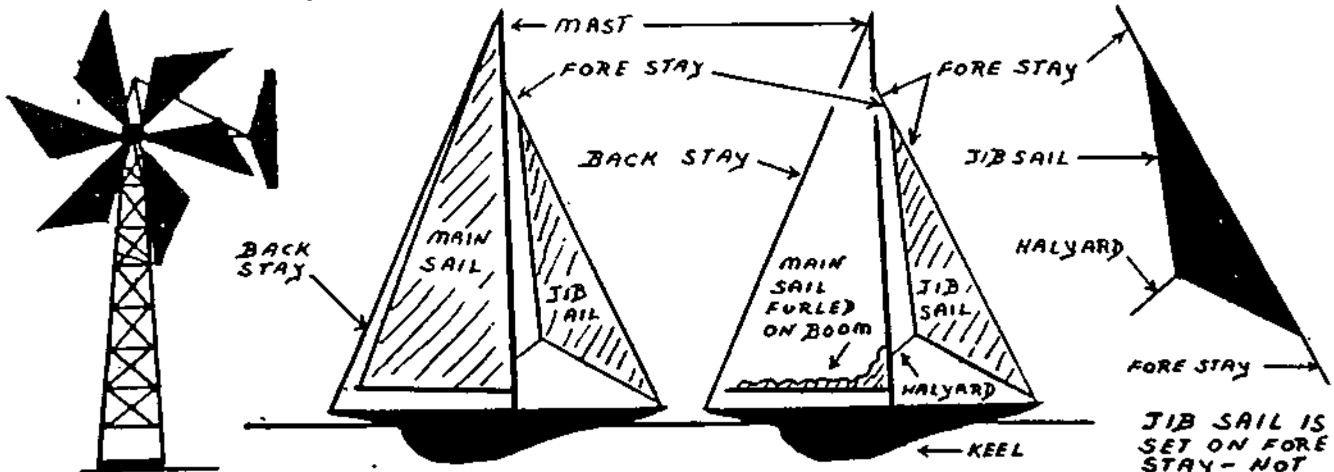
Fig. 5 and 6, show that the windmill sail works in the same way as the sail on a yacht when the yacht is sailing on a "beam reach".

A six sail windmill, therefore, has the same power as a yacht with six jib sails sailing on a beam reach.

PLATE No 48

- THE SAIL WINDMILL - I
- PRINCIPLES -

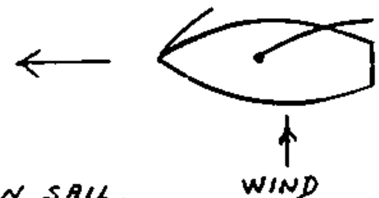
- WORKS LIKE JIB SAIL ON SAIL BOAT - WHEN BOAT IS SAILING ACROSS, OR AT RIGHT ANGLES TO THE WIND ON A "BEAM REACH" -

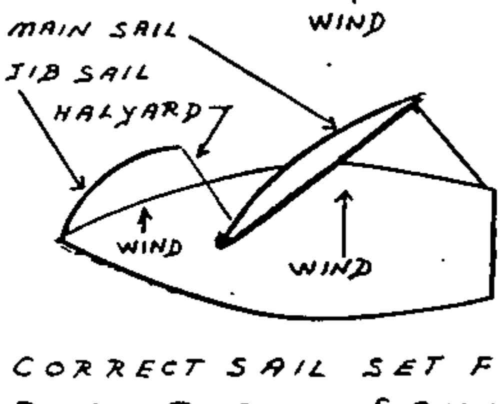


SAIL WINDMILL — RACING YACHT - BOTH SAILS SET — SAME YACHT WITH ONLY JIB SAIL SET — JIB SAIL IS SET ON FORE STAY - NOT ON THE MAST - AS IT IS WITH THE SAIL WINDMILL -

VESSEL SAILING ON BEAM REACH

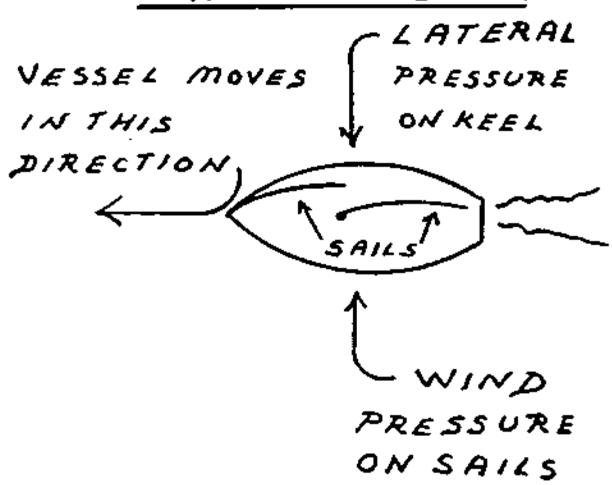
- WIND COMES OVER SHIPS SIDE (BEAM)





CORRECT SAIL SET FOR BEAM REACH - SAILING ACROSS THE WIND - AS FAR OUT AS SAILS WILL GO WITHOUT "LUFFING" - OR FLAPPING - AT THE FOREWARD EDGE CLOSE TO THE MAST OR FORESTAY - THE SAIL WINDMILL SHOULD BE SET IN THE SAME WAY - AIR FOIL PRINCIPLE -

HOW VESSEL SAILS ON A BEAM REACH



NOTE - WIND DIRECTION IS 90° TO DIRECTION OF VESSELS MOVEMENT -

- SAIL WINDMILL WORKS IN THE SAME WAY - EXCEPT THAT TOWER RESISTANCE TAKES THE PLACE OF KEEL RESISTANCE OR PRESSURE -

PLATE NO. 49

These designs are all for 15' masts and 30' diameter sail areas, (see plate no. 2), which are most effective in areas having expected annual seasons of very light winds.

For areas where the expected norms are for winds of 10 m.p.h., or more, the mast lengths can be reduced to 7' 6" and the sail diameters to 15'. All given measurements will apply in terms of the reduced scale.

The mast thickness here recommended for all mast lengths is the dressed Douglas Fir or Pine, 2" X 2" which actually measures 1 1/2" X 1 1/2".

Fig. 1, 2 and 3 show how the sails in fig. 1 can be "furled" to reduce the sail areas so that they resemble the sails in plate no. 2.

Sail sizes are reduced in area by "reefing" for reasons of safety, when wind speeds indicate that they might increase to alarming proportions.

To reef a sail, you take the selected reef strings, hanging from the reef points (fig. 3), and tie them together around the long side of the sail. Be sure to use proper "reef knots", or the reefs will be impossible to untie when you want to increase the sail areas.

Fig. 3 and 4 shows how the stays and halyards work. "Stays" are permanent support wires, while halyards are working ropes that run through a pulley.

The "triadic" stay is a wire cable that runs from masthead to masthead, as it does on a schooner, and, thereby, creates the permanent unbreakable circle.

The "halyard" ropes work through the pulleys on the mastheads to pull the sails up and out. The halyard ends must be coiled and tied off, or cleated, at the bottoms or "feet" of the masts.

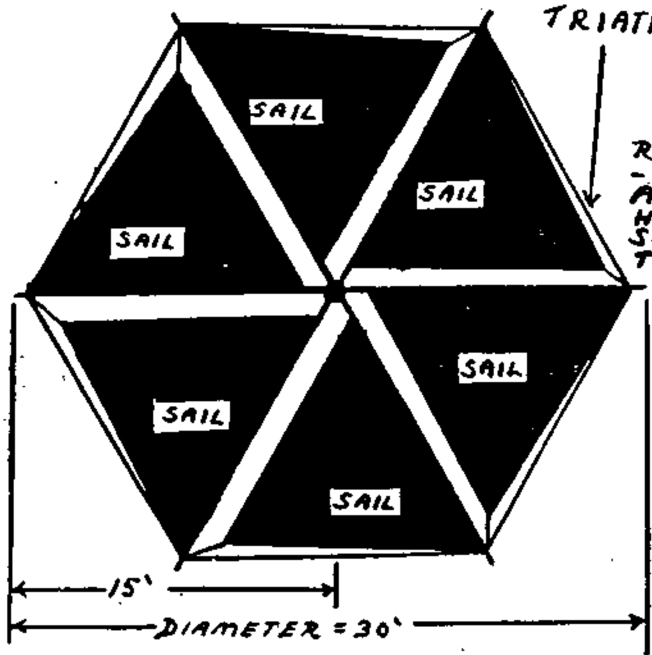
The sail windmill, especially with the 30 diameter sails, is designed to work on the wooden rotating table. Fifteen foot diameter sails, however, can be mounted on a metal rotating table, (see references in the "design relationships" section).

PLATE No. 49

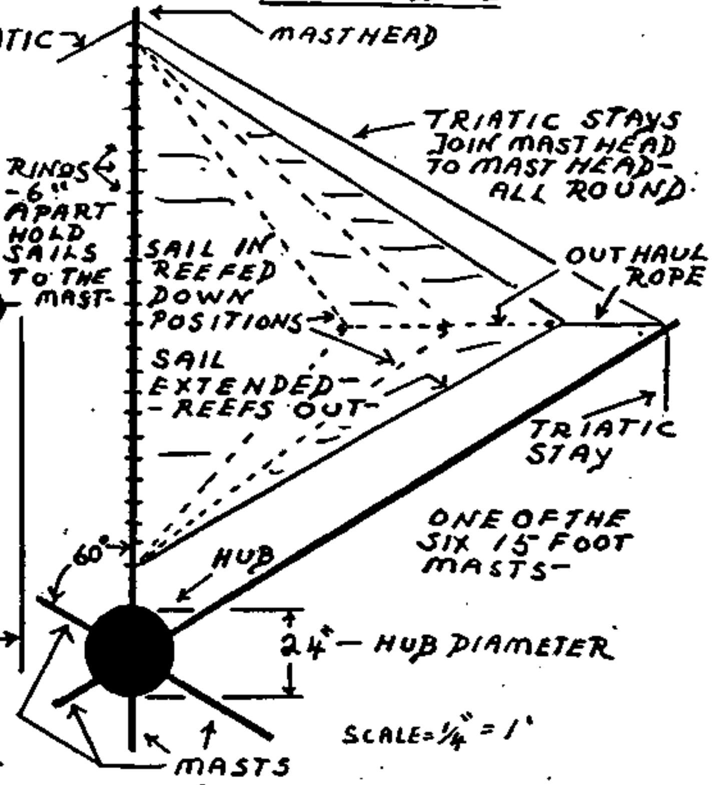
THE SAIL WINDMILL II
THE SAILS

- 30 FOOT DIAMETER WINDMILL — FOR AREAS WHERE WINDS ARE VERY LIGHT — OR TO CATCH DAILY ON SHORE BREESES AS IS DONE IN CRETE — TO MAKE SMALLER - 15 FOOT DIAMETER MACHINE - SIMPLY DIVIDE ALL DIMENSIONS BY 2 — :

SAIL AREA - FRONT VIEW

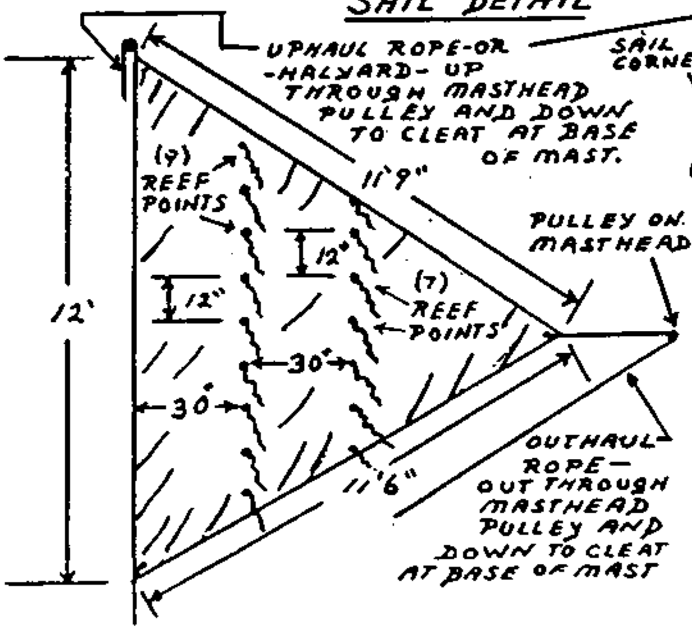


SAIL RIGGING

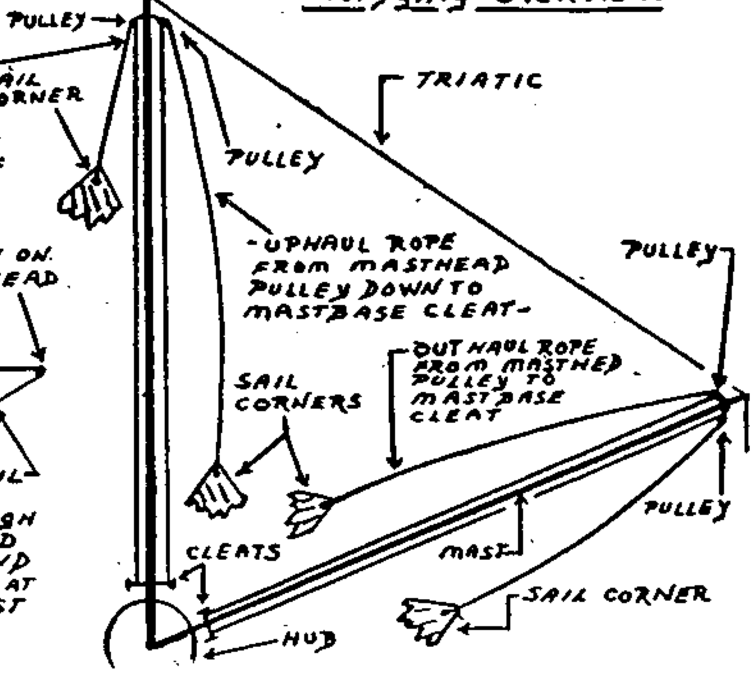


NOTE - ABOVE, ALL SALES ARE FULLY SET, FOR A VERY LIGHT BREESE - REEFS REDUCE SAIL SIZE TO DOTTED LINE AREAS.

SAIL DETAIL



RIGGING OVERVIEW



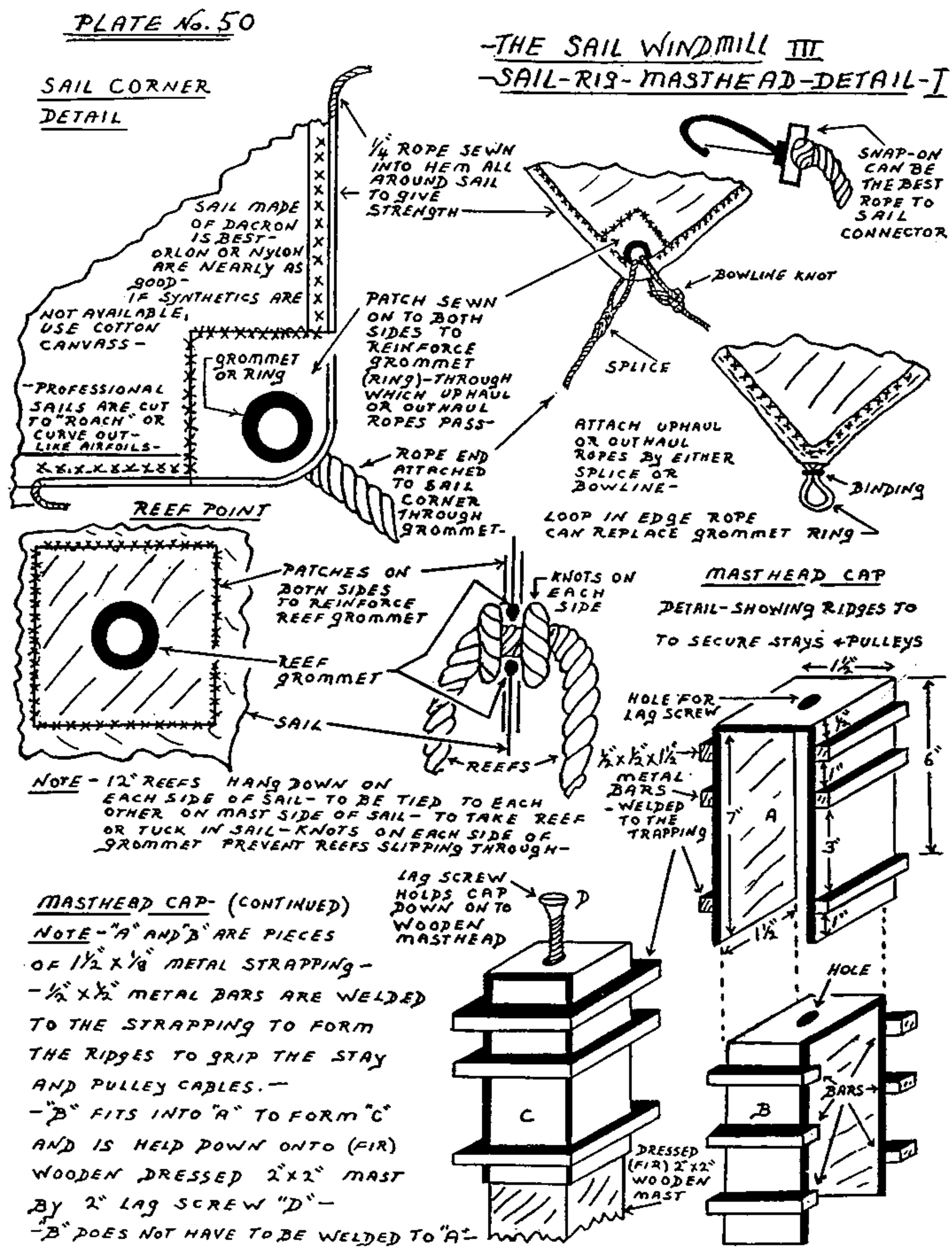


PLATE NO. 50

Fig. 1 to 6 show sail fittings that can be made at home or bought from marine supply stores.

Fig. 7, 8 and 9 show an easy to build masthead cap that will accommodate the stay cables and the cables that hold onto halyard pulleys.

PLATE NO. 51

Fig. 5, 6 and 7, show ring fittings that hold sails to masts that can be made at home. The only problem is that as the rings have to run up and down the whole length of the mast, which means that you can only have one fore stay, you can not have a second fore stay running of the rings from the top to the bottom of the mast.

The car and rail systems, shown in figures 8, 9 and 10, allow for the second fore stay, as illustrated in plate no. 53, fig. 5. These systems can be purchased, in total, from marine supply stores.

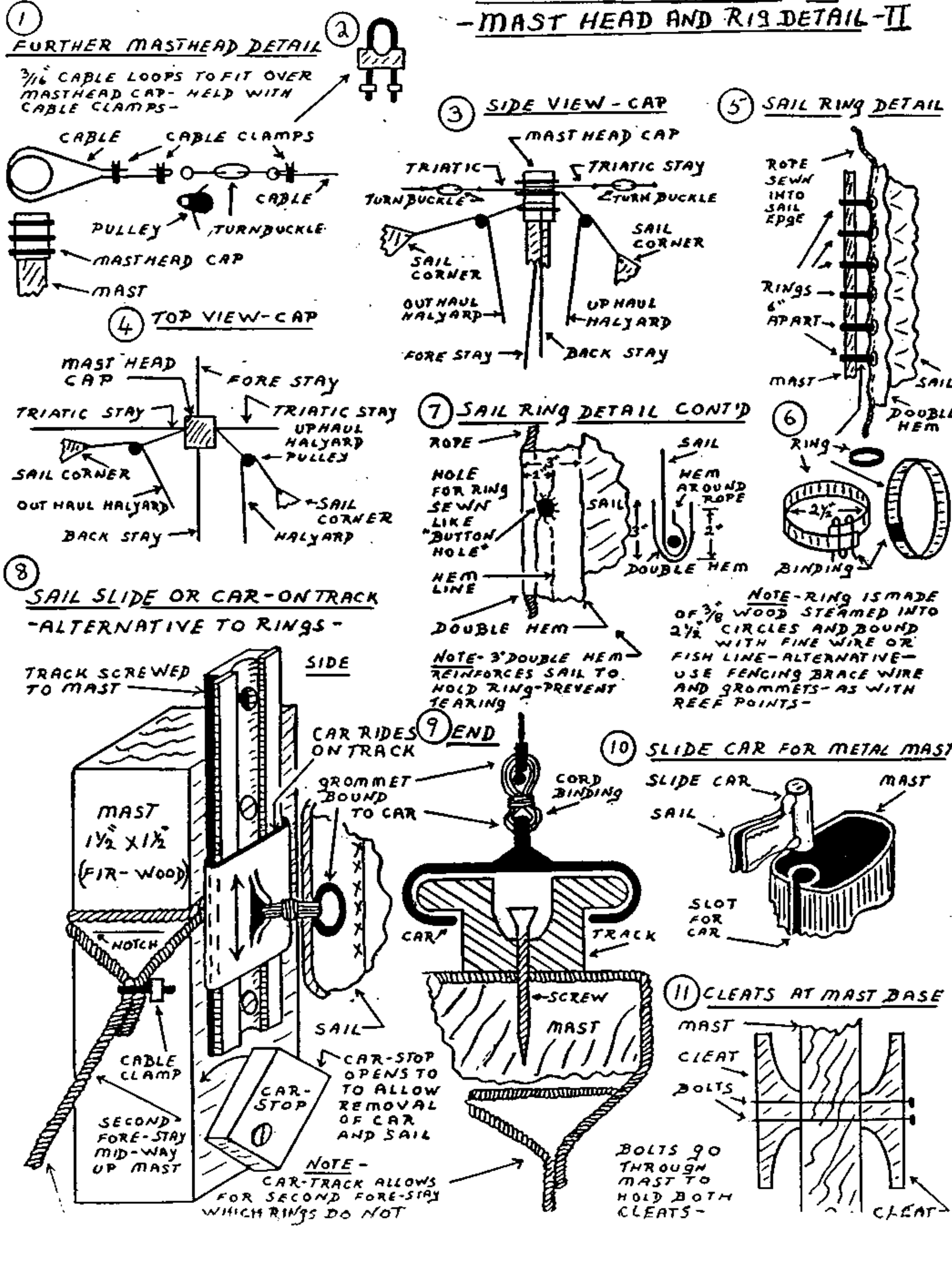
Fig. 10 shows an alternative that can also be purchased from marine supply stores. It also permits the use of a second fore stay at the centre of the mast. Fore stays run foreword and support the mast against the force of the wind.

Note the masthead stay and halyard arrangements, illustrated in fig. 1, 2, 3 and 4.

Fig. 11 shows the cleat arrangement at the base of the mast for tying off the halyards. The cleats can also be placed on the hub at the base of each mast, (see plate no. 52, fig. 3).

PLATE No 51

—THE SAIL WINDMILL IV
—MAST HEAD AND RIG DETAIL—II



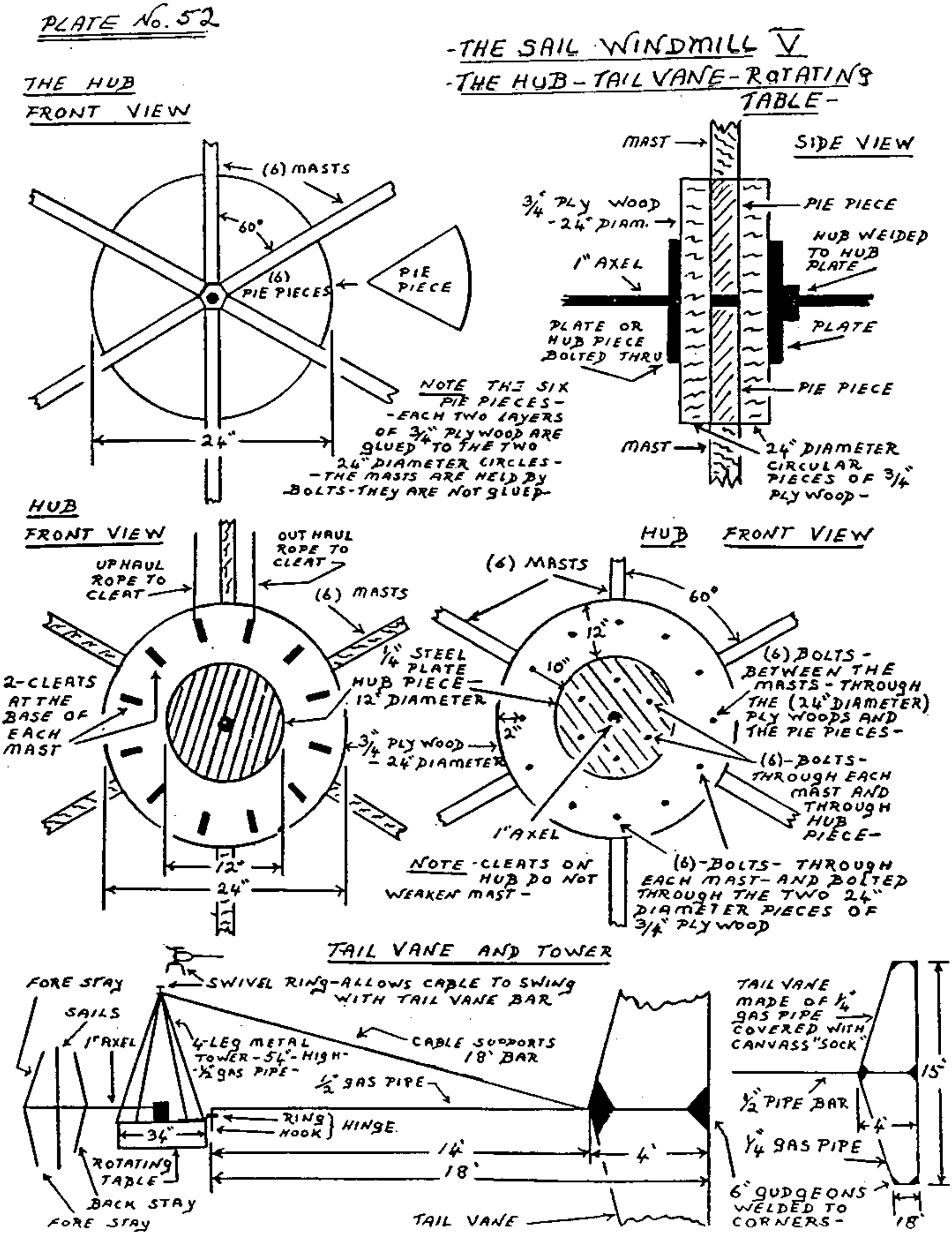


PLATE NO. 52

The hubs in fig. 1, 2, 3 and 4, work in the same way as the metal hub in plate no. 17. Take special note of plate no. 17, fig. 3.

Fifteen foot diameter sails can have a 12" diameter hub, but 30 foot diameter sails should have a 24" diameter hub. This is a question of properly "stepping" the mast.

Fig. 5 shows the need for the four leg metal tower to give proper support to the cable that supports the 18' tail vane for the 30 foot diameter sails. This tower will not be needed on 15' diameter sails. They can use the tail vane system illustrated in plate no. 36.

PLATE NO. 53

Fig. 1 and 2, show the "sock type" tail vane in which a canvas "sock" is sewn over a light (1/4" gas pipe), metal frame and then given a few coats of paint to make it stiff. The advantage of the "sock" type is its lightness, a necessary factor on an 18' tail vane bar.

Fig. 3 and 4 show how the fore stays hook onto the nose ring. The nose ring is constructed in the same way as the metal hub, illustrated in plate no. 17.

The nose ring is placed on the axle, 4' ahead of the main hub (fig. 5), in order to give proper support to the fore stays. If possible, you should use two fore stays because the wind force is always on the front side of the masts. Good support is necessary, especially if you use masts of 2" X 2" Douglas Fir or Pine.

Note also, the "back up hub", 4' behind the main hub. The purpose of the back up hub is to give proper support to the (wire cable) back stays.

This means that the main hub must be at least 4' 6" ahead of the thrust bearing on the rotating table. To take this strain, the axle should be at least 1 1/2" diameter. A 2" diameter axle would be better.

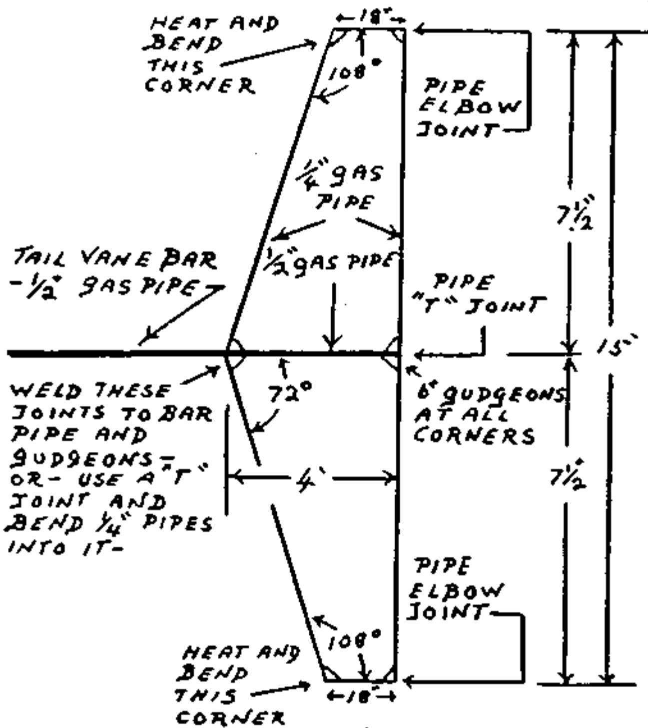
The 4' distance between the back up hub and the main hub also puts a lot of leverage, (upward pressure), on the second (ball bearing), pillow block. Make sure everything is very secure. This is a good argument for the wider, (wooden), rotating table that is possible on the concrete block tower, illustrated in plate no. 2.

Always make a scale drawing to make sure that the sail tips will not strike the tower legs.

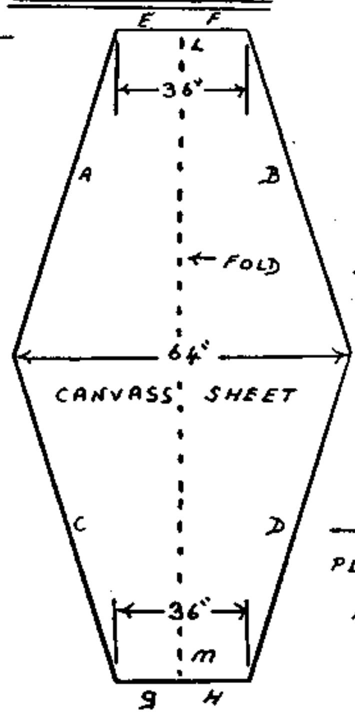
PLATE No. 53

-THE SAIL WINDMILL VI
-THE TAIL VANE II
-FORE AND BACK STAYS- HUBS-

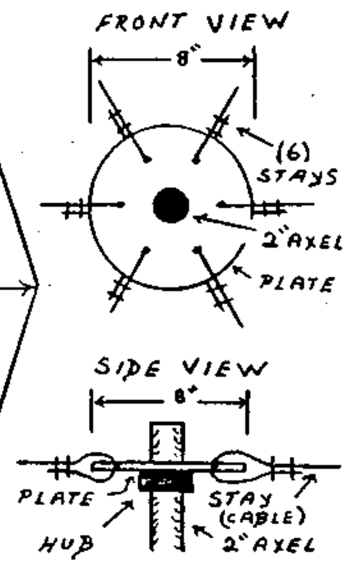
TAIL VANE



TAIL VANE SOCK



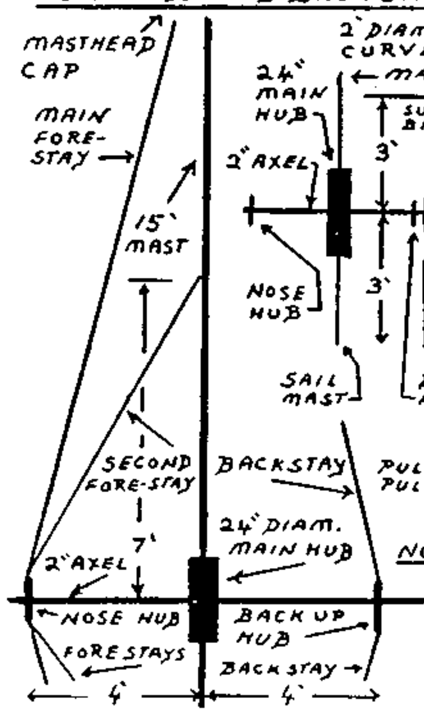
BACK UP HUB - OR NOSE RING



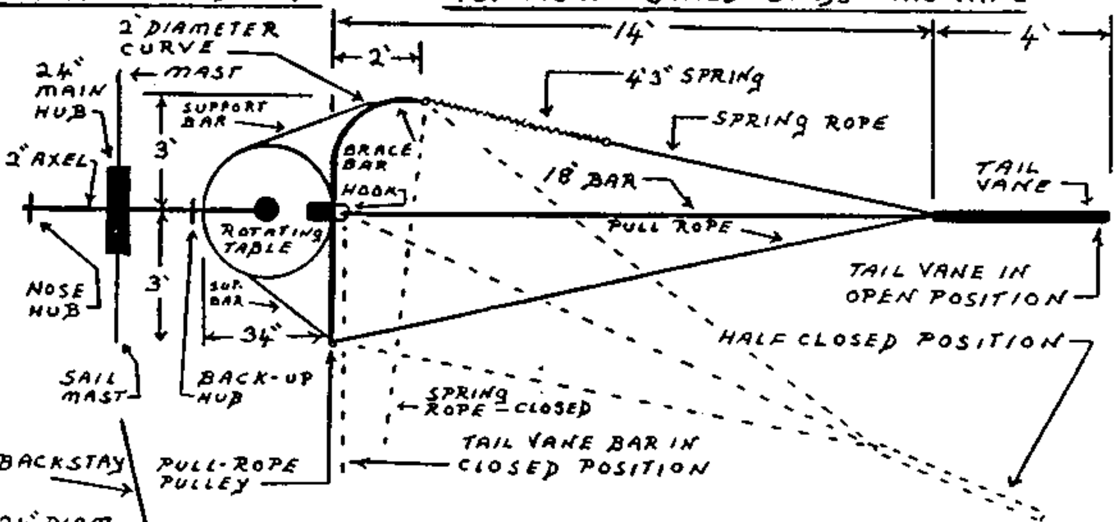
NOTE - THE BEST METHOD IS TO DRAW ACTUAL SIZE TAIL VANE ON SHOP FLOOR - BEND PIPES ACCORDINGLY TO ASSURE THAT ALL ANGLES -TOP AND BOTTOM- ARE THE SAME-

CANVASS SOCK- CUT TO SHAPE- FOLD ALONG DOTTED LINE - L - m - FIT OVER TAIL VANE PIPES- SEW; E TO F - G TO H - A TO B - C TO D -

FORE STAYS AND BACK STAYS - SIDE -



TOP VIEW SAILS - STAYS - TAIL VANE



NOTE - SECOND FORESTAYS CAN ONLY BE USED WITH SLIDE CARS AND MAST TRACK- NOT WITH SAIL RINGS-

NOTE - 1 1/4" OR 1 1/2" DIAMETER ALUMINUM PIPE CAN BE SUBSTITUTED FOR 2" x 2" FIR FOR THE MAKING OF MASTS - IN SOME COUNTRIES BAMBOO IS USED -

NOTE - MAST LENGTH CAN BE REDUCED TO 10' OR 5' WITH SIMILIAR REDUCTIONS TO ALL OTHER MEASURENTS EXCEPT ROT. TABLE-

The Wind Power Book. Park. Cheshire Bks/Van Nost. USA 1981. 0-917352-05-X.

Installation of a sail-wing rotor at the Park ranch in California. This 16-foot diameter rotor was eventually replaced by a larger version.

A Sail-Wing Water-Pumper

John Welles is an inventive tinkerer who has installed a number of wind-powered water-pumping systems around Northern California. In 1977, John loaded a "sail-wing" wind machine into the back of his Volkswagen Beetle and delivered it to my ranch. We set it up in only two days.

Water is available at this site from an artesian spring close to the surface; it does not need to be raised from deep in the ground. Wind power supplies the pressure needed to transport that water along 300 feet of plastic pipe and up 2 feet of elevation to a stock-water tank used as a reservoir for a small goat dairy and a trickle irrigation system for the organic gardens at the ranch. Much of this water pressure occurs because friction forces work against water flowing swiftly through a long water pipe. This friction back-pressure is referred to as the *friction head*. The total power the wind pump must generate is based on the total height water must be lifted (in this case only a few feet), the friction head, and the rate at which the water flows.

The design of this sail-wing windmill evolved from a notion that only hardware store components and materials would be used. The entire rotor, support structure, and pump are made from iron and plastic plumbing components. The sail spars are made from electrical conduit tubing. And the "tower" is a redwood fence post with clothesline-cable guy wires.

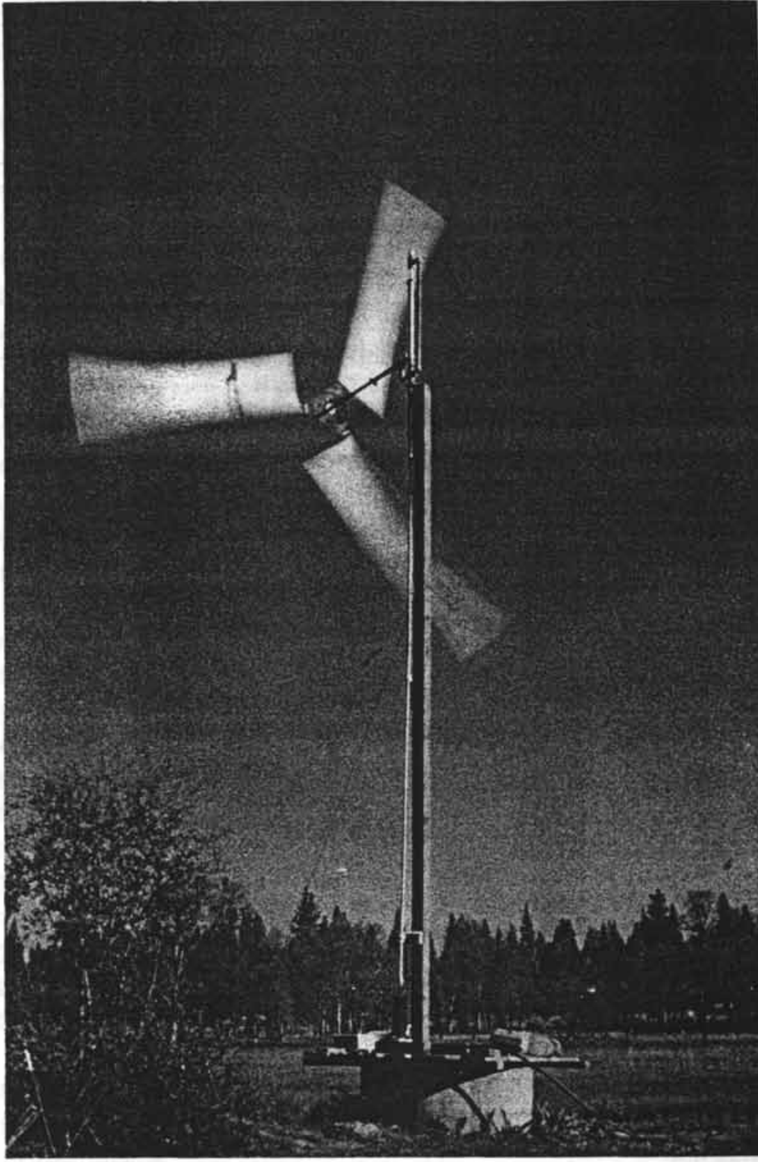
Originally the three sails spanned a diameter of 16 feet, but they now span 20 feet. In water pumping systems, the wind rotor (blades, hub and powershaft) must start turning under wind power against a heavy load of water. Rotor design for this type of load usually calls for a fairly large total blade surface area. This is why the familiar farm water-pumper has so many blades—it needs high starting torque. The term for the ratio of blade area to frontal area is *solidity*. The more blade surface area, the more "solid" the frontal area. The sail-wing machine at my ranch has few blades—or a small blade area relative to the large frontal area of the entire three-bladed rotor. Hence, it doesn't have much starting torque; fortunately, it doesn't need much because it only lifts water a few feet. With the 16-foot diameter rotor, the machine began pumping when the windspeed reached about 10 mph. The larger diameter rotor lowered this "cut-in windspeed" to about 7 mph. More blade area means higher starting torque and a lower cut-in windspeed. Extra area can be added by sewing wider sails or by adding more sails similar to those already installed. More blade area, however, means greater loads on the guy wires or cables that support the tower, because there is more surface area for the wind to push against.

Sail shape also plays an important role in determining the ability of the wind machine to pump water. These sails billow and flap about in the wind a bit too much. It's probably impossible to achieve perfection in sail design, but government and private research programs are exploring windmill sail designs to improve performance.

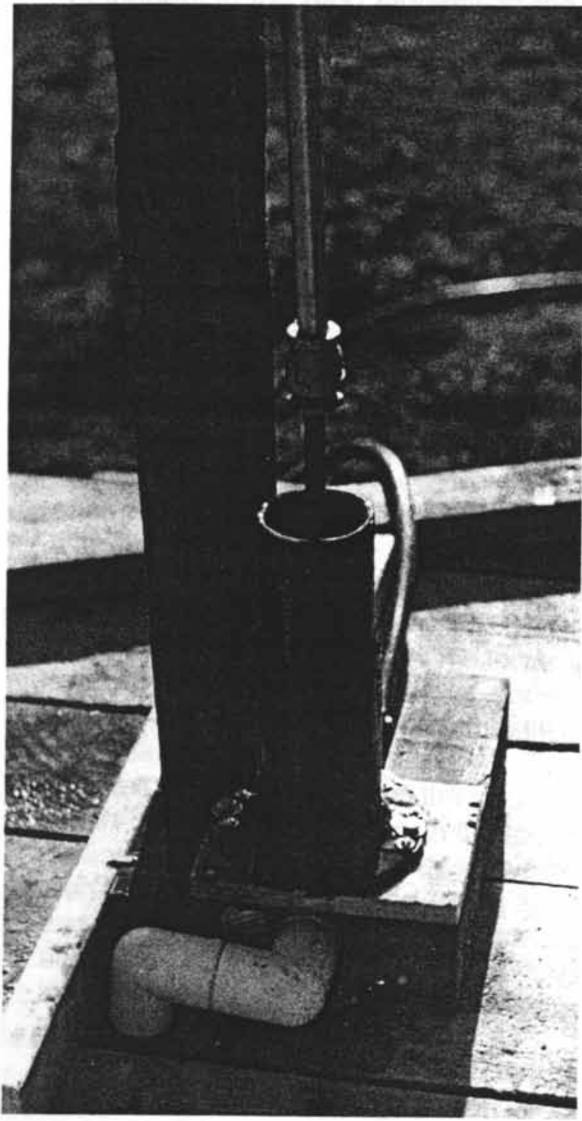
The sails on the rig at my ranch are sewn from sailboat-quality dacron cloth, although canvas or other materials could be used. Dacron is lightweight and very strong. It's also one of the few fabrics that can last a few years in an extreme outdoor climate. Freezing weather and strong sunlight combine to destroy the fabric eventually, but it lasts long enough to make a sail machine worthwhile. Screendoor springs connected to the sails hold them taut for normal operation. These springs stretch under sail loads imposed by high winds, allowing the sails to "luff," or flap, out of the wind. This simple "governor" protects the sails from damage. Because the governor lessens the sail loads, tension loads in the guy wires that support the tower remain low enough during high winds that short stakes such as goat-tether stakes are adequate for tie posts.

A simple crankshaft translates rotary blade motion into the up-down stroke needed to drive a water pump. This pump, a piston 3 inches in diameter with leather pump seals, is a "single-acting" pump. That is, it pumps only on the down stroke. This pump pushes water into the pipe in pulsing streams. However, peak water flow rates can be too fast for efficient operation. The faster that water flows in a pipe, the higher the friction and the resulting back-pressure against the pump. By installing a surge chamber (a simple tank with trapped air) in the water line near the pump, we created an air space where strong water pressure pulses could expand and slow down the peak flow rate. More continuous water flow resulted, and more water was pumped because of improved pump performance.

This sail-wing water-pumper has worked well for over a year, with only minor problems associated with the realities of a do-it-yourself system. For example, the 300-foot plastic water pipe was not buried at first, and whenever a horse stepped on the flexible poly-



The sail-wing machine in action, pumping water from an artesian well close to ground level.



Sucker rod and water pump used with the sail-wing. The sucker rod pushes down on leather pump seals, driving a pulsing stream of water into the plastic pipe at rear.

ethylene, a water lock was created that stopped the pump. Occasionally this occurred during high winds and broke a "sucker rod"—the long, thin tube that connects the crankshaft to the pump. Solutions included a stronger sucker rod and—finally—burying the water pipe.

Performance has been adequate. The storage tank requires about 400 gallons of pumped water per week. The wind resource at the site is minimal, about 8 mph annual average, but evening breezes of about 11 mph drive this sail machine long enough to keep the stock full.

This sail-wing water-pumper can be readily adapted to many sites. With deeper water, however, more sail area would be required to provide the necessary starting torque. The reliability of such a machine is directly related to the amount of care you put into the project and the time you devote to solving its early problems.

Choose a design for the task. Mechanical loads like piston water-pumps, washing machines, or piston compressors usually need high starting torque. Here, a recycled multiblade water-pumper or a Savonius rotor make sense. For loads like generators that do not "kick in" until they are spinning quite fast, choose a high-speed lifting rotor such as the two- or three-bladed propellor or a Darrieus rotor.

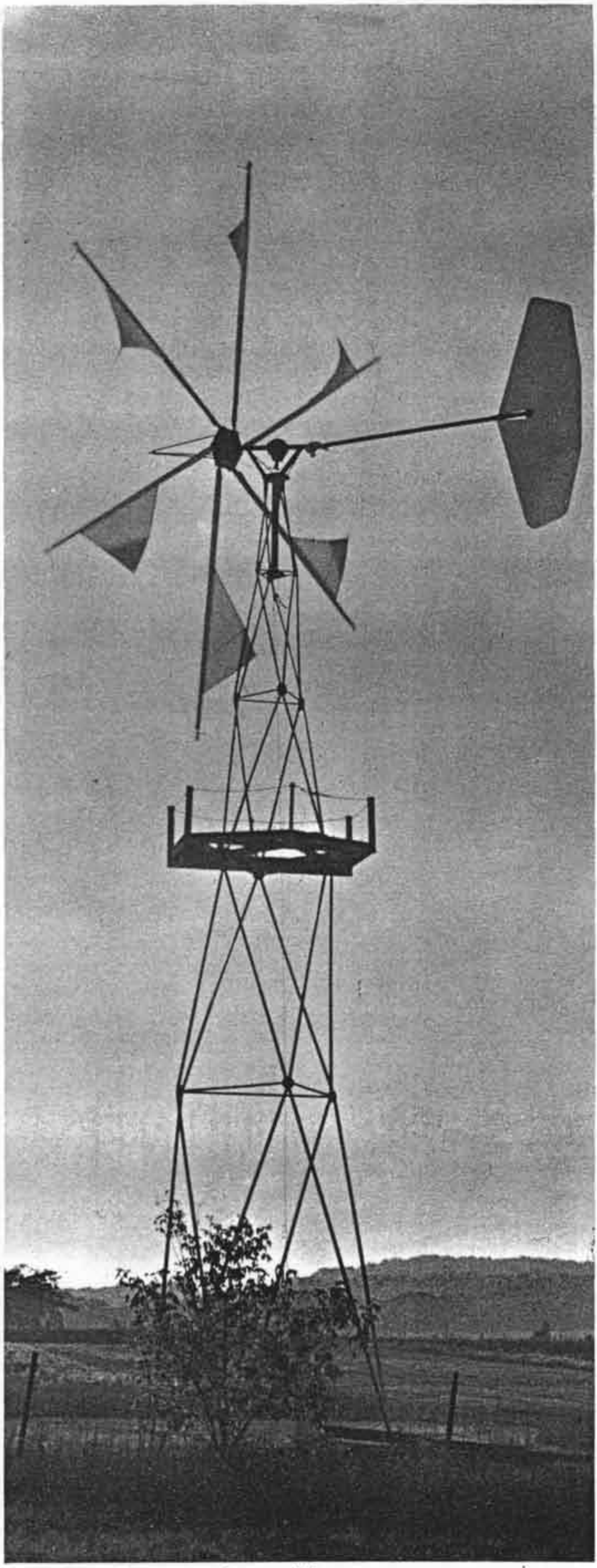
One overlapping design is the sail-wing rotor. Sew large sails and you have a high-torque, slow-turning rotor for water pumping. Sew smooth, narrow sails, and the rotor rpm increases—making electrical generation reasonable. The sail-wing rotor is also very appropriate for low-cost, low-technology systems constructed by owner-builders.

This mill, as opposed to the other two types, is slow speed, allowing much cruder construction and less demanding operating restrictions. This permissible roughness brings with it a proportionate decrease in efficiency, but this may or may not be significant. The fuel is essentially free, making the investment for a given power output relatively more important.

The sail windmills are the most suited to junk parts and home-made construction with a minimum of exotic components. Spars can be cedar saplings or laminated up with a hollow section. The hub can be wooden pillow blocks and a few pieces of metal. A differential can be used to transmit the power directly to the ground where any number of pieces of equipment can be hooked up. Sails can be home-sewn out of canvas, dacron, or cotton.

The difficulties with this type of windmill are pretty much the same as the advantages. In that it is slow speed, it is not easily adapted to electrical generation, at least not without a lot of gearing. Its slow speed results in good light wind operation and high starting torque, but then it operates at lower efficiency in all but the very lightest winds. Its efficiency in converting wind to mechanical power is about half that of the hard foils.

Sail windmills are self-regulating to the extent that they will accelerate until the sails start to luff. By changing the trim of the sails, the speed can be effectively regulated. This windmill though is the least automate-able. Changes in wind speed may require changes in sail trim, and heavy winds or storm conditions will require reefing.



Windworks sail windmill, 1974. Since the photo, driveshaft to base has been added to drive buzz saw and electric generator.

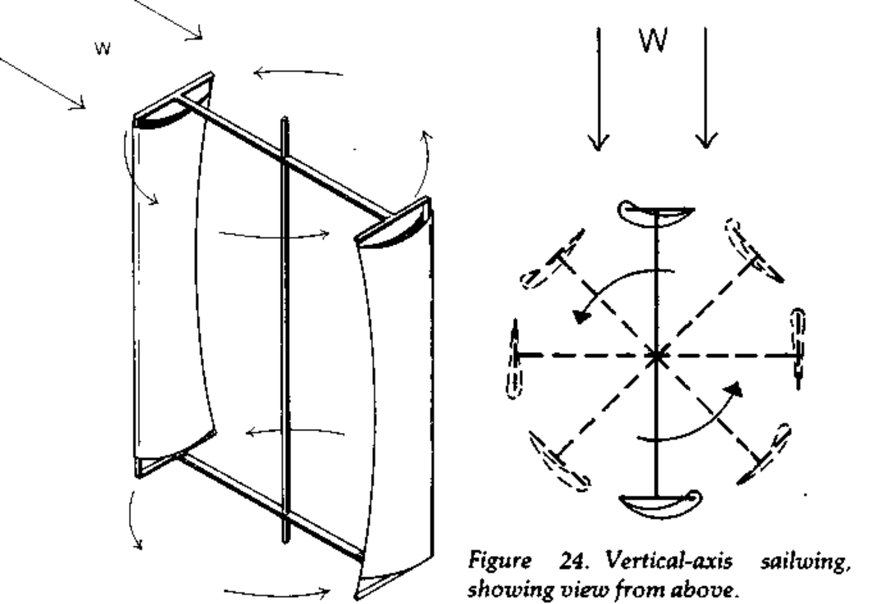


Figure 24. Vertical-axis sailwing, showing view from above.

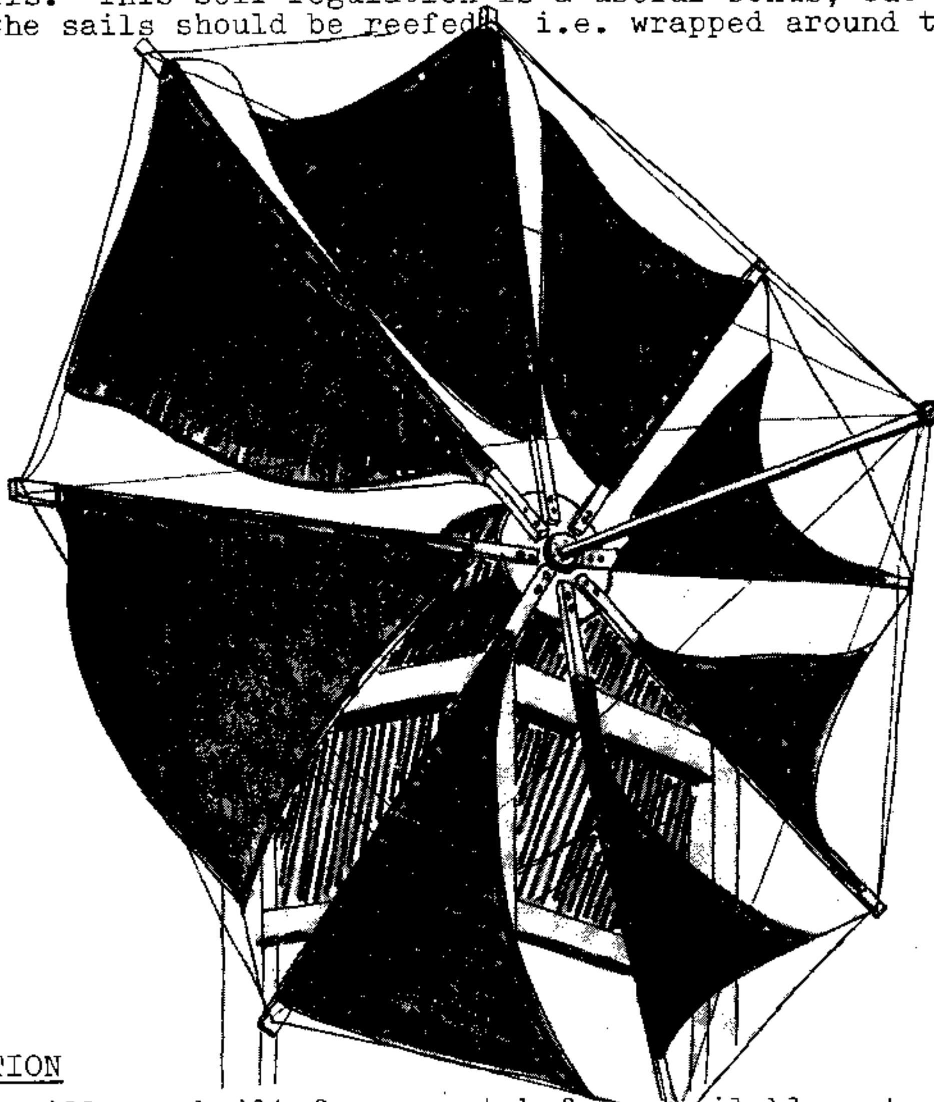
D.I.Y. PLAN 5

SAIL WINDMILL (CRETAN) PART 1.

A 12ft. diameter sail windmill, useful as prime mover for lathe and grindstone, or for pumping water; with a step-up of about 1:50 it may be used for electrical generation up to 700 W.

This plan deals with the windmill as Prime Mover. Part 2 includes turntable, tail and electricity generation, and is available from the Centre.

The Cretan is a slow speed machine, tip speed to wind speed of about $\frac{3}{4}$:1, which has a high starting torque in winds upwards of 8mph, and in our experience, rarely exceeds 50rpm, when the wind spills from the sails. This self-regulation is a useful bonus, but in high winds the sails should be reefed, i.e. wrapped around the spars.



ADAPTATION

The windmill was built from scratch from available material and scrap and some bought parts. It may be made in a number of ways. In Crete, chain is often used instead of rope for example, and iron spars instead of wood. We describe what we have done ourselves and would like to hear of variations others come up with.

TOOLS

Basic D.I.Y.. We made ours without the use of a power drill, but if you have one and a 3/8" bit, it would be useful on the tower structure.

COST

As in other plans in this D.I.Y. series, cost depends on the ability to find materials around. This applies even more to the Cretan, which may be made from all sorts of scrap. All we can do is to give prices of new materials, in the firm belief that like us you will be able to get most of it for a fraction of the cost.

MATERIALS - TOWER

Timber Sawn:	Length:	Quantity:	Price:
3" x 2"	7'6"	4	Approx. £10
	3'0"	8	
	5'0"	8	
6" x 1½"	3'0"	4	Approx. £12
	15'0"	4	
3/8" carriage bolts	5"	34	£ 3
	6"	22	
¼" bolts and screws			
Iron straps 1½" x ¼" x 2'0"		4	?

CONSTRUCTION - Tower

Because we live on the slate tip of a disused quarry, digging for concrete foundations is very difficult. We therefore mounted our Fig.1 tower on extended feet of 6" x 1½" timber, and weighted them down with lumps of slate. This method obviated all but approximate levelling, the feet being allowed to lie at their natural angles on the uneven ground, and the tower bolted and strapped in a vertical position to the feet. A sort of universal joint. It has withstood a couple of 70mph gales without trouble, and, in our locations, seems a satisfactory way of anchoring.

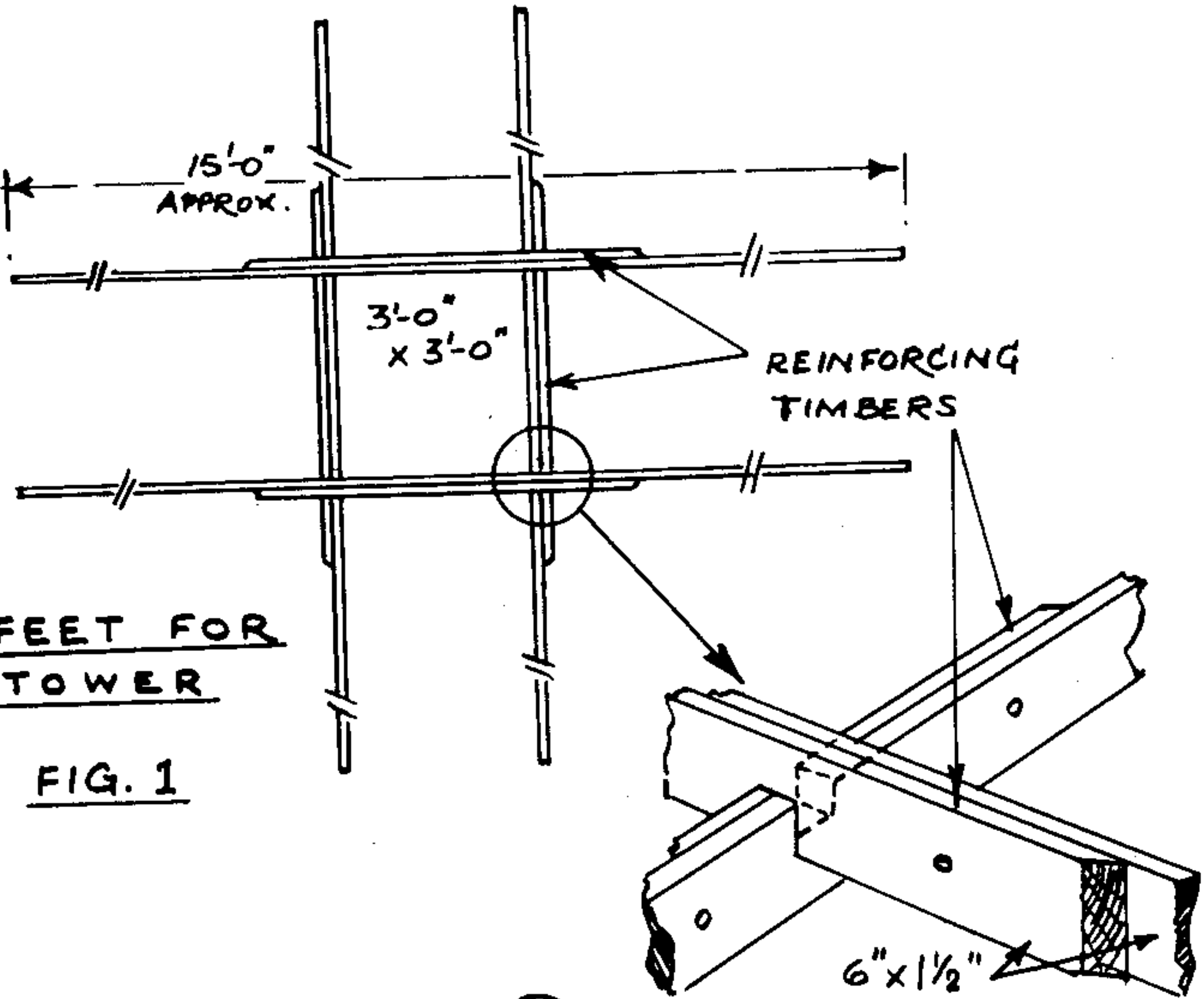
The tower itself is triangulated; 3" x 2" diagonal braces being bolted to 3" x 2" uprights, as shown, making a structure 3ft. square by 7'6" high. The merits of a low tower are that it is safer, and also - just as important - the spars are within reach for dealing with the sails. An unobstructed position for the windmill is, of course, necessary, but the large size of the rotor and its high solidity ensures some power output even in very low wind speed areas.

The tower (built, if possible, beside the egg-box type foundation Fig.2 feet) may be lifted by four people and dropped into the central square of the feet, and chocked up at the corners until it is exactly vertical. 3/8" holes were then drilled through the feet and the bottoms of the vertical tower struts, and bolted.

Iron straps were then bolted to the feet and tower at each corner.

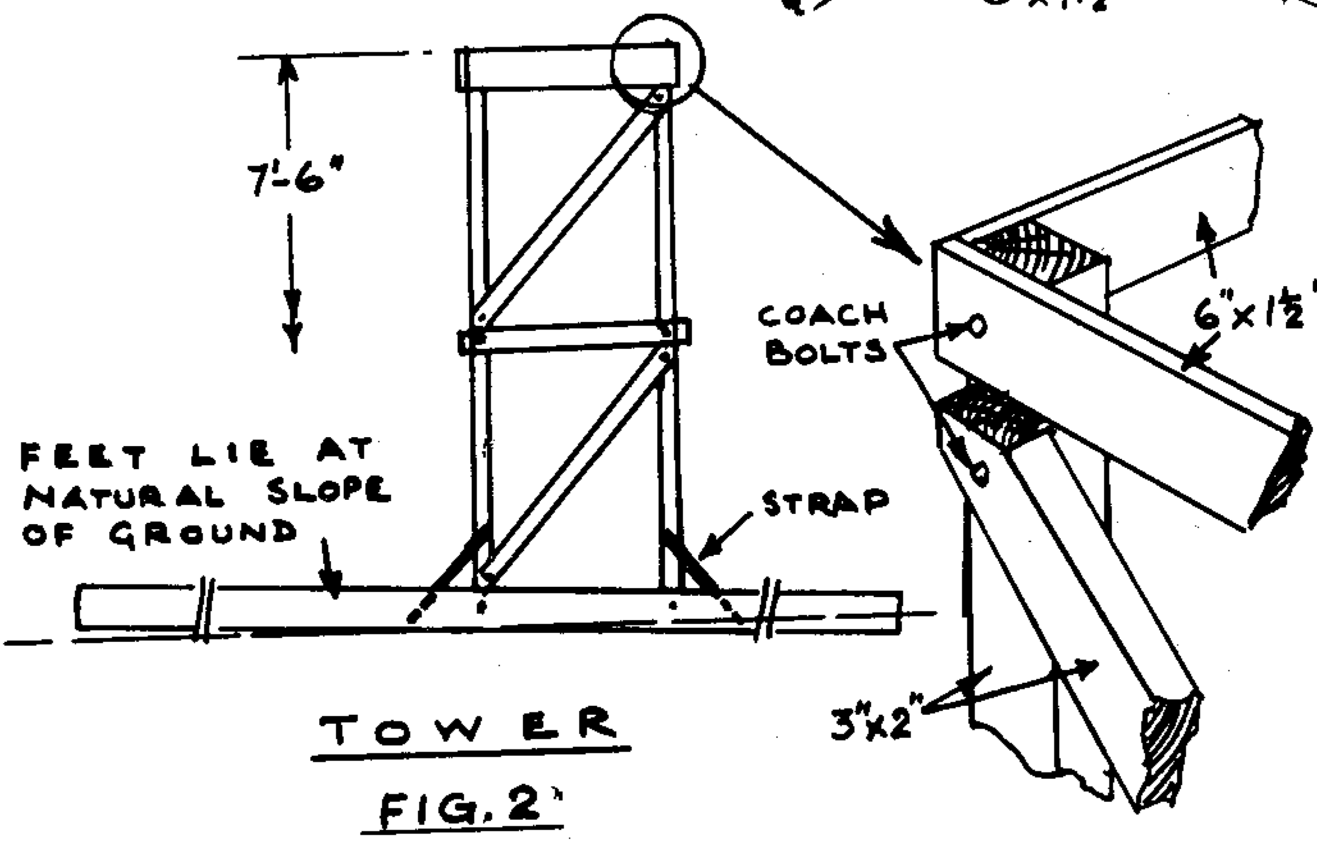
We laid railway sleepers over the ends of the feet and weighted them down with slate.

CRETAN WINDMILL



FEET FOR TOWER

FIG. 1



TOWER

FIG. 2

MAINSHAFT ASSEMBLY - MATERIALS

Timber Sawn	Length:	Quantity:	Approx. price 1976:
3" x 2"	4'6" 2'0"	2 3	£1.50
Plummer blocks 1¼" diameter		2 rigid or self-aligning	3.50 each 6.50 each
4" Pulley (Fenner) 6" Pulley (Fenner) Taper lock bushes (Fenner) 1¼" diam.		1 1 2	9.50
Steel pipe 1¼" O.D.	5'0"	1	3.00
Spars, ash, 2" x 1½"	6'0"	8	15.00
'Bowsprit' 1" O.D. pipe	4'6"	1	0.50
Plywood ring 1" thick, 3'0" O.D., 2'0" I.D. Plywood face plate 1" thick, 1'6" diameter (cut from inside of ring)		1 1	3.50

CONSTRUCTION

Fig.3 We made a cradle of sawn 3" x 2" timber on which to mount plummer blocks and shaft and brake; whatever power take-off needed; the faceplate; and the windmill spars.

The cradle should be carefully made with shallow half and half joints and bolted squarely together. The shaft and rigid plummer blocks must be mounted together to ensure the shaft turns easily, (Use shims under the bearings if necessary) or use the more expensive self-aligning bearings.

Fig.4 The spars are mounted on an 1" plywood faceplate, 1'6" diameter, and bolted to it with 2x⅜" bolts each. Large washers, or better still strips of metal, should be drilled and placed against the spars to lessen the bending stresses around the bolts. Each outer end of the spars is drilled with 2x⅜" holes, at right angles to, and just avoiding, each other.

The ply faceplate, bored 1¼" diameter, to take the shaft, is mounted onto a Fenner pulley, which is drilled and bolted to it. The Fenner taper lock bush is an excellent way of fastening the pulley to the shaft.

The shaft should protrude 2" in front of the ply faceplate, and be drilled for ¼" bolt as cotter pin. This is to hold in place the 'bowsprit' - a 4'6" length of metal pipe - for instance, electric conduit - which will fit easily into the bore of the 1¼" pipe that serves as shaft. This bowsprit, in our case, has a round metal plate screwed onto the end with 8 holes round the edge; this has caused
Fig.6 fraying of the cords: we suggest a hardwood block about 4" x 4" x 1½" thick, with the corners chamfered off and 8 holes drilled, plus a central one to fit the bowsprit. This should then be drilled and pinned with ¼" bolt to the sprit.

It is important to tighten all bolts well, and to locknut those on the faceplate: there is a lot of movement in high wind.

To return to the shaft and cradle: the brake on ours is from an old Morris. The drum was bolted to another Fenner pulley - 4"
Fig.3 diameter - and a taper lock bush fastened to the shaft. The faceplate was anchored to a short length of dexion, fixed to the cradle.

— CRETAN WINDMILL —

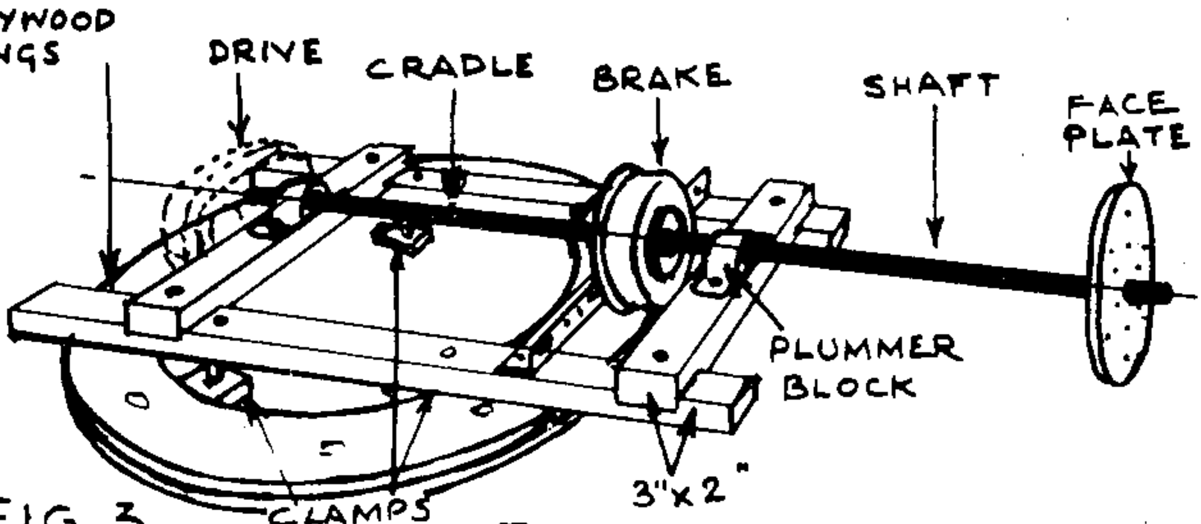


FIG. 3

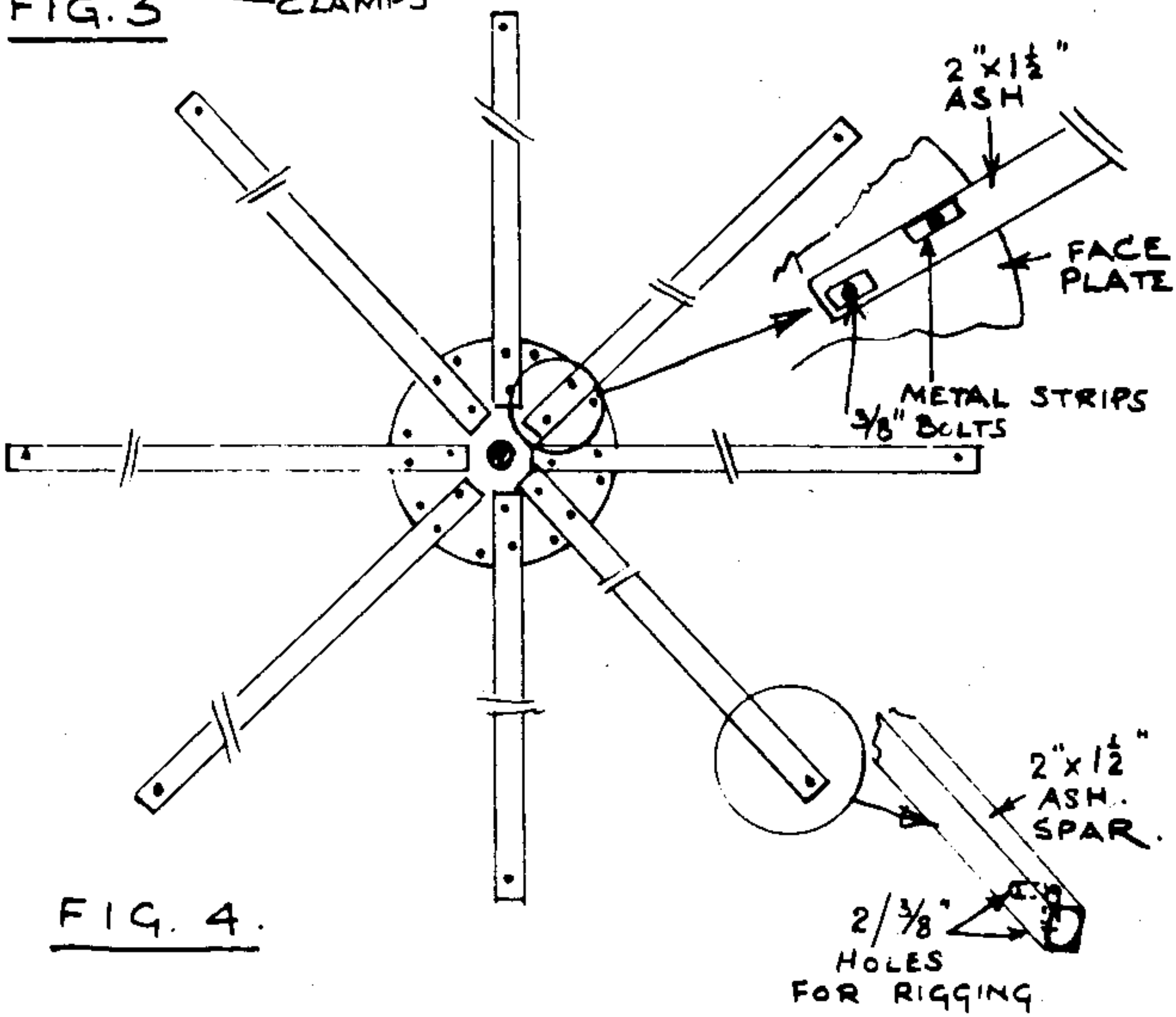


FIG. 4.

CRETAN WINDMILL

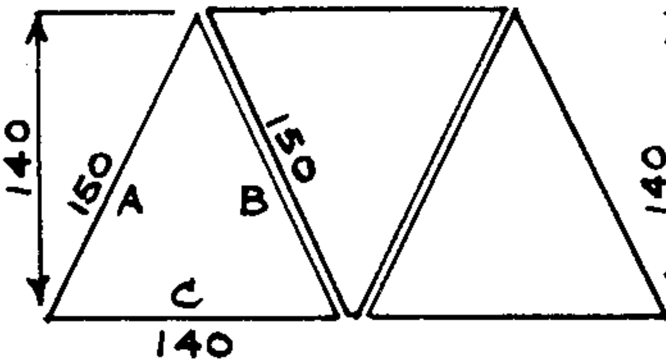
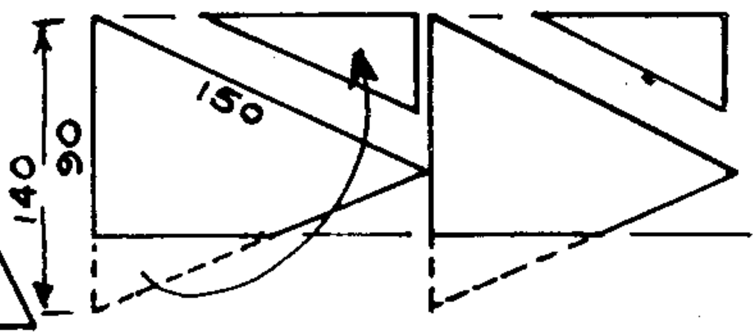
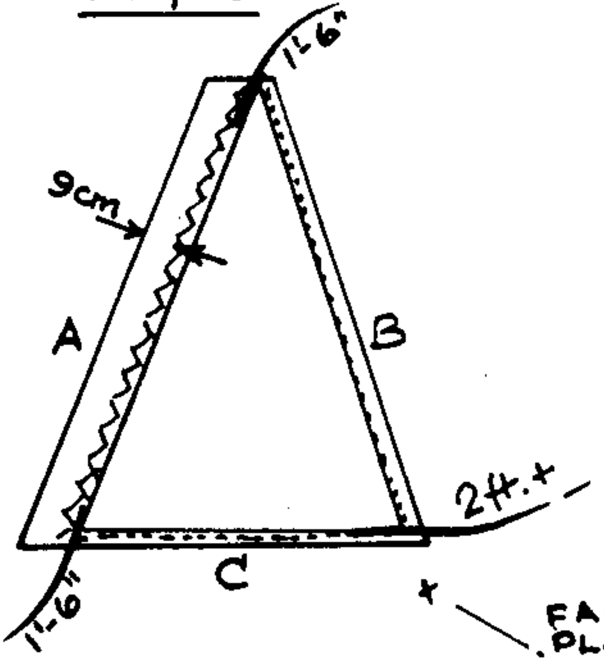


FIG. 5



SAIL PATTERN



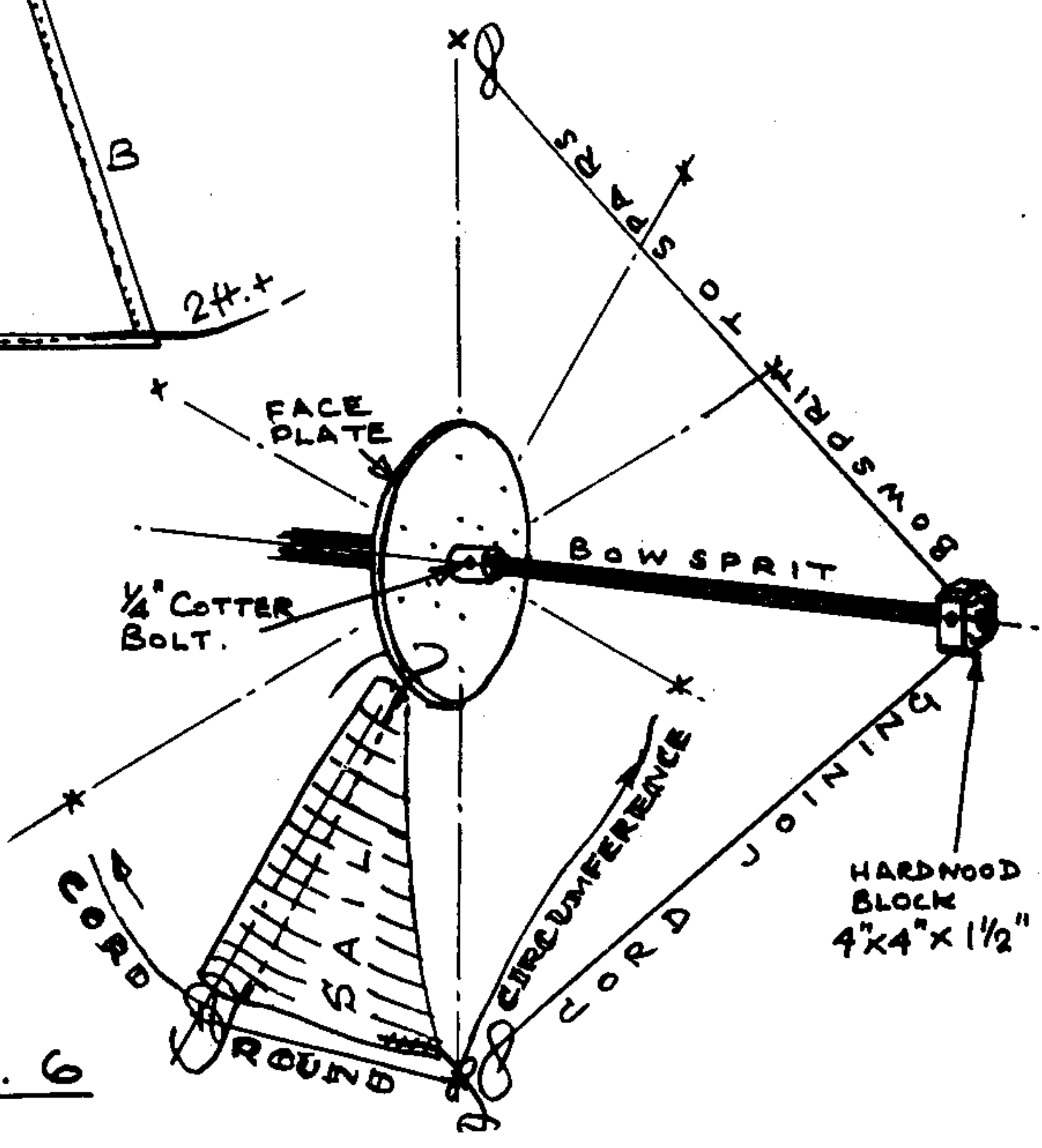


FIG. 6

This Cretan worked for 9 months without self-orientating. It took wind well from the prevailing S.W. quarter, and when the wind blew from the N. or N.E., we turned the sails into the wind by hand. However we now have a tail and turntable and D.I.Y. plan 5 part II describes how to build the tail, turntable and electricity generation.

We have a 1" thick plywood ring, 3'0" diameter outside, 2'0" diameter inside; this was screwed to the top skirt of the tower, and the cradle rested on it, as far forward as is necessary so that the spars will well clear the corners of the tower. The cradle we clamped with long 3/8" bolts and 6" pieces of 4" x 1" wood to the ring. The same bolts act to hold down the cradle and to locate it as it is rotated on the disc. This mounting method allows for power take-off down the centre of the tower.

SAILS

You will need:

6.30m of 140cm wide canvas, or
11.20m of 1yd wide canvas, 12oz approx. Approx. £25

Fig.5 28ft terylene cord, about ½" circumference
120ft terylene cord, ¾" circumference Total £3.70

1. Cut out 8 triangles as shown
2. Join very securely if using narrower canvas
3. Turn under 3cm hem on sides B and C, and double stitch with zig-zag if possible.
4. Turn under 10cm on side A for spar (folding in extra fabric at point X of triangle) and double stitch with zig-zag, leaving both ends open for spar. Check that spars are an easy fit.
5. Cut terylene cord into 1'6" lengths for top and bottom of sails, and 2' for the sheet lines. Sew them very firmly with through and through stitching.

RIGGING

Choose a calm day!

Measure lengths of ¾" circumference terylene cord for bowsprit and thread them through holes in bowsprit block. Allow plenty of tie through spar ends. Slide sails over spars and tie them top and bottom - through holes in faceplate and through spar ends.

Now take single length of cord and tie end to one spar. Take it through next one on circumference and knot it on itself, then to the next and so on. Make sure the distance between each pair of spars is the same, and that they are still the same when cord is pulled tight and knotted.

Next take the bowsprit cords and tie them in pairs to opposite pairs of spars. Turn the spars and make sure the bowsprit end doesn't wave about too much. Tie each sheet line through the neighbouring spar. Wait for wind ....

Many refinements will occur to you - wooden sliding guys, as on tent guy ropes may be used to adjust the sheet; a snag is that these work their way along the cord, allowing the sheet to billow, and even (as happened to ours) to tear on the tower.

A better method of fastening the sails should be devised to facilitate sail replacement.

ELECTRICITY GENERATION (introduction)

The low tip speed ratio 0.75 calls for a high speed ratio drive to the alternator, which has a cutting-in speed of 1,050rpm.

In order to achieve a cutting-in wind speed of 9mph, a 1:55 ratio is required. This is provided by a 1:20 industrial gearbox (Fenner: size B.20, shaft mounted, £85. 1977) and a 1:2.75 belt drive. Starting in low winds is no problem due to the high stall torque of this type of rotor.

A standard marine alternator type AC5, 24 volt 33 amp (Lucas) is used; this feeds central 24 volt lead acid storage batteries of 20 kwH capacity. The maximum power output of 700 Watts is reached at approximately 22mph wind speed.

A vee belt or a timing belt may be used for this alternator drive. The vee belt has the advantages of slipping under shock loads, thus relieving stresses on the rest of the system, and of being cheaper. The timing belt offers better efficiency at low wind speeds. We are using a single Fenner SPZ, V-belt at present, with good results.

The rotor is turned into the wind either manually, or in areas of constantly varying wind direction like ours, a tail vane is used with slip rings, or alternative electrical connections. Details of this are included in D.I.Y. Cretan plan, part II.

We are very grateful to Dr. N.G. Calvert of the Department of Mechanical Engineering, Liverpool University, for supplying some of the components and giving much useful advice.

Canvas for the sails may be obtained from Russell and Chapple Ltd., 23, Monmouth Street, London WC2H 9DE, 01.836.7521. They will also make the sails.

Other D.I.Y. plans, information sheets and books are available from the 'Quarry Bookshop' at the Centre. Please enclose a s.a.e. with any correspondence as we are a charity. Visitors are welcome.

Centre for Alternative Technology, Machynlleth, Powys, Wales
Telephone: Machynlleth 2400

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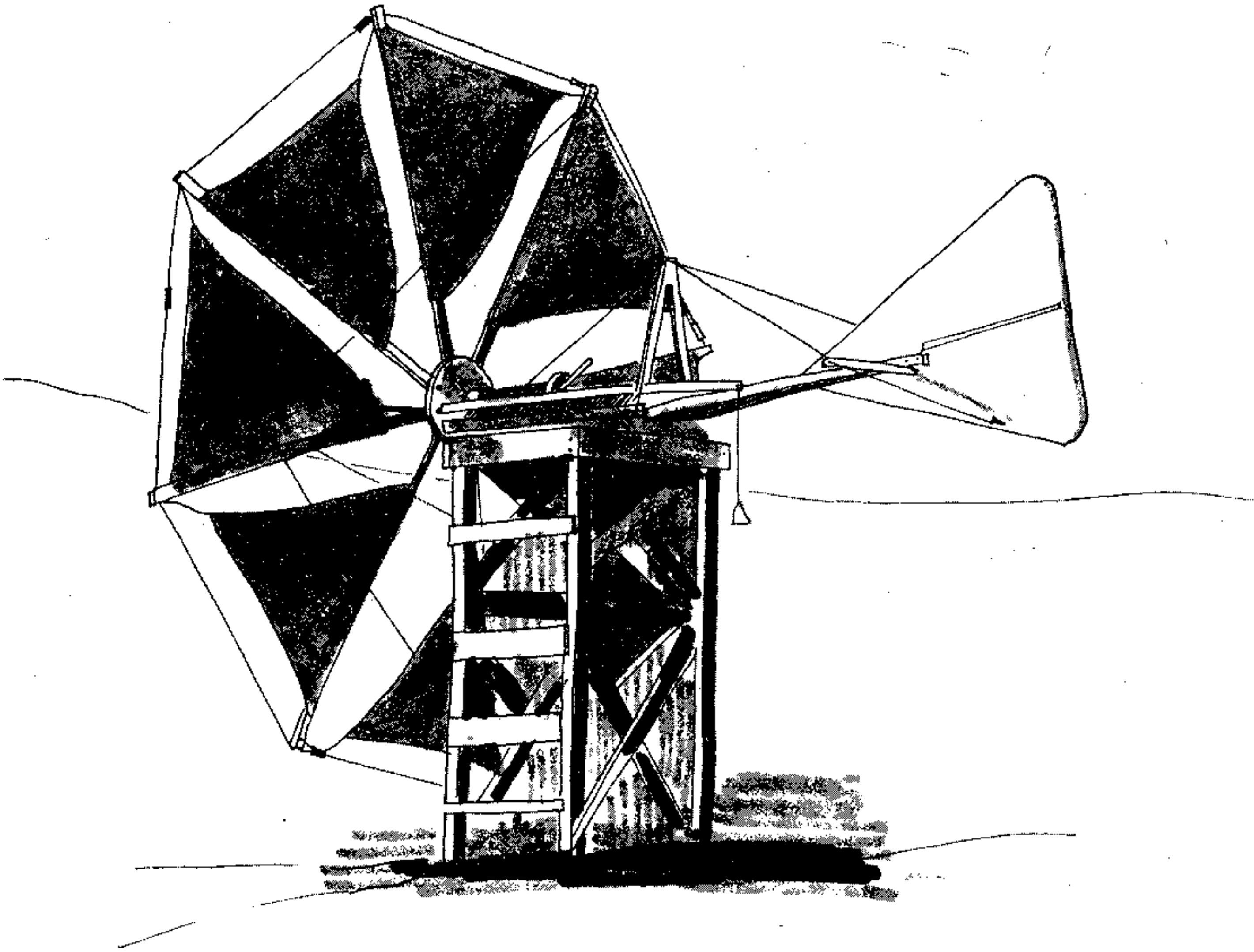
D.I.Y. PLAN 5

SAIL WINDMILL (CRETAN) PART 2.

PURPOSE:

The Cretan Sail Windmill described in its basic form as prime mover (DIY No 5 Part I) was in due course coupled to an alternator for generating electricity of maximum output of about 700 watts. The following is an account of our experience.



Gearbox

Dr G. Calvert of Liverpool University gave us an industrial gearbox of 20:1 reduction which was coupled back-to-front onto our main 1¼" dia mill shaft, overhung beyond its bearing by about 8" to receive it. (DIY 5 Part I). The gearbox had a lug and single anchor link which obviated the need to line it up, the only points to watch being that the output shaft was sufficiently clear of the carriage timbers to take an 8" pulley; and to fasten the anchor link on the tension side.

In the first experiments we made, with a vehicle dynamo, we were cautious of using more than a 40:1 step up ratio, largely on the grounds that the low speed torque at the dynamo magnified 40 times at the main shaft, would impede starting and make the cutting-in windspeed (when generation commences) unduly high.

We need not have worried: the Cretan has been working for nearly a year with a step up of 1:60 between main shaft and generator. At a mere 16 rpm of the sails - which takes place in a very light wind - we already had the generator turning at 960 rpm - about cutting-in speed.

The alternator we used is a CAV (Lucas) type AC5 marine alternator with built in rectifier, delivering 30 amps at 24V d.c. at 2,200 rpm. In areas of relatively low average windspeed, say less than 10 mph, it would be better to use a smaller alternator, perhaps with a slightly higher gear ratio to reduce the cutting-in speed. The loss in maximum power in rare high winds will be more than compensated by better operation at low wind speeds. The power is used for charging batteries. A large cross-section cable is needed to avoid excessive voltage drop between alternator and battery - for a 50 metre run, $10mm^2$ cross section is suitable (at 24V). Required cross section increases proportional to length.

For the final drive from gearbox to alternator we settled for Fenner toothed timing pulleys and toothed belt to give a 1:3 increase, an overall step up of 1:60. With the high belt speed involved of around 1,300 ft/min at 2,000 rpm at the alternator pulley of approx. $2\frac{1}{2}$" dia, we thought this a good solution. The friction losses involved with a normal vee belt would, we know, be very significant in light winds. However, due to shock loads caused by momentary breaks in the electrical circuit at the experimental slip ring unit, we broke several belts. We therefore reluctantly had to return to a vee belt with its lower efficiency. As we hoped, its slip cushions the snatch and we have had no more trouble. It must be remembered that this snatch travels through the whole system, and if the toothed belt was stronger - or two were used, for example, side by side,- then something else would be overstressed: the spar face plate bolts for instance, or the main shaft key, could shear. We were lucky, the slip ring device for transferring power from the rotating head was adopted after experiments with direct cable connection. In theory cables will only rarely be twisted more than once or twice in the same direction consecutively, but, we found in our wind conditions, the cable twisted seriously and broke. We have recently removed our slip ring assembly and reverted to direct cable connection but with the addition of the device shown in fig. 4. A weight, running in a length of plastic drainpipe, acts via a rope and pulley system on the turntable wheel thus turning the head back to the same position each time the wind drops. Allow enough cable and rope for a couple of turns in each direction. This method is working well.

TURNTABLE AND TAIL: A car back axle casing and half shaft, or large ball races set on the cradle, and rolling around the circular ring on the tower were both considered for the turntable but a storm that felled a tree across one of our caravans gave us the ideal thing - the axle and wheel unit that we salvaged from the wreckage. We cut through the solid steel $1\frac{1}{2}$" x $1\frac{1}{2}$" axle near one end, giving a long rigid support and wheel bearing unit, which, with tyre removed, provided an excellent turntable on which to bolt the windmill head (or cradle). First, however, we had to make the tail, so that we would know a bit more about the weight to be supported and balanced.

THE TAIL: What shape and size? Ours was guesswork informed by a year's acquaintance with the vaguaries of wind and windmill alike. It is probably too big.

CRETAN WINDMILL – THE GENERATOR & GEARBOX

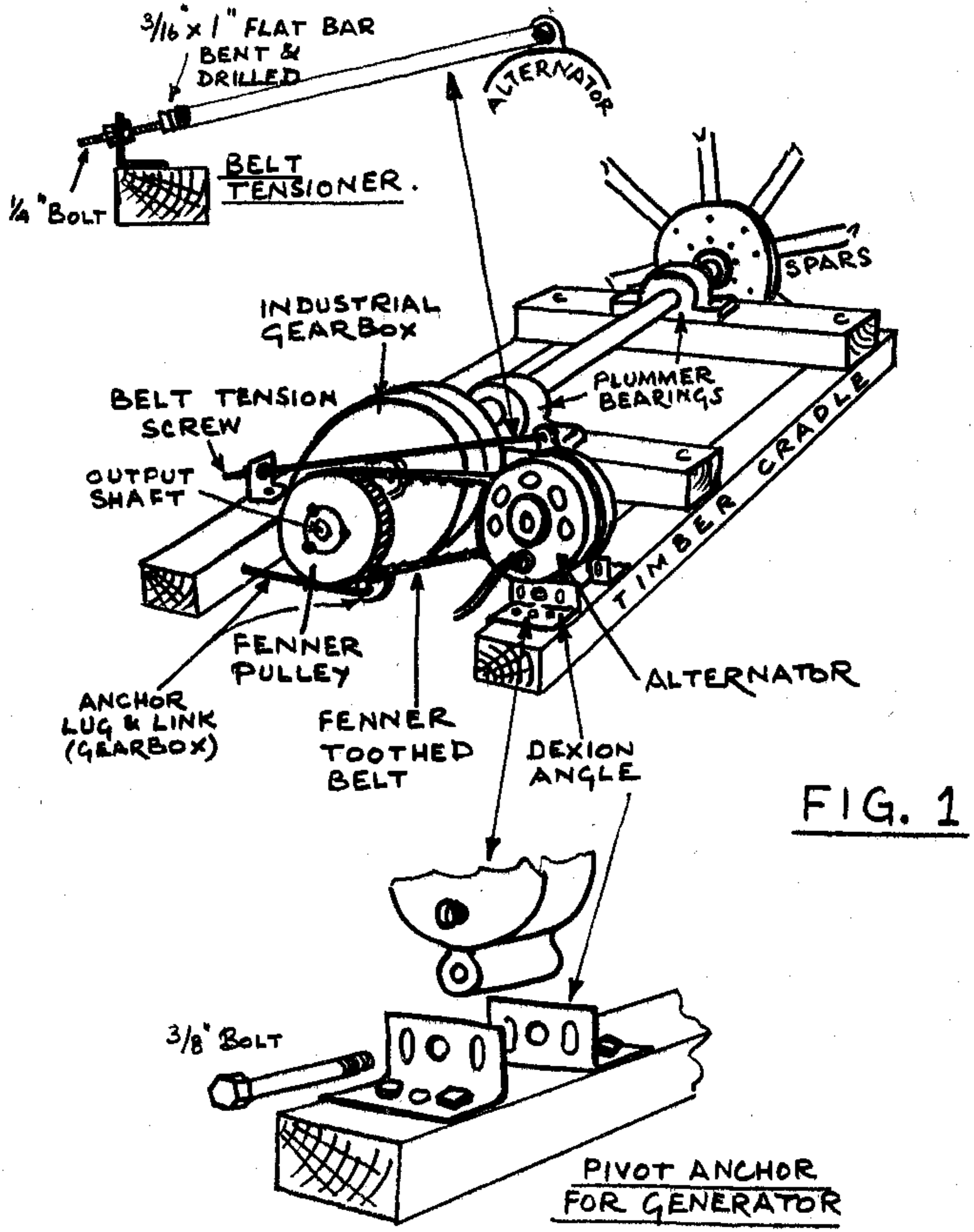
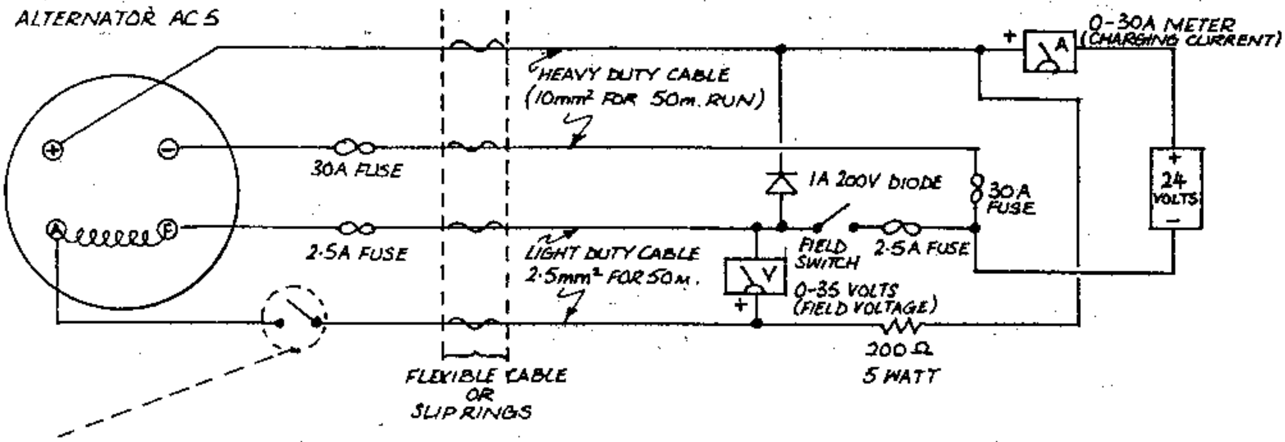


FIG. 1



OPTIONAL WIND PRESSURE SWITCH TO AVOID SLIGHT BATTERY DRAIN DUE TO FIELD CURRENT IN VERY LOW WINDS. CONTACTS ARRANGED TO CLOSE WHEN WIND EXCEEDS ABOUT 7MPH.

— NO VOLTAGE CONTROL IS PROVIDED — TURN OFF MANUALLY WHEN BATTERY FULLY CHARGED.
— CHARGING CURRENT IS SELF LIMITING.
— FIELD VOLTAGE METER RISES AT LOW WIND SPEEDS REACHING ABOUT 24 VOLTS AT CUTTING IN SPEED & THEN RISING MORE SLOWLY TO A MAX. OF 33 VOLTS AS CHARGING CURRENT INCREASES.

CIRCUIT DIAGRAM.

Too small a tail could allow the canvas sails to override it, a gust might easily, we thought, sweep the head round tail to the wind, when the spars would certainly snap. Too large a tail, and the head would follow each tiny change of wind direction like a demented weather cock, imposing undue stress on the rotor.

The size and shape of tail we settled on was an isosceles triangle of 5'9" sides and 4'0" base, made from ½" exterior ply, well primed with aluminium paint. Figure 2 shows the method of triangulation used to sling the tail out in an effective position. The length of boom or strut seems uncritical - ours is about 9'0". The criterion is achieving some balance of tail weight with that of the spars and sails (with gear box and generator between) to avoid undue stress on the turntable bearing.

Two lengths of 3"x1" pine were bolted (¼" bolts) one either side of the trianglar tail, centrally through one apex (1). A 3"x 1" hole was made through the tail immediately beneath them, about 1½ ft from the back edge of the tail, to receive the cross brace (2). This was centred and screwed to the pieces of 3"x 1" to keep it in place while working. It should be noted that the rigidity of the whole tail structure depends entirely on a successful system of triangulation, and not on individual joints.

The struts (3) were bolted at one end to the tail as shown, constrained in a shallow curve to be screwed with 3/8" coach screws (or bolted) to the insides of the cradle timbers. They are pivoted there, and should be left thus to allow for movement - stretch of the wire, warping of the timber, hammering by the wind. The stretcher (4) is a simple method we used to keep the struts constrained to their curve. The heads of the bolts, on tightening, bed themselves into the wood and thus stay put.

Two short pieces of 3" x 1" are drilled alike to take 3x¼" bolts (5) and these are used to clamp members (1) and (3) together. It will be seen that drilling the struts would seriously weaken them: further, clamping ensures that slight freedom of movement necessary to working structures exposed to the elements.

The shear legs (6) may be fixed in any of several ways: we screwed ours with 5/16" coach screws into the end grain of the cradle, and gave them extra support with two steel brackets. The metal plates at the apex we cut from an oil drum, and bolted with ¼" bolts to the shear legs. The 3/8" tube may be a bit of gas pipe - its function is to prevent the steel wire from chaffing.

CRETAN WINDMILL – THE TAIL

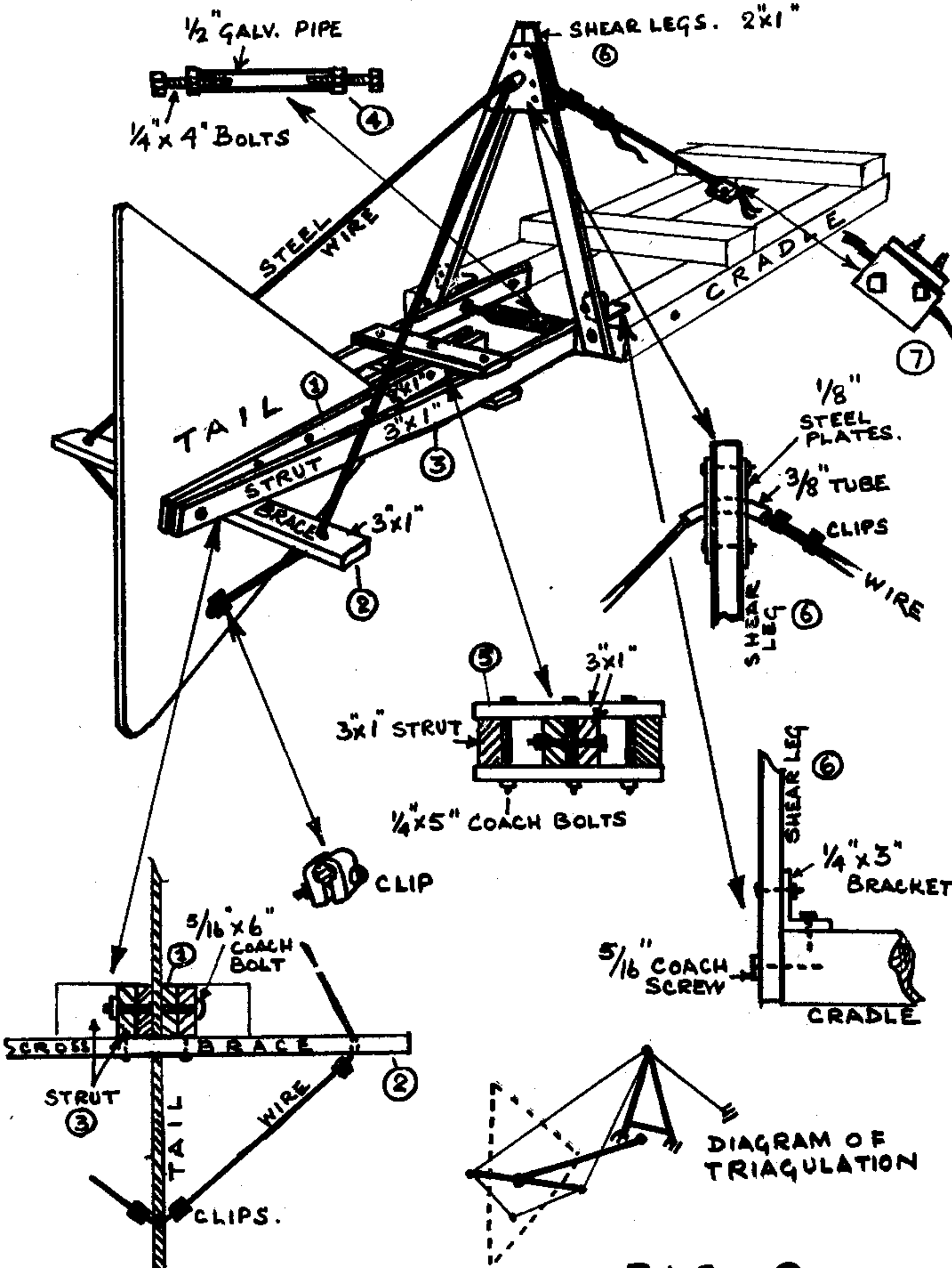


FIG. 2

The wire we used to complete the triangulation was ex-P.O. twisted, fairly high tensile, wire as used to tie telephone poles to ground stakes. The clips came from the same source. The wire, in one length, and starting from an anchor point at the further end of the cradle, was threaded in turn through the tube in the shear leg apex; a hole in one end of the crossbrace; the tail; the further end of the crossbrace; back through the shear leg tube and either clipped to the first length of wire, or anchored with it to the cradle by means of two steel plates and $\frac{1}{4}$" coach screws (7).

Care should be taken to get rid of all kinks and bends in the wire, and to have neat sharp turns at each point. This took us some time, ensuring the tail was inclined slightly upward to allow for subsequent droop, and working the wire through each hole until we were satisfied it was taut.

It will be seen how important it is to leave the inner end of the boom "pivoted", and not to be tempted to add further screws: the maximum moment occurs here, and the slightest drop of the tail would either wrench the screws or more likely split the booms. The tail thus described has weathered severe storms. Perhaps it could be smaller in area, otherwise it has proved satisfactory. Everything was well painted with aluminium primer.

<u>MATERIALS</u>:

2" x 1" pine approx. 6'
3" x 1" pine approx. 20'
$\frac{1}{2}$" ext. ply approx. 5'6" x 4'0"

$\frac{1}{4}$" Coach screws 2 x 2"
2 x 3"
3/8" Coach screws 2 x 3"
5/16" Coach screws 2 x 3"

2 Steel Brackets $\frac{1}{4}$" x 3" x $1\frac{1}{2}$" or dexion
Ex-P.O. wire and clips - approx. 18 ft

$\frac{1}{4}$" bolts - 3 x 5"
4 x 3"
6 x 2"

5/16" bolts - 1 x 6"

<u>TURNTABLE</u>: With the tail in place and the cradle complete with gearbox and generator standing on a bench, we bundled up spars and sails and hung them from the face plate so that we had the total weight of the head in its working distribution. We could now find the point of balance of the head, that is the centre line for the turntable. We rolled a broomstick under the cradle until the whole thing balanced, and marked the place on the cradle. We removed the tyre from the roadwheel of the caravan axle unit, and drilled the wheel so that we could bolt on two pieces of 6" x $1\frac{1}{4}$" hardwood, in length that of the width of the cradle (1) (Figure 3). These in turn were bolted to the cradle so that the centre of the wheel accorded with the marked point of balance. We checked there was room to replace the hub nuts on the wheel to refasten it to its brake drum and axle when the time came. The brake itself may be left intact - just check that it is not binding - as ours was after long disuse - it will be a useful way to check rotation of the head if maintenance is needed in a strong wind.

The mounting of the axle, vertically in the tower, is shown in Fig. 3. We used a length of 5" x $1\frac{1}{2}$" pine, bored centrally and chiselled to a square hole to allow the square axle to slide through and this was attached with Dexion brackets and $\frac{1}{4}$" bolts to the timber skirt at the top of the tower. It will be seen that the weight of the complete head is supported on an 1" dia bolt and nut in a bottom cross beam. We used 3" x 2" pitch pine; if white or yellow pine is used an unflawed piece of 3" x 3" minimum should be used. This beam was bored centrally to take the 1" bolt, and counterbored and chiselled to accommodate the nut as shown. A further short length of 3" x 3" is then bored and cut with a square hole to act as lower guide to the axle, and screwed or bolted to the crossbeam as shown (3) (4).

CRETAN WINDMILL – THE TURNTABLE

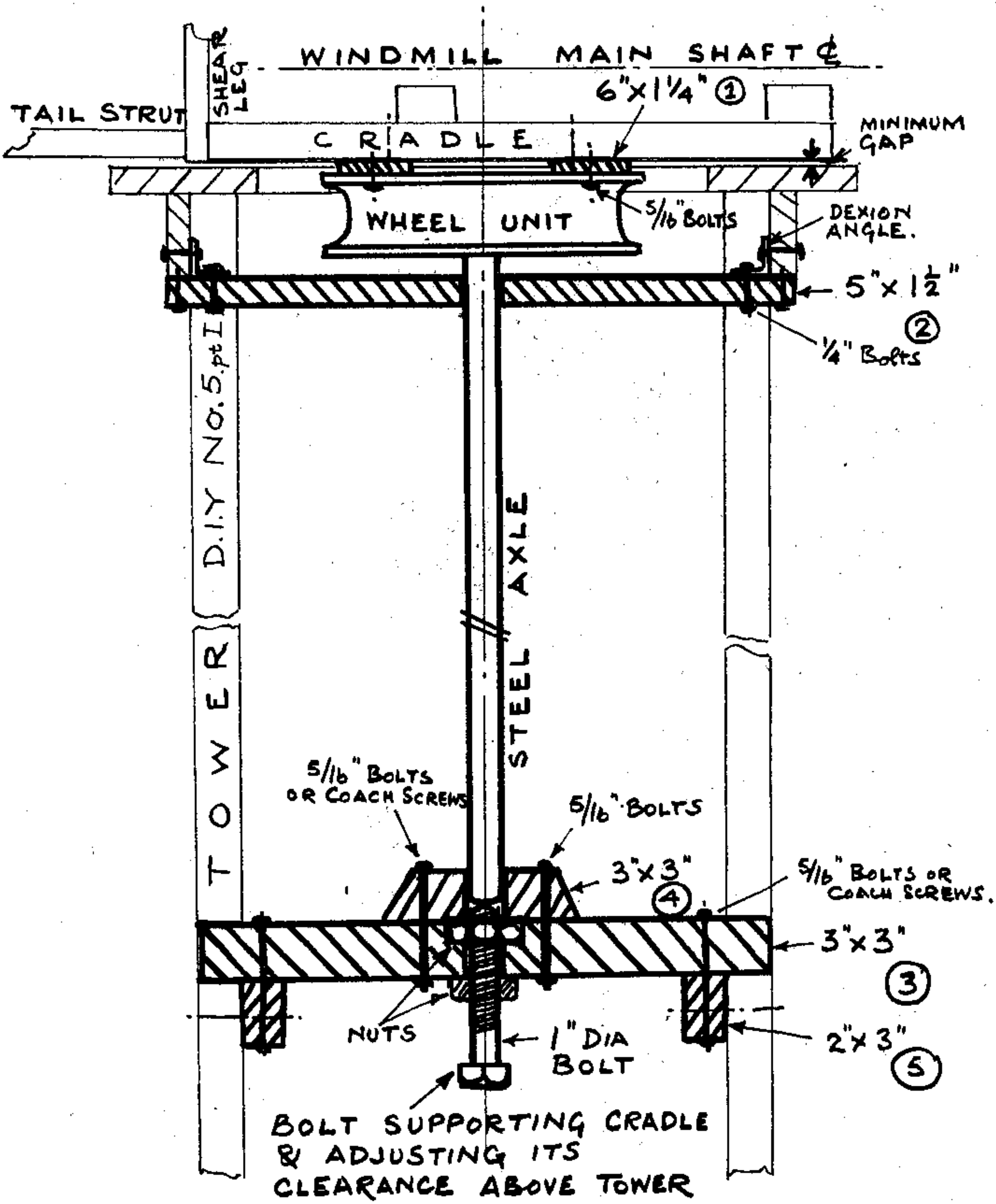


FIG. 3.

CRETAN WINDMILL - HEAD RETURN DEVICE

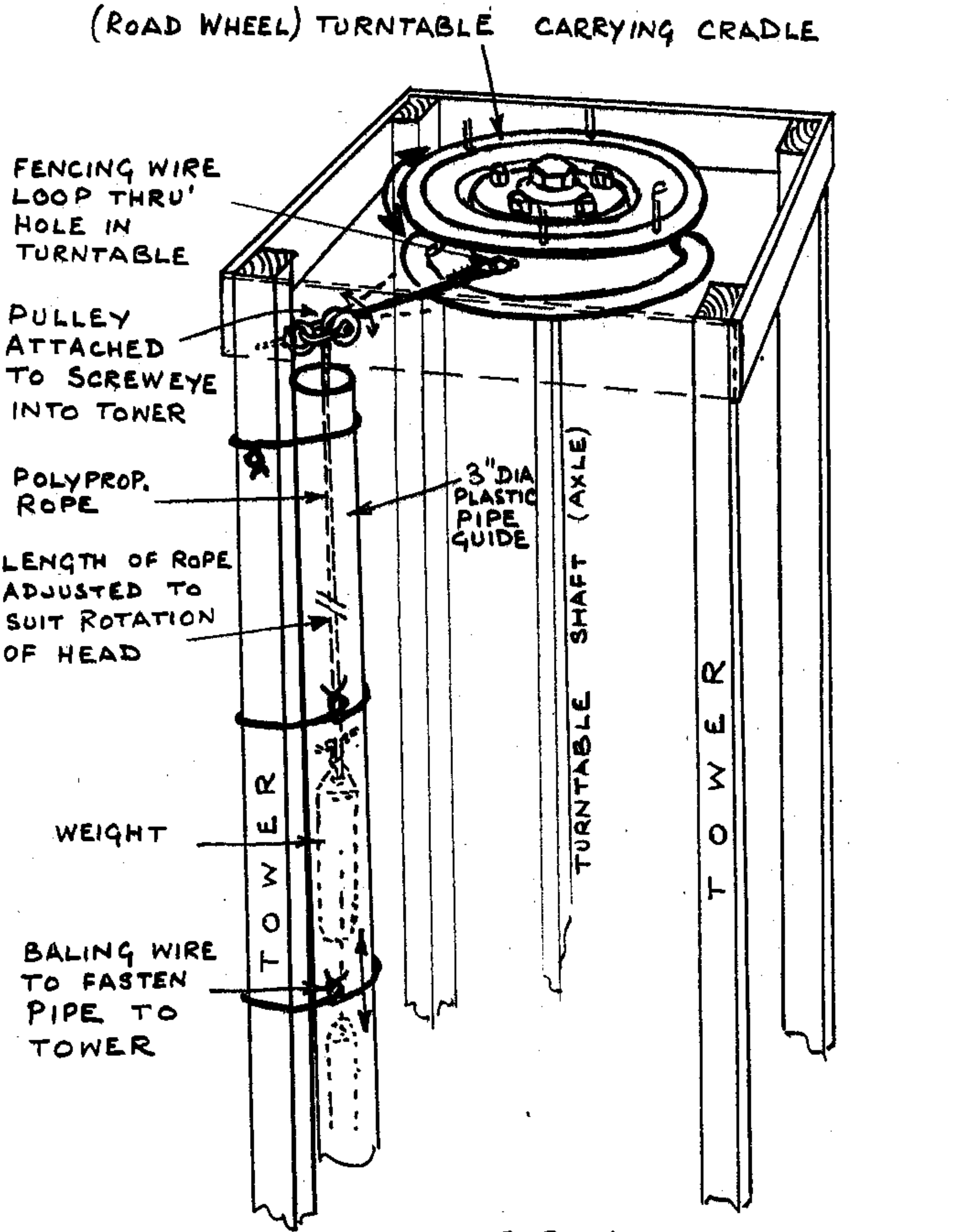


FIG. 4

Thus we have a bottom fixing which allows adjustment of the head to the minimum clearance necessary to allow the head to turn free of the tower. so that the rocking of the head in gusts of wind is reduced to the minimum.

We dismantled the tail, and as much of the head as necessary to carry it to the tower, and assembled the turntable on the tower. The top guide (2) of course has to be central and with that bolted to the skirt, the axle was passed through it until the hub unit rested on it. The cradle was then lifted onto the tower, and the caravan road wheel, already bolted to the cradle, was in turn bolted onto the brake drum hub unit. Ensuring that the axle was hanging quite vertically, the bottom beam (3) was then guided over the end of the axle, and its position marked for the two cross pieces (5) to be bolted to the tower. The adjusting bolt should be proud of the top nut by about 1/8"

Drilling the tower and cross pieces should be done accurately so that the axle remains absolutely vertical, and the supporting beam horizontal. The tail should now be rigged, and the spars and sails, gearbox and generator replaced and made ready for work. The supporting bolt in the bottom beam may then be screwed upward until the head swings with the wind with no interference. The checknut beneath the beam should be tightened.

MATERIALS:

1 5" x 1½" pine approx. 3'7"
1 3" x 3" pine approx. 3'0"
1 3" x 3" pine approx. 1'0"
2 2" x 3" pine approx. 3'0"

2 Dexion Angles x 5"

5/16" bolts - 4 x 2"
5/16" 4 x 6" or Coach Screws (x4½")
5/16" 4 x 5"

1/4" bolts - 8 x 2"
1" bolts - 1 x 5" + 2 nuts

Canvas for the sails may be obtained from Russell and Chapple Ltd., 23 Monmouth Street, London WC2H 9DE, telephone 01-836 7521. They will also make the sails.

This DIY plan has been prepared for the Centre by John Eyles. ©
The information contained in this leaflet has been given in good faith and is believed to be accurate at the time of printing. However, both the author and the National Centre for Alternative Technology decline all responsibility for errors and omissions.

Other DIY plans, information sheets and books are available from the 'Quarry Bookshop' at the Centre. Please enclose a S.A.E. with any correspondence as we are a charity. Visitors are welcome.

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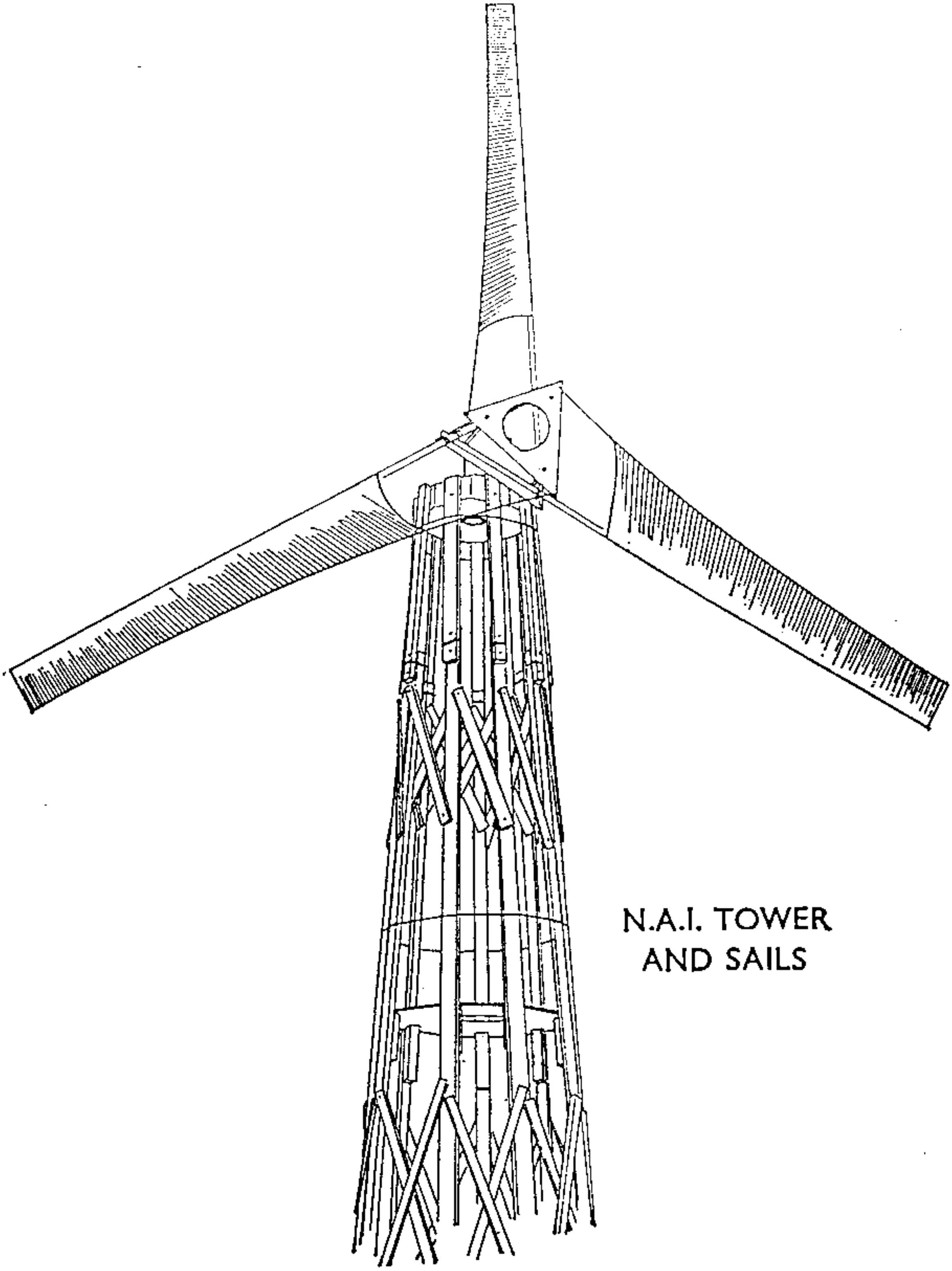


N.A.I. TOWER
AND SAILS

When building windmills, always
overestimate the strength of the wind and the forces involved. It pays to be safe.

This platform problem is so acute that there is a good case to be

Technological Self-Sufficiency, Robin Clarke Faber and Faber UK 1976
ISBN 0-571-11057-6 PP 138 - 141

made for building a tower and not using a mast. The top platform then adds strength to the tower, and another half-way up as well will help even more. The best design I know is for a 26-foot high tower built by the New Alchemy Institute-East on Cape Cod and fully described in the *Journal of the New Alchemists*, No. 2. The basic structure is made from 8 lengths of 4 × 2 timber each 26 feet long (all timber must be treated with wood preservative). The 2 platforms are fixed to the tower by nailing down into short lengths of 4 × 2 bolted to the main uprights (with eye bolts, on the centre platform, to provide a fixing for the guy wires). The NAI wires run inside the tower but anchoring them outside would in my view provide a better hold. The tower is tapered to a shape given by making the top platform an octagon 28 inches across and the centre one a circle of 48 inches diameter. The main uprights are fixed at the bottom with large bolts to 8 bits of telegraph pole 6 feet long driven deep into the ground. The top half of the tower is braced with 16 40-inch lengths of 1 × 3, and the bottom half with 16 58-inch lengths.

Such a tower (this one was designed for a 18-foot diameter sail machine) will give pretty good service. Bits of wood attached up the lee side will make a safe ladder, and some more pieces mounted all round about 3 feet from the top will give an easy toe-hold for working on the machine. If you want even more strength (and who doesn't?) the price of a third platform will be miniscule and help out of all proportion to its cost. By the time you've finished, such a tower is going to cost £100 or more, but a metal, commercially-available model to do the same job will add up to 3 or 4 times as much when you've finished paying for transport and import duty and all the other extras people can manage to think up. Build your own.

Sails and propellers

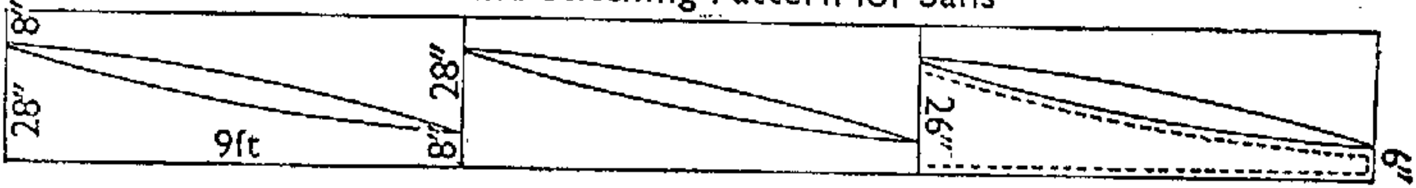
There are two nice things about windmill sails. First, they're easy to make, which means they're also easy to replace. Second, they'll never be as strong as the rest of your machine. That's an advantage because in a gale the sail is likely to get ripped up first, and once that's happened, of course, the wind machine will stop turning and no more harm can come to it. A rigid propeller, by contrast, can go on and on turning in a gale until the whole machine disintegrates.

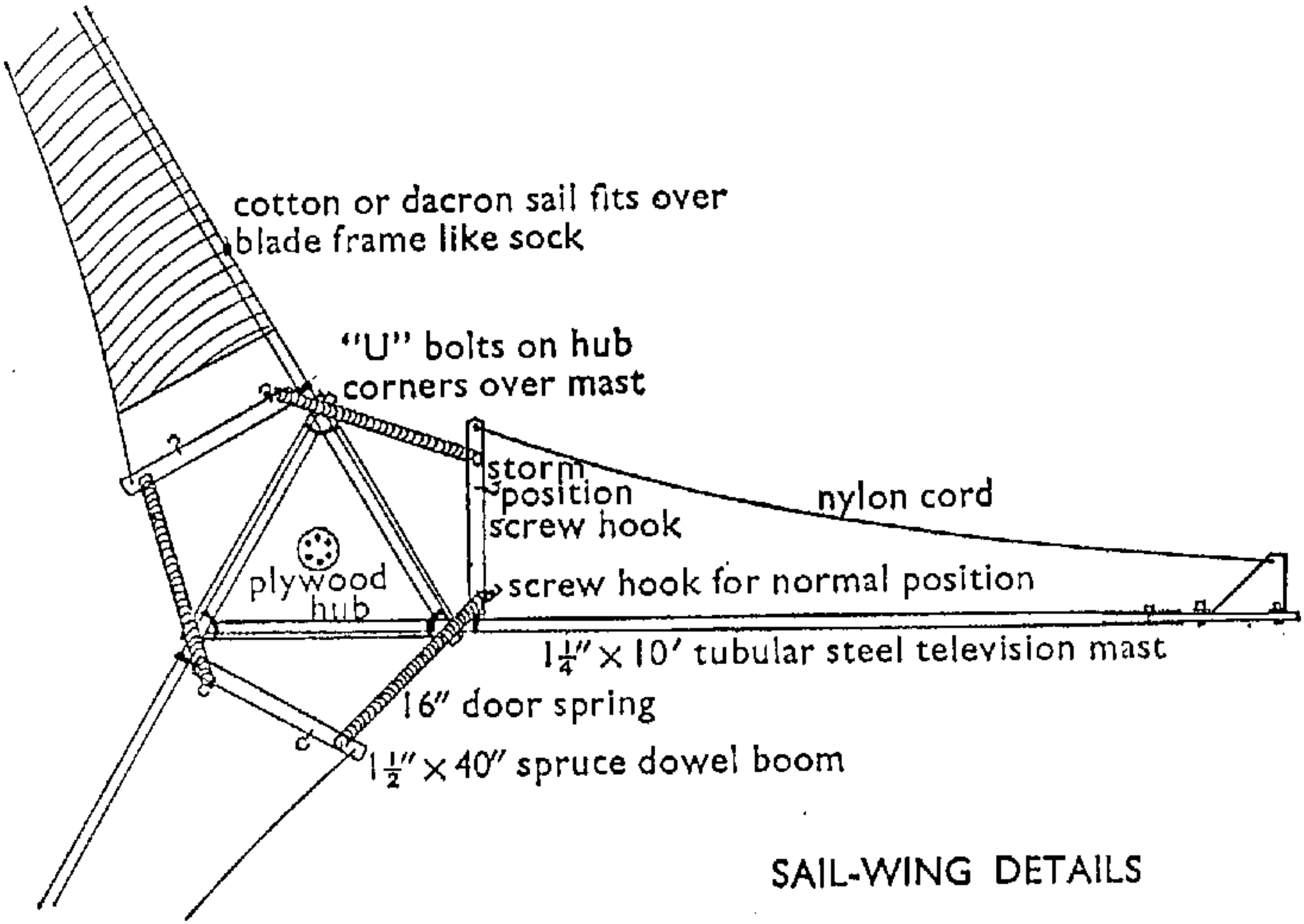
The sailwing idea has been recently developed by a team of scientists at Princeton University who were struck by the efficiency of a glider wing, with its blunt, rounded leading edge. The New Alchemy Institute has adapted the idea to make an 18-foot diameter water-pumping mill which works pretty well, even in a very low wind speed. The Princeton idea led to a 25-foot diameter machine, designed to produce 7 kW in a 9 metre per second wind.

The leading edge of the NAI sail is a 1¼-inch diameter steel television mast, while the trailing edge is made from a taut wire or nylon cord. As a result, the shape of the sail changes with windspeed, to take up the most efficient aerodynamic shape. The sail itself, made from cotton or, better, dacron (as in boat sails), slips over the steel and nylon cord frame like a sock. The drawing on page 141 shows the essentials. The steel masts are fixed with U-bolts to a 1-inch thick triangle of plywood, which serves as the hub, each side of the triangle measuring 30 inches. The rest is apparent from the diagram. Note the door springs fitted to give an automatic governing device for high winds. These have two positions, one for use in storm conditions. The NAI design has, however, come through gale force winds in the normal spring position. I would recommend an additional governing device (see next section), so I think you could dispense with the storm position for the springs – not a very practical idea, in any case, for they involve climbing the tower in a high wind to make the adjustment.

This unit has been tried and tested, and if you get into problems write to Marcus Sherman, c/o New Alchemy Institute-East, Box 432, Cape Cod, Massachusetts, for advice. The NAI machine was for water pumping, so the hub was connected to a crank shaft used to power the pump. Our machine will be an aerogenerator, so we will use a different system (see below). But it's worth pointing out now the main disadvantage of sails for electricity generation. The rotor will revolve relatively slowly, and will be far too slow to turn a car alternator at the right speed. Even with propellers, you need to gear up by about 10 to 1. For a sail machine of this type, you will need to gear up 20 or even 25 to 1. But, even allowing for the frictions that introduces, you'll still make more efficient use of slight winds than would a propeller machine.

Cutout and Stitching Pattern for Sails





SAIL-WING DETAILS

An Advanced Sail-Wing for Water-Pumping Windmills

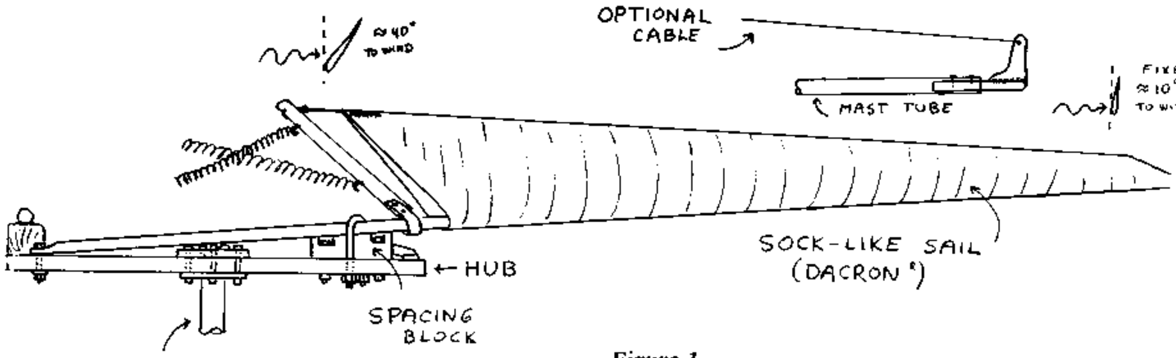


Figure 1
Simple sail-wing windmill details (one sail of three).

The development of sail-type windmills at New Alchemy was initiated by Marcus Sherman. The prototype was a water-pumping windmill which he had built in Southern India in 1972 to aid in irrigation. His windmill in Madurai used cloth sails, bamboo masts, teak pole tower legs and an ox-cart wheel (1). In 1973 Marcus built a similar windmill here on Cape Cod employing cloth sails to which had been added a spring-operated self-feathering mechanism (2). We have continued to develop the sail-wing windmill using it for aquaculture circulation and irrigation, and have found it to be, for our purposes, a workable and adaptable power source.

The vital part of the sail-wing windmill is the sail-blade, which consists usually of a fabric surface supported by a rigid mast. We have used Dacron (R) as a sail material because of its strength and durability. Figure 1 illustrates how the sail is slipped onto the mast like a sock and attached to the movable boom. The boom keeps the sail taut yet allows it to adapt to changes in the wind. Our first windmills had fixed-angle tips and feathering roots as illustrated.

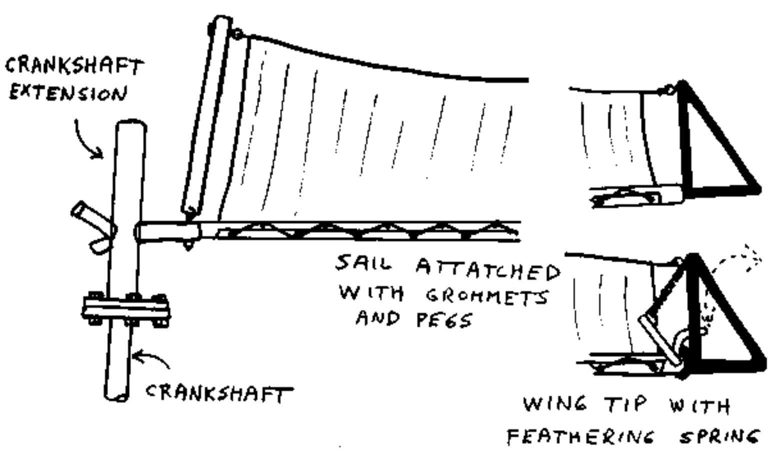


Figure 2
Advanced sail-wing details.

Figure 2 shows a later version of the sail-wing. An extension shaft holds the blades further from the tower. The sail is rigged with cord as on a sail boat, and the tip bracket has a feathering mechanism. Figure 3 shows how stabilizing cables may be positioned to prevent flexing of the blades.

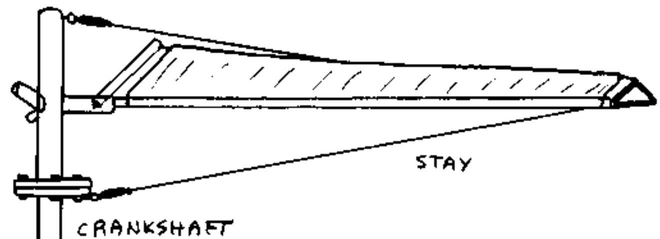


Figure 3
Stabilizing cables on advanced sail-wing.

The sail-wing windmill which we used for circulating water in the mini-ark in 1974 was strong enough to use two three-inch diameter piston pumps simultaneously. Figure 4 shows how the two pumps were connected by a swivel to the pump rod. The cast iron pumps were inexpensive. The packing boxes on each were fabricated from plumbing supplies (Fig. 5) (3). The double pumps were undersized for the strength of the windmill, however, and were replaced later by a higher capacity, more compact diaphragm pump which could be placed below ground (Fig. 6) (4). Figure 6 shows the buttresses on each leg of the windmill tower. It was felt prudent to strengthen the tower in order to give adequate support to the additional weight of the crankshaft, extension, cables and other hardware that were added subsequent to the original design.

The automobile crankshaft bearings used in the early windmills were adequate for the lighter type of blades, but required periodic lubrication on the

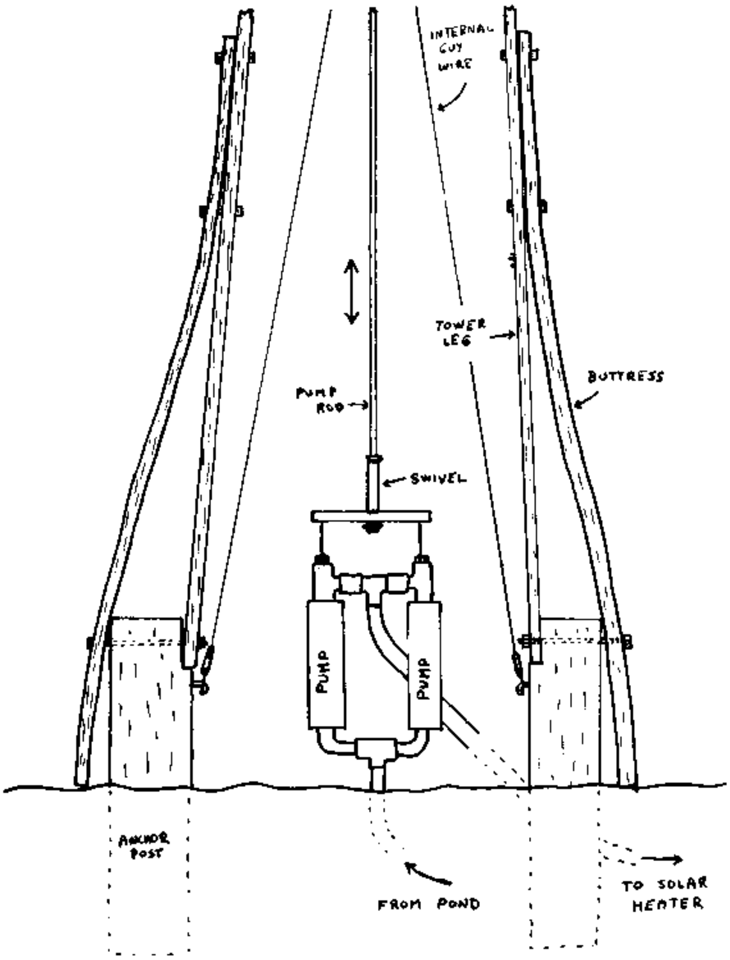


Figure 4
Sail-wing windmill with buttresses and two pumps.

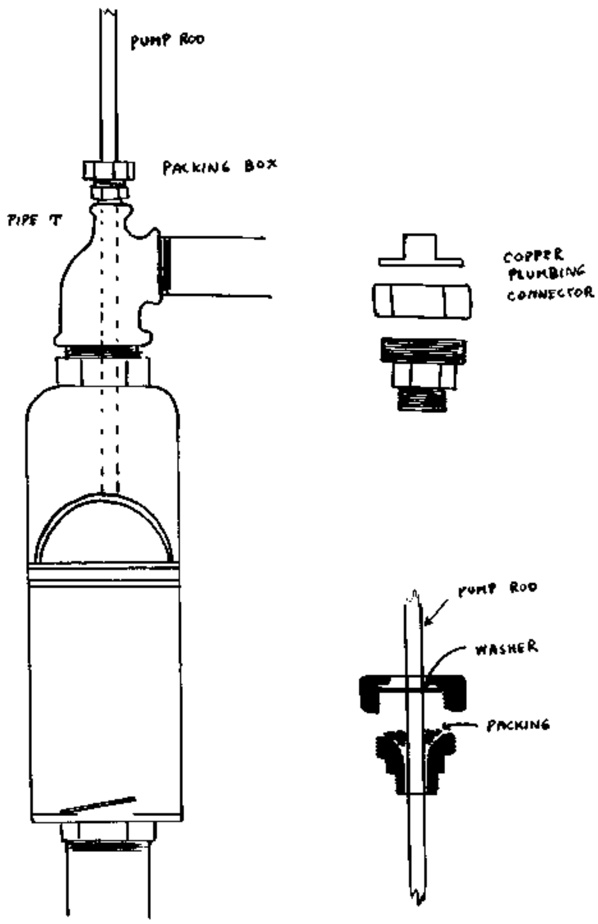


Figure 5
Inexpensive packing box for piston pump.

heavier models. Grease fittings are easily placed in each bearing clamp (Fig. 7). During one stormy period lasting several days, although there was no pumping load on the windmill, the extended period of high speed turning caused the bearing surfaces to wear through on the heavier blade end. It is advisable to balance the weight on each end of the crankshaft to maintain equal forces on the bearings.

The design for the latest windmill is moving into the realm of a heavy duty, long-lasting machine. Merrill Hall has constructed an experimental sail-wing windmill with several new features. The major change is that, for the first time, the blades face the wind. Previously, all of our sail-wings have trailed downwind. A tall, narrow tail tracks the blades into the wind. The main shaft, which has a two-inch diameter, runs in sealed bearings. Fitted to the end of the shaft is a plate on which a pin is fixed, offset from the shaft center point, to convert rotary motion of the shaft into cranking motion required for the vertical travel of the pump rod. The sail-wings are spring feathered at the base and centrifugally feathered at the tip. The results of these most recent innovations will be discussed after a season's operating experience.

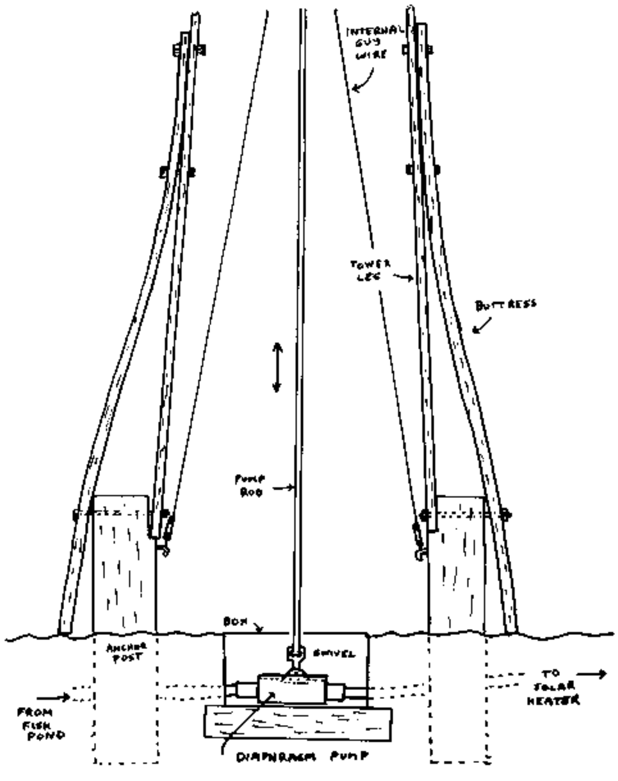


Figure 6
Sail-wing windmill with diaphragm pump.

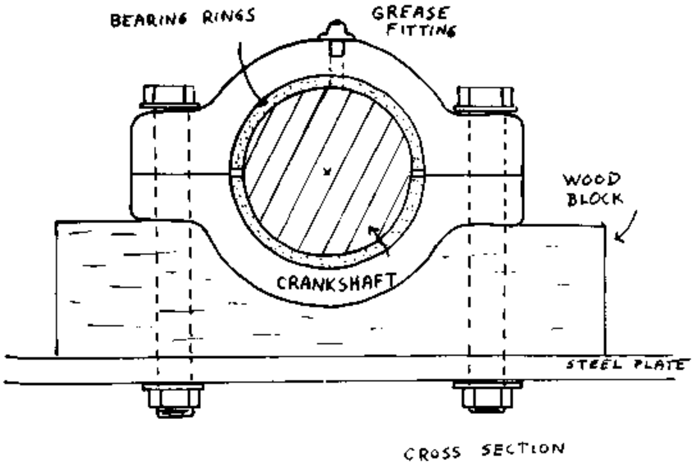


Figure 7
Windmill bearing showing grease fittings on crankshaft axle.

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2. Sherman, Marcus. 1974. "A Water-Pumping Windmill That Works." *The Journal of The New Alchemists (2):* 21-27 pp.
3. Model No. 350 - Shallow Well Cast Iron Cylinder from Mid-West Well Supply Co., Huntley, Illinois - $18.50 (1974).
4. Large capacity hand-operated diaphragm pumps. Edson Corp., Inc., 460 Industrial Park Road, New Bedford, Massachusetts - about $100 (1974).

– Earle Barnhart

When you've made your sails or propeller you have to fix it to something which will rotate in a bearing which can be anchored to the mast. The best thing is the complete rear axle and differential of a scrap car, which can now be obtained very cheaply from a junk yard (see next section). But assuming for the moment you've done that, you must now balance the rotor. This is important: if you don't balance the thing, the vibrations and the uneven weight will certainly be enough to shake the whole contraption loose. Your rotor, electrical equipment and probably your tower will crash to the ground. So balance you must.

Any good engineer will tell you you must balance dynamically – that is, when the thing is revolving fast. You can't – it needs complicated equipment. So you have to balance statically, which means first setting the thing up with the rotor in a vertical plane and spinning the rotor hard by hand a few times. Watch the point at which it settles to rest. If it's always the same point, you are unbalanced, and you'll have to weight the lighter arms. With a propeller you do this by cutting out an oval shape of metal and screwing it to the lighter blade with the screw offset from the centre. Find the right point by trial and error to screw in, which will give you rough balancing. Then twist the metal oval round on its screw to give you fine balancing. Then tighten the screw. To balance a sail, use your common sense; some pieces of lead flashing cut into thin strips and twisted round the metal strap at the tip of the wing might be good – but make sure they're firmly fastened or they'll come off in a high wind.

Transmission and governors

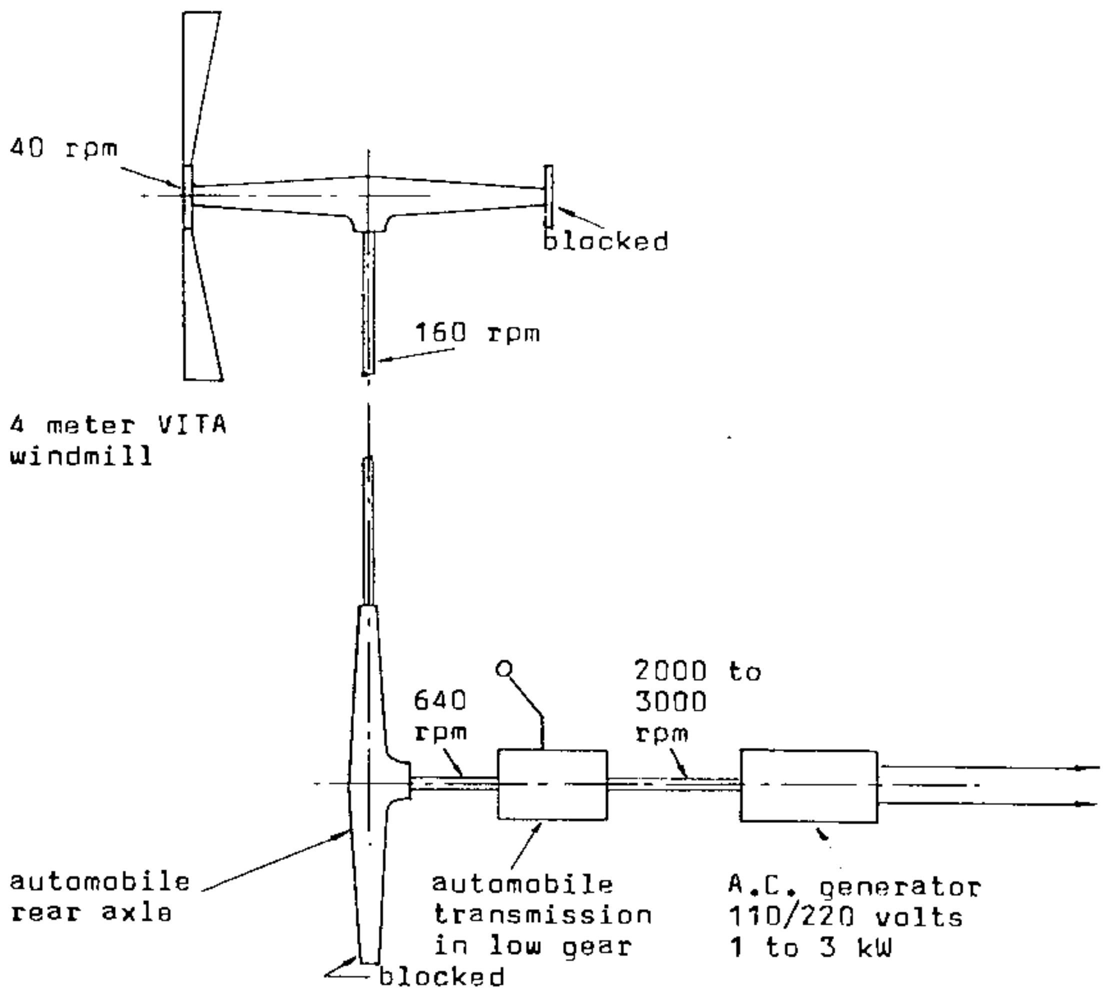
The problem of how to transmit power from a rotating sail or propeller to a device for producing electricity can be solved in two ways. You can build a shaft which will turn pulley wheels linked by a belt to an alternator. That will take you into buying and fitting bearings and pillow blocks from small mail order firms, or finding the right junk pieces in the right place. Jim Sencenbaugh has built a pretty successful 500-watt aerogenerator in this way and for $15 he'll send you a complete set of plans. They'll take you through not only all the mechanical problems, but round the electrical circuit (see below) as well. Even if you don't intend copying someone else's plans exactly, it's not a bad idea to get them because they contain many hints which you might otherwise spend much time puzzling over (address: 673 Chimalus Drive, Palo Alto, California 94306).

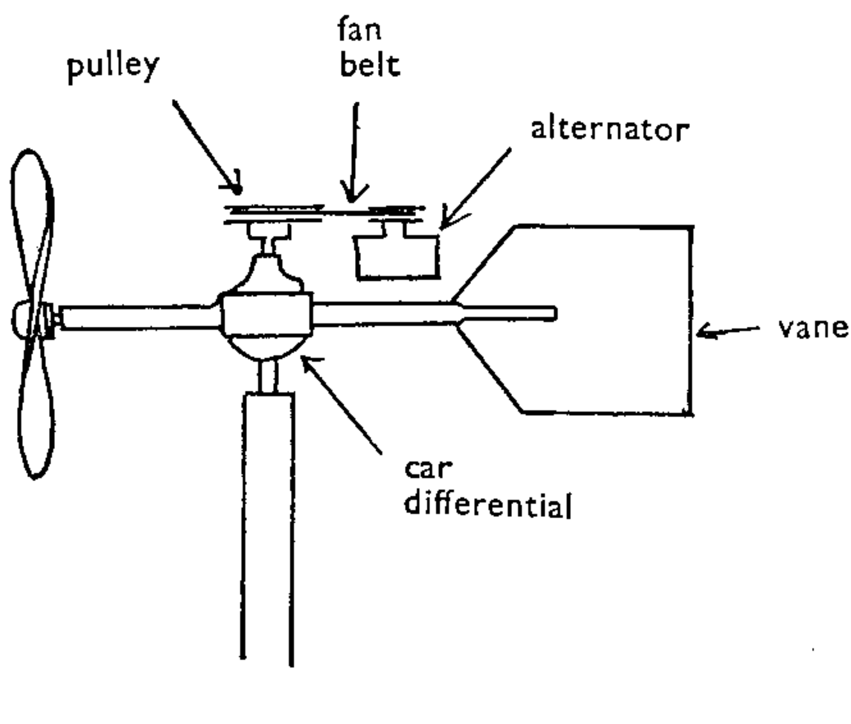
The second way of doing it, which I reckon is much easier, is to buy a complete rear axle and differential from a junk car dump. If you don't know much about what happens inside a car, now is the time to find out; the information will not only help you make the windmill, but it'll be very handy later on if you're still running a car. The beauty of this scheme is that it is cheap – and that you can use a wheel hub to solve your main bearing problem. Leave one hub on, and bolt a plywood plate on which the propeller is mounted to it. You then have to mount the entire axle and differential on a 1-inch piece of marine plywood, or a steel plate which is even better. This is the platform which will carry all the gubbins at the top of the machine – notably the axle, the alternators and some electronics.

Your second bearing problem is how to mount this platform on top of the tower. It must rotate freely so that the propeller or sail can always face the wind. The expensive way of solving this is to buy, as the New Alchemy Institute did for their sail mill, a steel turntable. For the record, theirs was a model no. M4-1214 series 1,000 Econotrak bearing (9-inch inside diameter) from Rotek Inc., 220 West Main Street, Ravenna, Ohio 44266, and it cost them about $129. It's undoubtedly a splendid device but you can do the same thing with another wheel hub. Ideally, I would buy a scrap tractor hub and axle. Disconnect it from the differential and bolt the differential housing to a platform near the top of the tower. The

Suggestion for

Electric Power Generation Using VITA 4 meter Windmill





DIFFERENTIAL MOUNTING

top platform can be cut out to take and support the axle housing near the hub. Now mount the propeller platform onto the wheel mounts on the tractor hub.

It's a good idea to leave the handbrake cable trailing from both these hubs – the propeller mounting hub and the platform hub. That will then give you a manual method of (a) stopping the propeller from turning in a gale; and (b) stopping the turntable at a position where the propeller is at right angles to the prevailing wind in a gale. A double precaution.

The axle and differential can be mounted most easily on the platform with the differential sticking up – in other words, the vehicle drive shaft, were it still attached, would be pointing vertically towards the heavens. It then remains to attach a pulley wheel, spinning horizontally, to the car drive shaft mounting, and to link that pulley with a belt drive to the alternator(s). When you've done all that, you've got another balancing problem. It's very important that the platform, and all that you've installed on it, is weighted in such a way that the centre of gravity falls immediately over the mounting on the tower. If it doesn't, the weight, plus the vibrations from the rotation, is certainly going to tear the top platform out of its tower mounting, and you'll lose the lot. If you are using more than one alternator, the balancing can probably be done by positioning them to achieve the desired effect. Otherwise you'll have to devise some other method of weighting the platform.

Mounting the differential this way may lead to two problems. The lubrication may not work well and pulley belts may slip off. There is a case, therefore, for mounting the thing as it was in a vehicle – with the differential horizontal and the pulley wheels vertical – but it's usually more difficult.

The drawing on page 146 shows the main elements of the platform and its mounting. You must now build a fairly substantial vane, and attach it to the rear axle at the opposite end to the propeller or sail. This is what will turn the mill to face the wind. And you're now straight up against the problem of governors.

If you just leave your mill to go faster and faster in stronger and stronger winds, make no mistake but that you will lose the lot. Maybe not in the first gale – but certainly within a few months. You must therefore install some device either for slowing the propeller down in strong winds, or for turning it somewhat out of the wind.

The electrics

The simplest way of generating electricity with a windmill would be to hook it up to an alternator which provides you with a.c. current, as in your domestic supply. But it's the worst way. Domestic a.c. comes to you at a constant 50 or 60 cycles a second. What your windmill alternator will produce will be very a.c. – so a.c., in fact, that its frequency will change with every gust of the wind (the frequency depends on how fast the rotor is turning). With such a supply you could run only two things – heating elements of an electric stove, and incandescent electric light bulbs. Even those will blow hot and cold as the wind gusts.

If you're building a windmill, as distinct from buying one (see last section), it means you don't have much cash. In which case you don't want to go out and buy a new alternator or generator. That would cost you a lot of money. Instead you can get one for almost nothing from a junk vehicle lot. There are two types of device used on vehicles – earlier models had a generator which produced 12 volts d.c. direct, and later models (and most trucks) produced a.c. but incorporated a rectifier to change the a.c. back into 12 volts d.c. It is the latter, the alternator, that you want – it's simpler, more effective and produces current at a lower rotational speed than the old-fashioned generator. You'll find alternators on all trucks, and on the larger and newer cars. When you've found the alternator you want, it's a good idea to purchase a service manual for the vehicle from which it came. The manual will tell you the performance of the alternator, and give you some idea of how to treat it, test it, and service it. When you disconnect the alternator from the vehicle make sure you take the voltage regulator that goes with it. You need this to ensure your batteries get charged at the proper rate.

At this point you need to know some basic electricity – power in watts equals volts times amps. For instance, if you get hold of the alternator from a Volkswagen bus with a 1,700 cc engine, you'll find it's rated at 14 volts and 55 amps. Multiplying those together tells you you can get up to 770 watts from the device. That's only the nominal rating. You can take more power from it than that, providing you do it intermittently. That's quite a lot of power, and you certainly won't need more than two such alternators.

You'll also find the optimum power of the alternator comes at 2,200 revolutions a minute. If your aerogenerator ever gets up to that speed, you'd better run for your life because the surrounding countryside will shortly be spattered with bits of windmill. In fact, the sailwing type will not produce more than, say, 150 rpm and the propeller rotor no more than 300 rpm – unless conditions are exceptional. As I've said, you must therefore gear up – by, say, 10 to 1 for a propeller and 20 to 1 for a sailwing. Don't forget there is already a gear up between your rear axle and the drive shaft. If you don't know what it is, then test it by rotating one and counting the number of revolutions of the other. It'll be something between 2·5 and 5 to 1. The rest of the gearing up is done with different sized pulley wheels fixed to the drive shaft mounting and the alternator (when calculating the effect, it's the ratio of the diameter of the wheels to each other which gives the gear ratio). Use a fan belt to connect the pulley wheels. Don't worry too much about the exact ratios – you can't know what will give the perfect result, and anything roughly right will give you the power you need.

If you're using two alternators, you can connect them both via one belt drive to one pulley wheel on the axle. But I'd recommend you use two belts and two pulleys. For one thing, if one belt snaps or some other fault develops, you've still one left and the batteries will go on being charged. Further, you may find that the heavier winter winds will work two alternators all right, but that in the summer you're better off with one. It's then easy enough to remove one of the belts.

The alternator has three connections. One must be earthed to the differential. The second, to which will have been originally connected a very thick cable, is the stator terminal which supplies the juice. This you connect to the positive pole of the battery, using very thick cable capable of carrying whatever current the alternator is rated at (the VW alternator, for instance, should carry 55 amps). Now to get the current from the top of the tower to the bottom, where the batteries will be, is a bit of a problem. It is done on manufactured wind generators by a complicated series of slip rings which transfer the current to some part of the tower. The reason is that the platform on which the alternator is mounted is constantly revolving to follow the wind. If you connect a cable from the alternator on this platform to the battery on the ground it will eventually get twisted round the tower. Now I reckon that the design of slip rings for a 55 amp current is beyond my, and probably your, capabilities. You must therefore use plenty of cable – enough to allow it to get twisted round the tower two or three times – and provide a plug and socket for it before it enters the battery. You can then periodically disconnect the plug, untangle the cable, and start again. No good using an ordinary 13-amp plug and socket, though. You'll need to find a special one capable of carrying the 55 amps.

A solemn warning. You must never disconnect the plug when the alternator is turning (that is, when the propeller is going round). If you do, you will damage the alternator, as you also will if you ever connect the battery terminals to it the wrong way round. If alternator and batteries are ever separated from each other, the propeller must be anchored or the alternator disconnected from its drive belt.

There is an obvious danger that your power cable will twist round the tower and eventually pull itself off one of its connections. To prevent that you must attach a length of strong wire, slightly shorter than the cable, from the platform to some point on the tower so that it will physically restrain the platform from making that last revolution which will snap the power cable. A bit of common sense will see you through all right.

The third connection on the alternator is to the field coils, and this provides you with your last problem on top of the tower. It is connected by ordinary electric cable to the positive side of the battery, and draws only a small current. But it's a crucial one, because it provides the magnetic effect which causes the alternator to produce current when it is rotated. The trouble comes in calm periods when the wind is too feeble to turn the blades. If you leave the field coils connected to the batteries, the latter will soon drain away, and you'll lose a lot of valuable stored juice. Some system has to be devised for breaking this connection when the wind isn't blowing, and for making it when it starts to blow. For that you need a relay.

The first way of operating it is to mount a small additional vane on the side of the platform. Spring-load it so that it will trip a mechanical relay, and thus connect battery to field coil, when the wind gets to the desired speed. Jim Secenbaugh operated his machine this way, adjusting the spring to work the relay when the wind got to 8 mph, and he says it works very well.

Possibly a better way is to use an electrically operated relay. For this you need one of those bicycle dynamos which rub up against the rim of the bicycle tyre. Set this dynamo to rub against one of the drive belts to the alternator, and use it to operate the relay which will connect the battery to the field terminal. When the wind starts to blow, the alternator will begin to revolve, and the belt will start to turn the bicycle dynamo. The current produced will close the relay and the alternator will start to charge the batteries.

An advantage of both these systems is that they overcome another starting problem. Propellers and sails do not get under way very easily in light breezes. If the field connection is made, they also have to turn against the load of the alternator, and so will not start to move until the wind is fairly strong. But if in a calm the field connection is broken, there is no load to work against. The rotor will start to turn in calmer conditions and, once turning, will close the field connection and you'll get power at lower wind speeds than would otherwise be possible.

All your electrical units on the tower – alternator, voltage regulators, relays, must be well earthed to the differential. They must also be protected from the rain by some kind of cover. At ground level earthing is provided by a long stake driven deep into the ground. As your windmill is a perfect target for lightning, you must arrange at some point for there to be a ¼-inch gap between the positive lead from alternator to battery and a lead coming from the earthing stake. You can either make such a gap, or buy one designed for use on a television aerial.

FOOD FROM WINDMILLS

A report on the wind mill irrigation project initiated by the American Presbyterian Mission at Omo Station in Ethiopia

by

Peter L Fraenkel B.Sc. (Eng)

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Intermediate Technology
Publications Ltd
9 King Street
London WC2E 8HN
England

CONTENTS

CONTENTS (continued) **Page**

1. INTRODUCTION

This report describes work done to improve and evaluate a series of wind-mills developed for irrigating small plots of land on the banks of the Omo River, using river water. The systems were developed by the American Mission for use by the local people in order to permit all the year round cultivation which is not otherwise possible. At the time of the author's visit (July-August 1975) some 19 windmills of various types were operational and under the control of local villagers and a further five were in operational condition on mission land for cultivation, experimentation or demonstration. Eleven further sail wind-mills had been completed and awaited installation for villagers requiring them.

The American Mission had applied to OXFAM for funding to allow the construction of further wind-mills. A condition of the grant was that an engineer should visit the project in order to evaluate, advise and report.

Objectives

(i) to seek methods of improving the general design and performance

(ii) to evaluate the performance of the machines

(iii) to advise on the collection of meteorological data and to make a preliminary assessment of the suitability of the wind régime

(iv) to provide a detailed report describing the project and to suggest circumstances under which this type of system might be used in other situations

(v) to make recommendations for further development work.

Acknowledgements

I should like to acknowledge with gratitude the assistance given by numerous people with this project, and in particular the kindness and hospitality received throughout my travels in Ethiopia. Particular thanks are due to the American Mission, especially the Rev. and Mrs. J R Swart who conceived this project and were very kind hosts during my stay at Omo Station, and to Mr. E O Pollock the inventor of the original Polomo mills and the source of much inspiration. Special thanks are also due to Mr. P H Stern, ITDG Water Consultant in Ethiopia, who proposed and arranged my visit and who gave valuable technical support, and to Mrs. Stern for their kind hospitality in Addis Ababa. Thanks are also due to OXFAM who financed the field work needed to prepare this report and to ITDG who contributed financially and made many of the necessary organisational arrangements.

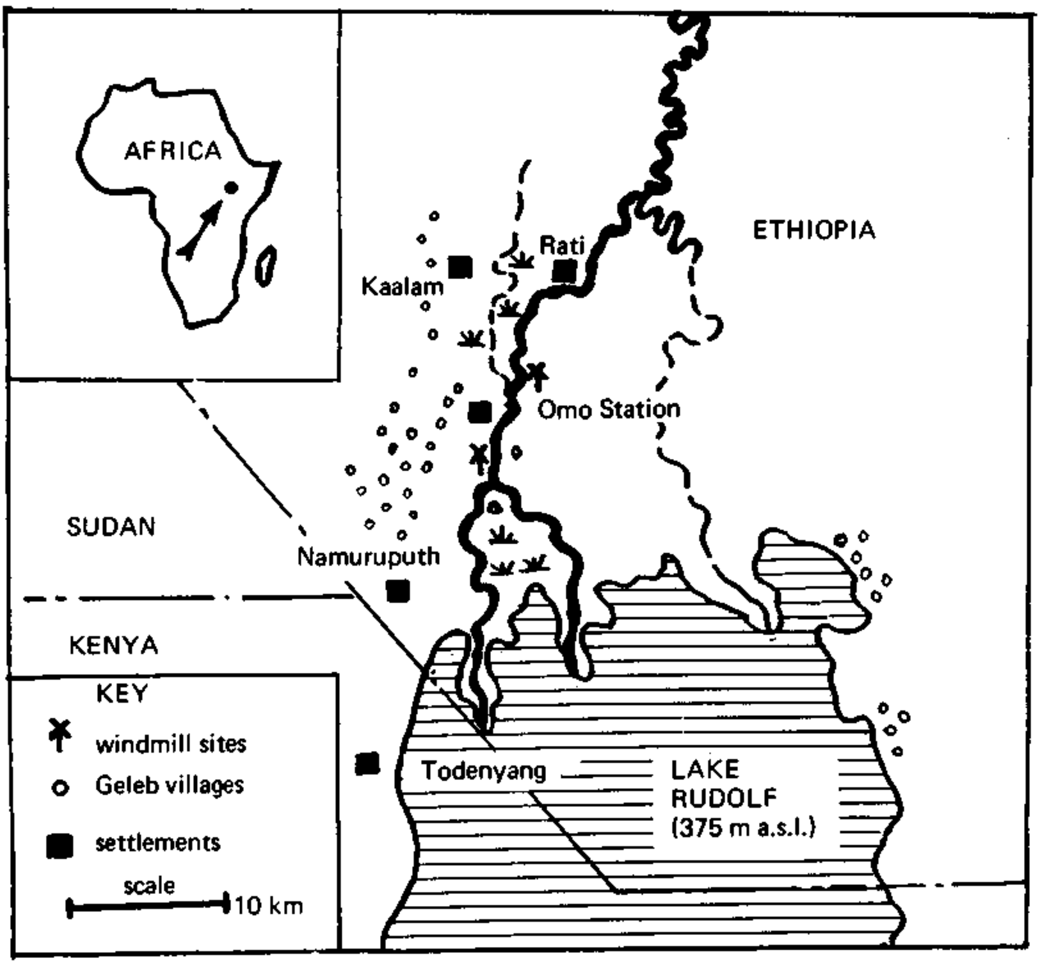


Fig 2.

Fig 1. Modified 16 ft diameter Cretan sail windmill. The inner concentric ring of bracing wire indicates the original wind-wheel diameter of 11ft. This experimental unit was also fitted with two opposed single-acting pumps and an interim extended tail vane.

2. BACKGROUND TO THE PROJECT

Location

The Omo mission station is about 10km north of Lake Rudolf in the extreme south-west corner of Ethiopia, in Gemu-Gofa province, situated on the west bank of the Omo River. The area is low-lying, about 380m (1240 ft) above sea level and arid with under 400 mm of rainfall per annum. Precipitation is seasonal, with most rain in April, but occasional falls of generally under 1mm are known in most other months. Temperatures range from around 20°C at night to maxima of around 40°C. A fuller account of meteorological conditions in the area follows later in this report, particularly with reference to the wind régime.

The vegetation cover away from the river is mainly semi-desert, being grass or thorn scrub savannah on mainly sandy soils; however the river margins, particularly the areas subject to annual flooding, have a narrow but non-continuous belt of riverine tree/shrub savannah on alluvial soil.

The area is inaccessible, having no all-weather road or track connections with the Ethiopian plateau. Heavy materials for the mission are generally delivered once a year by four-wheel-drive truck, which can take about seven days to get there from Addis Ababa. Access to Kenya is physically easy, (the border is only 10km from the mission) but there is no official international border crossing so there are political problems in crossing the frontier at the present time. People and lighter cargo are generally transported to or from the mission by a light aircraft of MAF (the Missionary Aviation Fellowship), based at Jimma. The mission is in regular radio contact with Addis Ababa and MAF and can order any smaller essential items in this way, but freight costs are obviously high.

The water supplies for the "Food from Wind" project and for the mission are derived by pumping directly from the Omo River. This river flows all the year and provides an estimated 80 to 90% of the input to Lake Rudolf with a discharge somewhere between 15 and 25 x 10^9 cubic metres per annum. The river responds closely to the seasonal rainfall changes on the Ethiopian plateau where it has its sources, being low from December to April and reaching its maximum level towards early September; the annual change in river level in the lower reaches is of the order of 2m.

The only other permanent settlements in the area are a district police post at Kelam, about 9km north of the mission and an EPID irrigation project at Rati, about 15km upstream.

The local people

The local people call themselves Dasanech and they are known officially, in Amharic, as Geleba, (and as Marille in Kenya). They are akin to a number of the Nilo-Hamitic groups found in the region, and traditionally live a semi-nomadic existence, their primary activity being cattle herding. They tend to live in small villages or village clusters varying from a few huts to several hundred. Their huts are beehive-shaped structures woven from twigs and branches and covered in hides and matting (Fig 3). Most of the mill-owners come from a large semi-permanent community that lies alongside the mission, but about half a kilometer from the river.

Their traditional agriculture

Stock raising has always been the main over-riding activity for the Gelebs, but they have traditionally cultivated millet (sorghum), maize and beans plus several types of gourd and tobacco on areas which are seasonally inundated either by river flood-water or by seepage. This has generally allowed them one harvest (in December) from a rather limited area. Grain is stored in raised woven bins on platforms in their villages, but even given a good harvest, losses are great and food has traditionally always been in short supply for the six months of the year prior to the harvest. In common with most similar peoples, they do not normally kill cattle for meat as the size of a herd provides a measure of wealth and a big herd is more likely to survive a period of drought or other adverse circumstances. They do however bleed and milk the cattle. The men traditionally devote themselves to tending the cattle and agriculture is practised primarily by the women and children; crop cultivation is, therefore, to some extent considered to be womens' work.

Chronic food shortages have probably always been a feature of the traditional Geleb way of life but a number of circumstances have combined to make it even less viable. Firstly the area open to them for grazing their cattle has been reduced by the imposition of national boundaries in the area. A certain amount of international grazing between Kenya and Ethiopia has been agreed, with Geleba going south and Turkana coming north, but they are no longer free to roam into the Sudan at will. Similarly, national governments now attempt to enforce "law and order", and all the local tribes are discouraged from raiding their neighbours' herds of cattle; the police generally make them return stolen cattle. This was a means by which a desperate tribe whose herds had suffered through some natural disaster could restock with the unwilling help of some less unfortunate neighbouring group, not that this was the only circumstances in which cattle raiding took place. The area open to grazing has also been reduced by a southern movement of the range of the Tsetse fly.

The level of Lake Rudolf has fluctuated by about 20m during the last century so that the delta shoreline has moved 60km between 1898 and 1955 which were the maximum and minimum mean-level years, and the level is rising again; as a result certain areas which were cultivable at one time cease to be and vice-versa. Currently, for example, many areas that used to be cultivated upstream of the mission no longer flood. Also, there is a natural increase in population which has no doubt been aided by the medical facilities provided by the mission and the government. These factors can combine to provide increasingly serious food shortages, and it was recognition of this that promoted the American Mission to seek the solution described.

History of the project

The Omo Mission station was founded in 1965, and Mr. and Mrs. Swart lived under canvas for the first three years.

Mr. Ted Pollock, the Mission's builder, designed the mission buildings, including an advanced geodesic (triangulated) dome type of roof construction which has the advantage that the pre-formed triangular roof panels were all air-transportable to the site, (a feature which is important in this area).

Due to the difficulty and expense of supplying diesel fuel for the mission's diesel-electric water pumping system, supporters of the mission in the United States were asked if they could supply a small commercially-available all-steel wind-powered water pump, of the kind commonly found on American farmsteads. This was to allow irrigation of the mission vegetable plots and fruit trees which otherwise demanded excessive consumption of fuel. The supporters in America were more successful than expected with their fund raising, and Dempster Industries who supply wind-pumps were generous with discounts, so that to the surprise of the missionaries no less than four 8ft diameter Dempster multi-blade fan type wind-pumps arrived, two at the end of 1973 and the rest in early 1974.

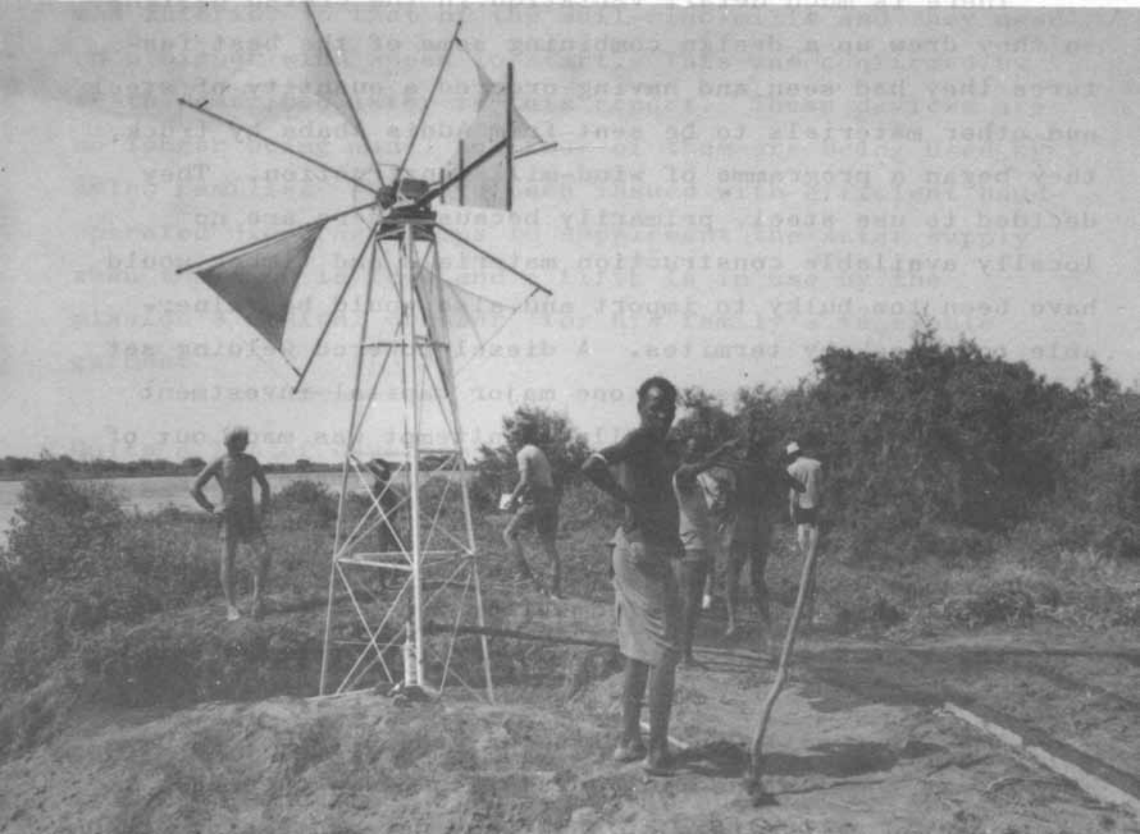
A number of local Geleb men had been employed by the mission to help with crop cultivation and they had also been encouraged to expand their own cultivation efforts and to try a few new crops. Several of the keener ones were loaned hand pumps to allow them to cultivate on the river bank by pumping water out of the river. The mission, slightly embarrassed by the unexpected glut of windmills, decided as an experiment to set up two of the Dempsters on a plot of Geleb land to allow the people to cultivate an even greater area, and it was this that began the "Food from Wind" programme. The first of the Geleb operated Dempsters was commissioned in April 1974 and is now irrigating about half a hectare which is being cultivated by several families (Fig 4). About three harvests per year of grain crops have been achieved, and rapid-growing fruit trees such as banana and paw paw yield fruit within

about one year of planting.

The wind-mills were an immediate success with the Gelebs, which is perhaps surprising when it is considered that these people are almost completely without any formal education and have had very little contact with outside influences or with machinery of any kind. However the wind and the machines are relatively reliable and the people very quickly recognised that this could help provide food all the year around and thereby remove their chronic annual food shortage which had caused them great misery in the past.

The mission however could not consider importing sufficient factory-built machines to satisfy the potential demand as these cost about Eth $2000 (US $1000) each, landed at Omo in early 1974, even with discounts. Therefore the Rev. Robt. Swart and Mr. Ted Pollock decided to investigate the possibility of building their own wind-mills and having done a little research discovered the sail-windmills that are widely used on Crete for irrigating small plots of land. They both arranged to visit Crete during "stop-overs" when travelling from furlough in the United States, where they photographed the wind-mills and interviewed some of the mill owners.

Fig 5. Typical 11ft diameter sail wind-mills built at Omo Station. (These are now being modified to 14ft diameter).



There is much detail variation in the Cretan designs, so they drew up a design combining some of the best features they had seen and having ordered a quantity of steel and other materials to be sent from Addis Ababa by truck, they began a programme of wind-mill construction. They decided to use steel, primarily because there are no locally available construction materials and timber would have been too bulky to import and also would be vulnerable to attack by termites. A diesel-powered welding set was also brought in as the one major capital investment for the project. Incidentally an attempt was made out of interest to use entirely local materials, these being some scarce local timber or driftwood from the river, plus woven matting for sails (of the kind used to cover Geleb huts), but this original windmill proved difficult to construct; it was too fragile and unreliable in operation.

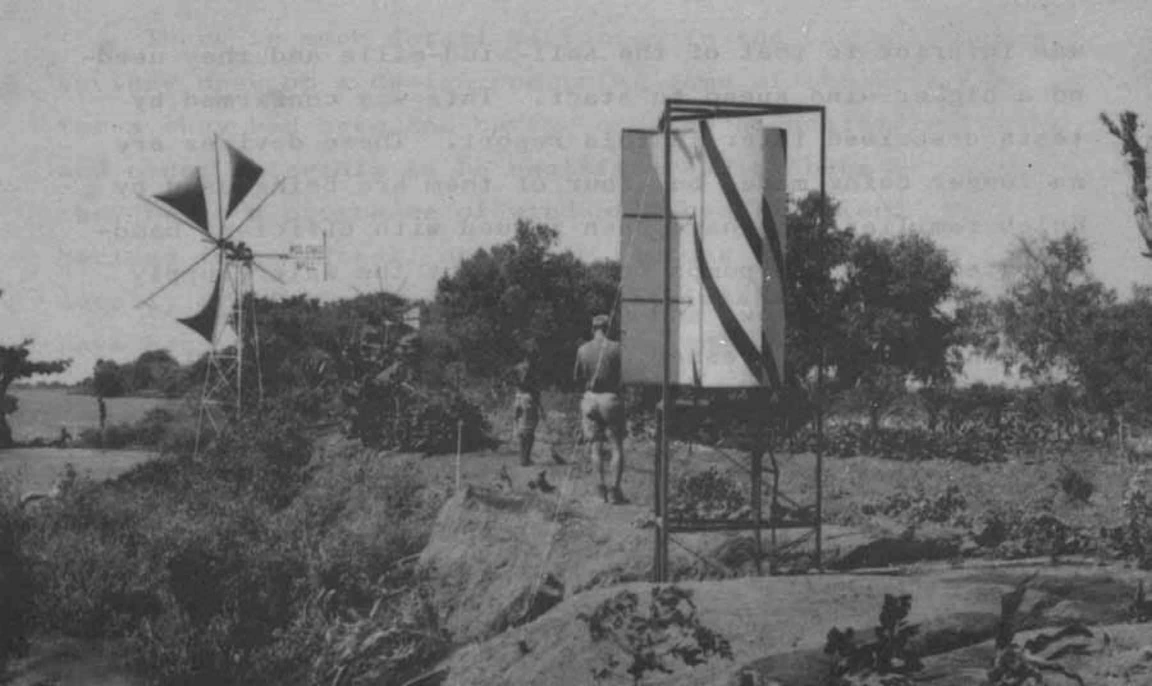
The first sail wind-mill to be used by a Geleb farmer was commissioned in June 1974 and new ones have been erected at the rate of about one per month since then (Fig 5) although this rate has accelerated during 1975, (see Appendix 1). A number of volunteer helpers came to the mission to work on the project, and Mr. Ted Pollock manufactured the head assemblies at the mission workshops at Ghimeera, as those on the early models were too complicated to construct with facilities at Omo Station. They are then flown down by MAF. The Swarts' son Dick, who has been trained at welding, assembled a large number of wind-wheels and towers prior to his return to the USA, and he also manufactured a series of experimental vertical-axis wind-mills, known as Savonius Rotors or 'S' rotors. This type of wind-mill has been promoted by VITA in the USA and by the Canadian Brace Research Institute, but it is not as efficient as most other types of wind-mill and also intercepts a rather small cross-section of wind. Although Dick Swart's 'S' rotors performed as well as can be expected for that type of machine, it soon became apparent that their performance was inferior to that of the sail-wind-mills and they needed a higher wind speed to start. This was confirmed by tests described later in this report. These devices are no longer being made, but four of them are being used by Geleb families, who have been issued with efficient hand-operated diaphragm pumps to supplement the water supply when the wind is low, and a fifth is in use by the mission's medical dresser for his family's vegetable garden.

Quite a lot of development work had already been completed on the sail wind-mills prior to the author's arrival. This included research into the best type of pump, an investigation into different types of sail material and an attempt to improve the performance by increasing the wind wheel diameter from 10ft to 11ft.

Much thought has also been given to distributing this equipment among the Gelebs and to providing the necessary instruction to and support for the users. The mission has set out from the start to try and ensure that aspiring mill owners really wish to use this technology and to aim to minimise their dependence on supervision. A prospective wind-mill farmer has to pay Eth. $5.00 per year for his wind-mill (the Dempster users pay double this figure) for twenty years; this sum was thought to be sufficient to ensure that any potential user was serious, but to be within the limited means of the local people who have only small sums of money circulating in their isolated subsistence economy.

The mission also has a policy of not employing Geleb workmen for longer than three months at a time, to prevent a dependence on employment being developed, but an exception has been made with one man, called Achao, who has considerable talent for dismantling and assembling the wind-mills. He is capable of organising maintenance and of advising any mill-owners having difficulty, and he operates as a

Fig 6. Savonius rotor or 'S' rotor type of wind-mill (on right) introduced experimentally in early 1975 but no longer being produced since the sail wind-mill (left) can pump twice as much water in the same wind and is cheaper to build.



permanent wind-mill technician.

Any new mill owner gets a kit of equipment in addition to the wind-mill (Fig 7). This includes several hand tools such as a hoe, trowel and shovel, plus a small battery-operated tape-player with a cassette pre-recorded by Achao, which explains the operation of the wind-mill and advocates such ideas as crop-rotation. The new owner is also helped with the initial work on his plot; he and his family must clear the land, but mission staff and workmen install the windmill and help lay out and dig the system of irrigation channels (Fig 8). The mission also provides seed or young fruit trees, although the choice of crop is left entirely to the mill-owner. An American agronomist, Mr. Larry McAuley, arrived at the same time as the author for an extended stay, and he is advising on various cultivation and crop problems.

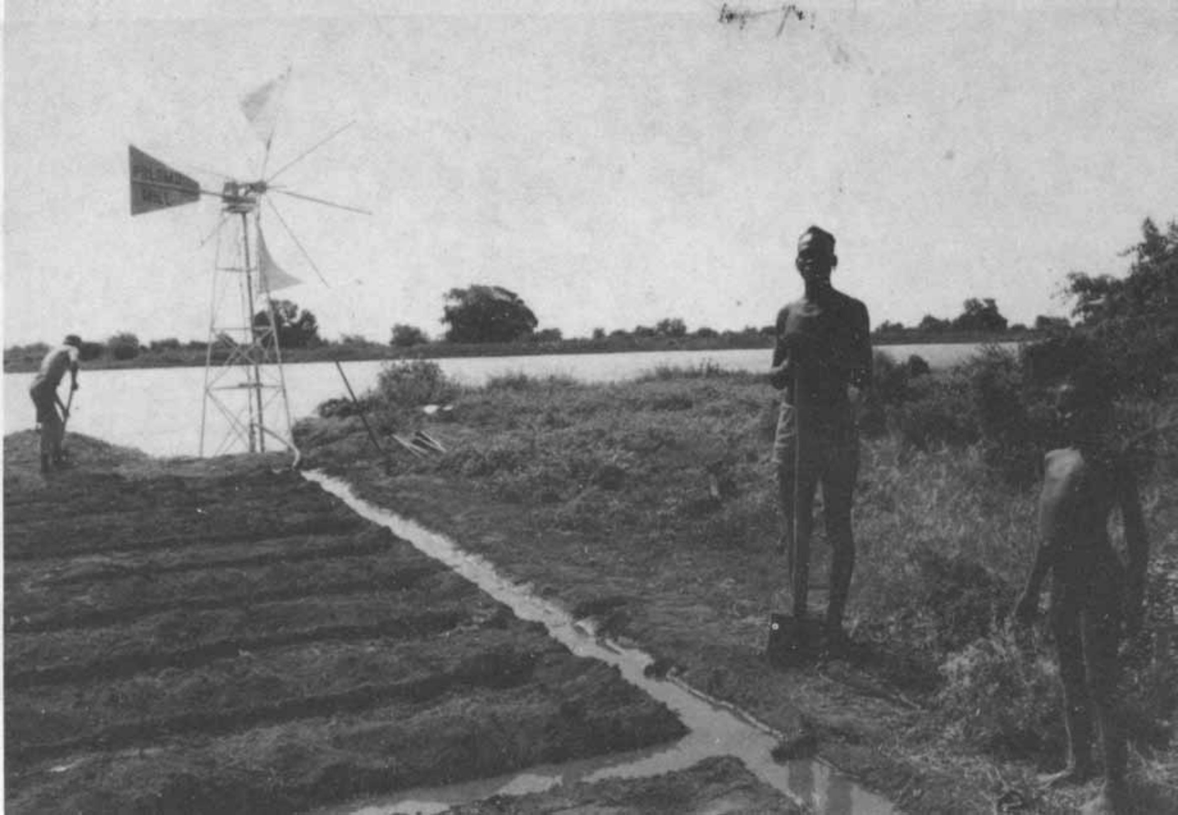
Meteorological conditions and data collection

Any reasonably precise prediction of wind-mill performance in a particular location depends on the availability of long-term and detailed data on wind velocities and directions. Appendix 3 shows how wind energy is related to mechanical power; it will be seen from this that the power produced is proportional to the cross-sectional area of the wind-stream intercepted by the wind-mill, (i.e. the area of the wind-wheel) and it is also proportional to the <u>cube</u> of the wind velocity (i.e. a doubling of wind velocity produces an <u>eight</u>-fold in-

Fig 7. The Rev. Bob Swart stands beside the complete kit of equipment that is included with each wind-mill together with all the wind-mill components necessary for a new installation. Note casette player and hand tools displayed on sail. Head has direct metal-to-metal bearing, wind-wheel is 11ft diameter. Suction hose and float on right.


POLOMO
MILL

Fig 8. Freshly dug irrigation channels for a newly commissioned sail wind-mill, (the new owner and his son on right).



<u>Fig 9</u>. Cup-counter anemometer as used at Omo Station. The small window displays the total wind run down to the nearest 1/100 of a mile.

crease in power output, all other conditions being unchanged ($2^3 = 8$). Hence variations of wind speed can have a much-magnified effect on power produced and on the resulting volume of water pumped, (the volume of water pumped will be roughly in proportion to the power produced for driving the pump). Because of the non-linear relationship between wind velocity and volume of water pumped, it can be shown that a widely fluctuating wind régime with a given average velocity will in fact allow more power to be generated than a steady régime of the same average value. Therefore it is important to know not only the average wind-speeds, but also the short term variations that generally take place.

Wind data collection is a statistical science; no two years will be exactly the same, but once data from a succession of years is available, reasonably sound predictions can be made. It should of course be noted that the wind displays certain superimposed cyclic patterns; short term gusts ranging from a few seconds to several minutes in duration; diurnal variations caused by daily temperature changes; seasonal variations caused by changing global weather patterns. Wind conditions in a given place will also vary depending on the height above ground level at which measurements are made and depending on the proximity of obstructions ranging from quite distant hills or mountains to nearby small bushes or tussocks of grass, which can set up local eddies or swirls.

Certain standard equipment and procedures have been determined for recording wind data. Any meaningful wind survey from the point of view of wind-mill specification depends on the collection of wind speed data for several years continuously. Ideally, a continuously recording anemometer on a 10m high pole should be used; in practise this type of sophisticated equipment is usually only used at major meteorological stations, such as are found at major airports or at institutions conducting meteorological research. Hence it is generally accepted that a useful compromise is to use a simple cup-counter anemometer (Fig 9) which records miles or kilometers of wind run. This is mounted on a 3m high pole (to allow ready reading of the indicator window) and generally it is thought sufficient to take readings three times every day such as at 0700, 1300 and 1900 hours. This allows the wind run for the morning hours, the afternoon hours and the night to be assessed, i.e. average morning, afternoon and night wind velocities can be computed. This is the most commonly used system and due to the few staff free to take readings, it was decided to institute this procedure at Omo Station.

Unfortunately there has been no weather station in the vicinity (the nearest would not give comparable conditions) until the mission was helped to establish one following the inception of the "Food from Wind" project. Equipment has been supplied on loan by the Ethiopian National Water Resources Commission, which runs numerous weather stations throughout the country. At the time of the author's visit, an anemometer, rain gauge and max./min. thermometer had arrived (by MAF flight), but an evaporation pan (which will provide data to assess crop water requirements with more precision) had not arrived as it has to await the next freight delivery by lorry. Therefore wind data is only available for the months from May 1975 onwards, other than a certain amount of data recorded for July and August 1968 by a Chicago University expedition that investigated certain aspects of the Omo delta. There is, therefore, only reasonable certainty of wind conditions for the months May through August of one year at the time of writing. However certain assumptions, reinforced by the subjective opinions of the mission staff in the area are possible. The primary assumption is that the wind régime is not seriously affected by large scale seasonal and continental wind patterns at Omo, partly because the global wind pattern in tropical latitudes (Omo station is at about 5^{o}N) is one of mild wind speeds and there are no marked changes in climate with the seasons in this area. The primary wind régime is diurnal, a "sea-breeze" effect caused by the close proximity of the relatively large expanse of water of Lake Rudolf (the lake extends some 200km from north to south and is up to about 50km wide). The wind mechanism results from temperature differentials between the land and lake surfaces during the day in particular, when the sun rapidly heats the surrounding semi-desert causing a strong breeze to blow off the lake. The effect is less marked at night, when the breeze reverses. The main evidence for this is wind direction data logged by the 1968 Chicago expedition plus the general observations of people at the mission who are used to the wind blowing more often than not, from the south or south east. Wind speed measurements taken in early morning, early afternoon and in the evening indicate highest mean velocities in the morning (usually speeds of 10 to 15 mph (16 to 24 km/hr)) less wind in the afternoon and very little wind at night. The Geleb wind-mill owners are sufficiently aware of this pattern to confine most of their cultivation work to the period from about 0700 to 1200, when good winds can be expected. After this the day gets uncomfortably hot for working and anyway the wind generally falls to a light breeze.

There have been certain local problems in recording meteorological data. One of these is shortage of staff; the local people are illiterate and could not readily be trained to record the necessary readings, hence members of the mission staff must take the readings three times every day. This normally works well, but every now and again some unexpected task or crisis prevents anyone being free to do this at the correct time, so occasional unavoidable gaps in the record occur every few weeks. These will be less important once a longer period has been logged, but they can effect averages taken over short periods. There is also a major siting problem for the weather station. All equipment must be located within the fenced mission compound area, mainly because otherwise it would be very liable to be tampered with by the local people out of curiosity. Ironically, the success of irrigating the mission land has produced fairly thick tree cover (mainly fruit trees) which has left no area sufficiently exposed to fit the specification for an open wind speed measuring site. The river bank provides a reasonable site so long as the wind follows its normal pattern and blows off the river from the lake, but the exposed area of river bank that is best suited for siting the anemometer is cut off by flooding for a month or two every year, necessitating the removal of the instrument to a more sheltered but accessible spot beside the mission. There seems to be no completely satisfactory solution to this problem, but some suggestions are made in section 5 of this report under the heading "Conclusions and Recommendations".

Land ownership on the Omo River frontage

Although the Gelebs appear to have no concept of land ownership for grazing lands away from the river, nearly all of the river bank frontage, regardless of whether it floods (and is traditionally cultivable) is owned. Ownership generally rests with the more senior men in the tribe, such as the elders, and tends to stay within families. Many of the younger men and some of the poorer or less influential families have no automatic rights to grow crops on the river bank. In the past, areas of the delta newly exposed by a fall in the level of Lake Rudolf or by a change in course of the river were open on a "first come ..." basis, but once occupied, a plot remains the "property" of the original claimant. Despite the Ethiopian government's land reforms that have been enforced in other parts of the country, the Gelebs traditional river bank ownership continues, mainly due to their isolation. Indeed, it might be counter-productive to enforce land reform on them in the context of wind-mill usage as it is doubtful that they would understand its purpose without an accompanying educational programme.

Because of this, any prospective wind-mill owner must own rights to a site or get permission from someone with a suitable site. There are also a few other natural constraints; some parts of the river bank are sandy or have fissures which prevent the effective distribution of irrigation water, other areas are being rapidly eroded, so that any long-term crops such as fruit trees would be at risk. So, some people with rights to a stretch of river bank may not have a suitable spot for cultivation. A further complication is the existence of stock watering points and places where cattle are traditionally herded into the water to be swum across the river; these also have become established by tradition and cannot readily be blocked off by a cultivated plot. Therefore many of the pioneer wind-mill users are people who happen to have rights to good plots or whose close relations have these rights. Appendix 4 indicates in a little more detail some of the difficulties a few potential mill owners have experienced in finding a suitable plot.

This problem has been mentioned at some length as it seems to be one of the most serious constraints to the expansion of the programme; there are known to be a number of people who would like to have wind-mills but who do not as yet have any rights to suitable sites. As will be explained later, there are some hopes that most of these will eventually be able to get permission to use suitable plots. At any rate a number of senior members of the local clan with land rights have permitted others to set up mills on "their" land. One man however has tried to charge a rent for land, and although his area would be very suitable for wind-mill cultivation, he has found no one prepared to pay him and it remains unused.

Water distribution and crops

The standard water distribution system is for the water to be delivered by a short length of 1½" diameter pvc pipe, perhaps 6ft (2m) long, directly to a feeder channel dug at right angles from the river bank across the plot. A series of perpendicular channels are dug from the main feeder and water is fed into each in succession by building small earth dams to direct it, (Fig 8). Every time a channel fills, it is sealed off with a small pile of earth and the water from the feeder is directed into the next channel. Cereal crops are planted along the humps between the channels. Small circular channels are provided around young trees (Fig 10). Most of the plots are about ¼ hectare, although they vary somewhat depending on the nature of the site, the crops being grown and the ambitiousness of the owner and his family.

Some plots are more porous or have cracks and fissures which cause losses of water, but probably one of the primary variables in the efficiency with which the pumped water is distributed lies with the owner of the plot. Some seem to have grasped the best way to distribute their water and their crops look fairly even, others, in fact the majority, tend to over-water the rows nearest to their mill and to under-water the furthest rows; in such cases the crops nearest to the mill are noticably taller and greener than those further back. Efforts are being made to overcome these mistakes by education; it is in fact not at all surprising that there should be some difficulties of this kind for people using what is for them an entirely new technique (the floodlands they used to cultivate did not of course require any irrigation, but only yielded one annual crop).

Human nature being as it is, the Gelebs are generally rather prone to try and grow traditional crops they are familiar with; prestige crops being grains such as millet and maize. One of the pioneer mill-owners has grown five maize crops in succession in about 15 months on the same plot; not surprisingly they have got progressively worse both due to soil depletion and due to the spread of a corn bore beetle. The mission does not enforce any kind of crop growing policy, but attempts to guide the mill-owners instead. This man after his fifth harvest has apparently recognised the mistakenness of his cultivation; one of the primary lessons that Mr. Larry McAuley is trying to get across is the need for crop rotation. He is hoping to get some mill-owners to divide their plots into four and rotate corn-legume-corn-fallow on each quarter.

The mission has introduced a number of new crops some of which have found ready acceptance, including sweet potatoes, bananas, paw-paws (papayas) and mangoes. Fruit is a new introduction in this area and is particularly well liked. It seems that a number of the mill owners have recognised that fruit trees are a good investment for the future, as they need less attention once established and provide shade for other crops, although fruit bats and birds are beginning to discover the new trees and may well prove a problem in the future.

The Gelebs have always had a local strain of bean, but the mission is seeking to introduce soya beans as it is thought they will produce a better yield, they will provide a useful source of protein and will also be very suitable for crop rotation with the favoured traditional grain crops. The Rev. Swart organised a special gather-

Fig 10. Method for irrigating young trees, (note Savonius Rotors in background, 2 bladed on left and 3 bladed on right).

ing of all the mill-owners, plus their immediate families and associates, both to offer an opportunity of letting them sample soya beans as well as to introduce the author and Mr. Ted Pollock (who arrived a few days after the author) and to give the Gelebs a chance to mention any problems they were having with their mills. The soya beans were fried by Achao's wife on a typical Geleb open fire using their familiar utensils, to make it clear that they could readily cook them themselves, and they were well received (see Figs 11 & 12). This illustrates a problem inherent in introducing any new food needing preparation; the people do not automatically know how to cook it and prepare it, so that this kind of exercise was clearly a useful and essential part of the programme. In a few cases the local people invent their own dishes; Achao's wife, for example, adds pounded ground-nuts (another new local crop) to her maize-meal porridge (a traditional food) making a more nutritious dish which is apparently popular with her family.

3. AN APPRAISAL OF THE OMO "CRETAN SAIL" WINDMILL DESIGN

By the time of the author's visit a number of the problems that were apparent earlier in the year, notably the choice of pump and of sail material had been satisfactorily resolved and a reasonably standardised design had been adopted and put into production. Up to about April 1975, a variety of different ideas were being tried out with varying degrees of success, including the use of vertical axis Savonius rotor type wind-mills.

The entire sail wind-mill system can be subdivided into a number of primary components (see Fig 7. which shows all the parts laid out on the ground). These are the suction line/foot valve, the tower, the pump and connecting rod, the head assembly and tail and lastly the wind-wheel and sails.

Suction line and foot valve

All the wind-mills draw water from the river through a $1\frac{1}{2}$" (36mm) diameter thick-walled, but flexible, pvc plastic pipe. The pipe is securely attached to the suction (lower) end of the pump with an adjustable pipe clip and carries a factory-manufactured brass foot-valve at its lower end. The foot-valve is supported by a float consisting of a block of expanded polystyrene (Styrafoam) jammed into half an oil barrel; the float is essential to prevent the foot-valve getting clogged with silt, as would happen if it lay on the river bed. A glance at the cost break-down (Appendix 2) shows that the entire suction line/foot valve assembly costs about Eth $185, which is about 25% of the entire material cost of the wind-mill. However it is not really practicable to omit or reduce parts of this assembly; attempts have been made to save the cost of the Styrafoam and oil-drum half (worth Eth $22.50) by using a log of wood as a float, but there is not much wood available that is sufficiently big and buoyant, and any that have been used deteriorate rapidly and become water-logged despite all efforts to prevent it. It is not practical to try and support the foot valve on a stake driven into the river bed, because the river is deep and fast-flowing when in flood (and carries large branches and logs which could up-root any stake); also the level varies considerably and a wooden stake would be susceptible to water-logging and rotting. Similarly, the pvc pipe, which costs about Eth $90 for the suction line, is an expensive but not readily alterable component, (it should be mentioned that this piping is manufactured in Addis Ababa, although the pvc raw material must presumably be imported by the extruders). A foot-valve can be improvised, (in fact a home-made one was tried), but unless it functions efficiently the pump loses its prime and has to be constantly refilled with water, which makes the entire wind-mill operation more difficult and less reliable. Hence it seems justifiable to invest in a precision-machined component for this function. The half oil drum is only necessary to protect the Styrafoan block, and although by no means cheap at 10.00 is probably the cheapest suitable casing available. Therefore, although the float system is rather expensive, it is extremely reliable (in that it rarely causes trouble) and is effective.

Tower

The tower is a completely welded assembly and forms a single rigid component when completed. This has the advantage that no foundations are necessary to ensure accurate alignment of the tower footings, which can simply be embedded in impacted soil. The original tower had four corners, but this was modified to a three-cornered tower at an early stage, thereby saving one 12ft length of $1\frac{1}{2}$" x $1\frac{1}{2}$" angle per tower without any excessive loss of strength. The lateral members are lighter 1" x 1" angle with cross-bracing of 1/4" concrete reinforcement rod. Although the towers are possibly somewhat stronger than is strictly necessary for structural integrity, there is no effective way of significantly reducing the number of cross-braces without removing their secondary function of acting as ladders. The mill-owners have to climb the towers to fix the sails on when starting their wind-mills and also to stop the mill by pulling the tail sideways to the wind; since access may be needed from any side of the tower to avoid the side where the wheel is turning, a symmetrical structure is important. At times when there is insufficient wind the Gelebs often climb the towers and turn the wind-wheel by hand and again, this would not be possible if there was not such a good selection of horizontal members. As the tower is only 12ft tall, there is no way of reducing its cost by making it any smaller. In the circumstances, bearing in mind the relative indestructiveness of the towers and their likely long useful life, they seem to have evolved, even at Eth $ 200, into a reasonably cost-effective component. (Some further observations on tower design follow in the section on the author's work programme, in which he investigated a possible tubular tower).

Pump and connecting rod

Factory made semi-rotary, diaphragm and piston pumps were evaluated in early 1975. Of these the most satisfactory proved to be a piston pump, manufactured by Dempster Industries specifically for wind-mill operation. Because the mission is able to obtain this pump with a 50% discount from the manufacturer, it costs only Eth $80.00 landed at Omo Station. It performs most reliably and efficiently and no pump of similar performance and reliability could be manufactured locally for a comparable price. It should be mentioned that Dempster originally supplied a 3in diameter cast steel pump with a brass cylinder lining and gun-metal bucket and valve components, plus a single leather washer. However, they then substituted an alternative 3" diameter pump with a thick-walled pvc cylinder and two leather washers on a similar gun-metal bucket. The disc valves in both cases were of gun-metal and brass. This pump is slightly cheaper and appears to function with virtually no apparent wear after a year of operation. Both types of Dempster cylinder are in use plus one 2½" diameter cast iron piston pump of Indian manufacture that cost slightly more but was available ex-stock in Addis Ababa; this however wears leathers rather faster, as is common with iron or steel cylinders, and due to its smaller bore has a markedly lower delivery rate. All the Dempster pumps operate with a stroke of 7in on sail wind-mills and with a reduced 5in stroke on the Savonius rotors, which are incapable of starting if the linkage is set to produce a 7in throw.

The outlet from the pump is generally via a standard "T" pipe fitting, with an olive-wood plug bored to take the pump plunger as the only sealing device. As will be explained later, this is not entirely satisfactory and a number of modifications are proposed to reduce water leakage.

The pumps are driven from the tower head by a connecting rod, made from $\frac{3}{4}$in black water pipe. A simple ball and socket joint was developed by Dick Swart to allow for non-alignment of the head and pump and to allow the top part of the connecting rod to turn with the windmill head when it moves to face changing wind-directions, and this also forms the link between the pump rod extension and the connecting rod. The pump rod extension is kept in alignment with the pump by a wooden cross-head, this being a plank that straddles the tower at the correct level with a hole bored in it for the rod. The top of the connecting rod has a split piece of water pipe welded to it, with reinforcement flanges to support it and prevent buckling. The split water pipe has two drilled lugs to allow it to be bolted around the crank journal on the head. Although steel to steel plain bearings of this kind are not sound engineering practice, the loads transmitted are quite low and no serious wear has yet occurred at this point on any of the mills. Lubrication is by heavy grease, which seems to last without replacement for a considerable time. The split bearing is mounted with its axis suitably inclined to allow for the slope of the mill-wheel shaft.

Head assembly and tail

The head assembly consists of an angle-iron frame carrying two mountings for the main shaft bearings and the side members extend backwards to include an integral tail unit. The frame rides on a 1/8"x$1\frac{1}{2}$" flat-bar ring of 12" diameter welded into the top frame of the tower; earlier models had a square sub-frame made of $1\frac{1}{2}$"x$1\frac{1}{2}$"

square section steel tube slotted to carry four flanged wheels made from 1" water pipe and washers, which rolled around the flat-bar ring in the top of the tower (Fig 13). Problems were experienced with this frame, which could not readily be fabricated at Omo Station (they were made by Mr. Ted Pollock at his workshop in Ghimeera); also there was difficulty in getting sufficient grease into the wheel hubs so that the flanged wheels tended to wear the bolts acting as axles rather rapidly and also did not turn freely. As a result some mills were tried with the head frame angle iron chassis lying directly on the tower ring, which with plenty of grease seemed as good as the arrangement with small wheels as far as resistance to turning is concerned. The head is prevented from lifting by four hooks bent from flat bar which project down through the centre of the frame and curve round underneath the ring in the top of the tower. When the square frame carrying the frame was omitted, new shorter hooks were introduced to allow for the lowering of the frame by just under 2", and the connecting rod had to be shortened similarly.

The problem of devising a satisfactory head support bearing was tackled under the author's work programme and resulted in the evolution of a new type of roller head bearing described more fully later on, (see Figs. 13 & 14 which shows the two different types of head bearing).

The main shaft is carried at its rear end by a self-aligning sealed ball-race in a metal housing and at the front by a plain olive-wood bearing, split horizontally and packed with grease. A few mills have either both bearings wooden or both ball-races. Within the time-scale so far experienced there is little to choose between the two types of bearing; olive wood is theoretically cheaper, but the mission was given a consignment of 100 sealed ball-bearings. One of the advantages for putting one of each type of bearing on each mill is that it will eventually allow a ready means of comparing the durability of the two types. The friction of the wood bearing is probably marginally higher, but it is sufficiently low to prevent undue heating of the bearing blocks and it has no measurable effect on wind-mill performance.

The shaft is made from a length of approximately $1\frac{1}{4}$" hexagon bar; the cross-section being not from choice but because it was the only sufficiently strong bar available from the steel suppliers in Addis Ababa. The hexagon cross-section caused problems in that a piece of water pipe has to be welded around it where it passes through the wooden bearing, and it needs to be laboriously ground and filed to fit the steel ball-race at the rear end. The few mills with ball-races for the front bearings had to have them fitted by cutting the shaft, grinding and filing to take the ball-bearing and then welding the cut-off end back after fitting the race, which was one reason to favour wooden bearings at the front. A last point on bearings is that the lip where the shaft was filed to fit the rear bearing acts as the thrust surface to take axial thrusts from the wind-wheel.

The shaft was cut so as to permit two pieces of $\frac{1}{4}$" steel plate to be used to offset the crank journal, these being butt-welded to the cut shaft ends. "Counterbalances" were added to the opposite ends of the crank webs on the suggestion of a volunteer, but this in fact serves no purpose and a resulting recommendation is to omit them in future. The fabrication of crank shafts was another task carried out in the workshops at Ghimeera, as local facilities at Omo are not suitable for readily achieving the correct alignment.

The front of the main-shaft carries a hexagonal flange drilled to match the hub of a particular wind-wheel, (the hub and flange are drilled together to ensure they will fit exactly).

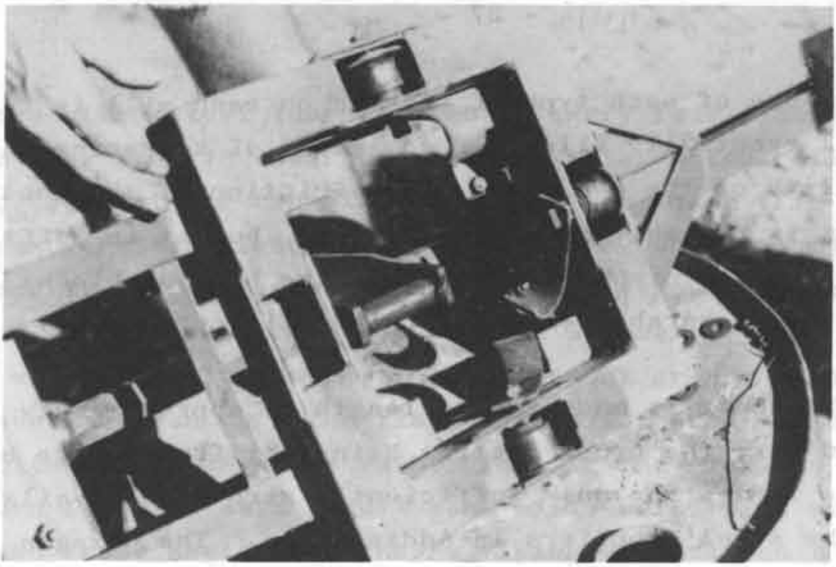


Fig 13. Original square head sub-frame running on flanged wheels.

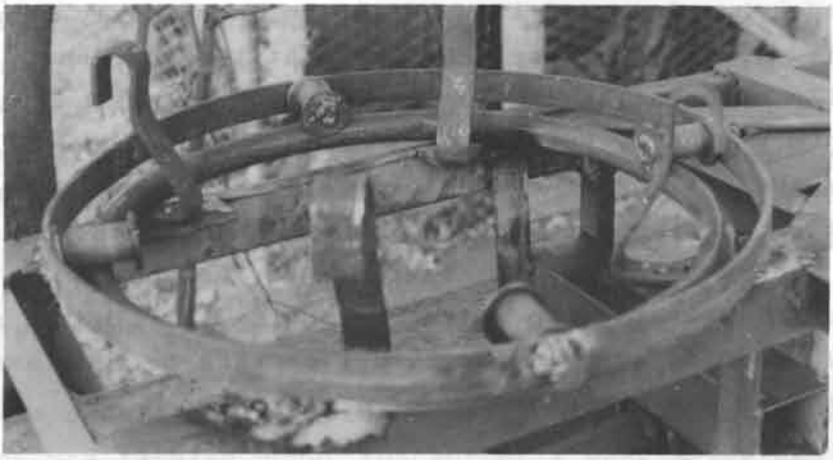


Fig 14. Modified system running on rollers.

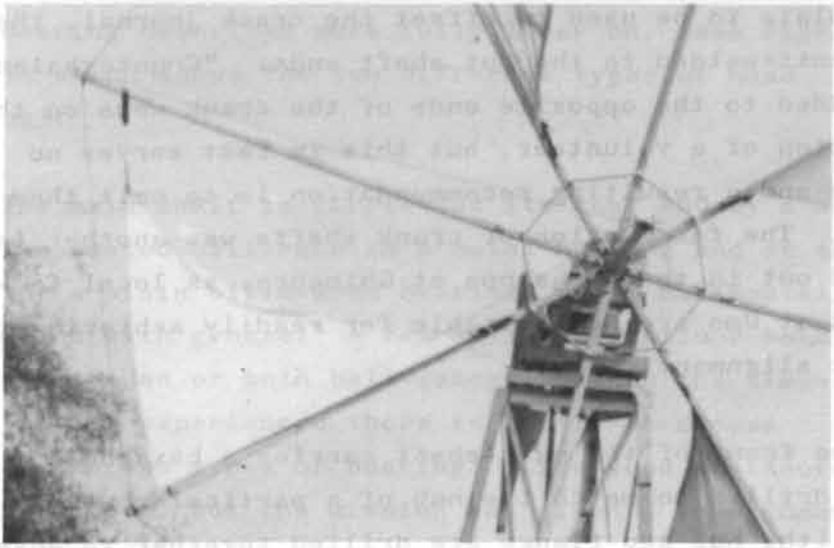


Fig 15. Close up of sail arrangement.

The tail unit is carried on a pair of $1\frac{1}{2}$" x $1\frac{1}{2}$" angles cantilevered from the rear of the head frame; it consisted of a suitably shaped panel of flat galvanised sheet steel bolted between the flanges of the tail boom with extra vertical flat-bar stiffeners. Certain modifications to the design of the tail unit are also proposed for reasons to be discussed in detail later in this report.

Wind-wheel and sails

The wind-wheel follows the classic Cretan type of pattern, with a number of arms radiating from a central hub which carry the leading edges of a series of triangular textile sails. The whole structure is braced with wires radiating from an extension to the shaft mounted on the hub to prevent axial distortions of the arms and by wires connecting the tips of the arms to control radial movements. The trailing corner of each sail is sheeted to a point on the preceding arm (Fig 15).

Most of the Omo sail wind-mills have eight arms, allowing provision for eight sails, although one was made with six arms as an experiment. The arms are of $\frac{3}{4}$in black water-pipe and are curved forward slightly, giving a negative coning angle, in order to give as much clearance between the wheel and the tower as possible (the inclination of the main shaft helps with this too). The wheels were originally built to an overall diameter of 10ft, (3m), but this was modified to 11ft early in 1975 in an attempt to improve wind-mill performance. The central extension from the hub, to carry the bracing wires, is generally made from two lengths of 1in x 1in angle welded with their flange ends in contact to make a square cross-section, and the bracing wires consist of standard galvanised fencing wire.

Various types of cloth were tried for making sails, but most standard woven textiles proved inadequate. This is because any flexible material is inclined to flap and crack in gusty wind conditions and most materials are susceptible to rapid degradation under continuous strong sunlight, the ultra-violet part of the spectrum being responsible. A further problem with most materials is a tendency for a tear to run rapidly once initiated. Therefore it is clear that a heavy, relatively inflexible, run-resistant and u.v. resistant material is essential for sail wind-mills if frequent sail replacement is to be avoided. The mission was fortunate to be able to obtain a large roll of Dacron sail cloth, a synthetic material specially formulated for yacht sails; this would normally be rather expensive compared with most textiles, especially landed at Omo station; however their stock was donated by the manufacturers Dupont Chemicals of the USA. A nylon kite material was also evaluated, but being flimsier than the Dacron it was prone to flap in gusts and would be unlikely to last as long. To date none of the Dacron sails have torn in use, although stitching occasionally needs replacement. The thread used for hemming the sails needs to be equally strong and resistant to u.v. degradation, so an extremely strong synthetic (nylon) thread is used. Cotton is not generally strong enough and long-lasting enough for this service.

Sails on the traditional Cretan wind-mills are generally reefed by rolling them around the arms of the wheel, but this is not a practical means in southern Ethiopia as cloth, being a rare and valuable commodity in this locality, is likely to be taken during the night if a mill were left unattended with reefed sails on it. Also it is a trickier operation to wrap sails around the arm than to completely remove or refit them. Therefore an ingenious method of fitting them had been devised by the Rev. Bob Swart, in which rubber loops cut from motor-cycle inner tubes are attached to the corners of each sail with lengths of polypropylene rope; the sails can then very rapidly be fitted or removed by attaching the loops onto metal hooks welded at suitable points on the arms of the wheel. The rubber allows for any inaccuracies in the sail or wheel and keeps the sails stretched into an effective shape for catching the wind. This system has a number of important advantages; firstly it allows rapid adjustments to be made to the area of sail being carried if the wind strength varies, (it was noticeable that the Geleb mill-owners learnt quite quickly to put an appropriate number of sails up; they did not try and over-do things by putting all their sails on regardless and it is a common sight to see mills operating effectively with just two sails when a good breeze is blowing); secondly, no mill-owner will leave his mill with sails on and unattended for fear of losing them. When work finishes for the day the people remove the sails and go back to the village with them; therefore there is no risk of a windmill being damaged by an unexpected increase in wind-strength while left in operation unattended. The Savonius rotor wind-mills, being all metal, are quite often left in operation by their owners and have been damaged by sudden storms before staff from the mission could get out by motor-cycle and stop them, (this is partly because the Savonius rotor pumps rather less water and there is a resulting temptation to leave it running to make up for this. When this happens it is not possible for the owner to return t, switch it off quickly as most of them live about one hour's walk from the cultivated plots).

A number of modifications to the wind-wheel have been tried and certain recommendations follow; most of these were aimed at gaining improvements in pumping performance, particularly in low wind conditions.

4. WORK PROGRAMME–21 JULY TO 16 AUGUST 1975

Identification of problems

Analysis of the various features of the sail-windmills at the state of evolution just described revealed a number of technical problems needing attention; these can be summarised as follows:-

(i) a need for an improvement in pumping performance, particularly in low winds

(ii) wind-wheel orientation to face changing wind directions was not entirely satisfactory, especially when six or more sails were fitted

(iii) lack of an adequate seal at the point where the pump rod enters the top of the pump precluded the delivery of water against a head of more than a few inches

(iv) a need to minimise the cost of the system by reducing the size or modifying some of the components

(v) consideration of alternative sail materials in case the supply of free Dacron ceased to be available

(vi) a need to find a straightforward, but meaningful method for testing wind-mills, so that the relative merits of any modification can be objectively evaluated

A number of operational problems also became apparent:-

(i) the need to obtain permission to set up a windmill from "land-owners" in cases where a prospective user has no traditional rights to the river bank

(ii) inefficient water distribution and wind-mill utilisation

(iii) poor choice of crops and lack of understanding of crop rotation

The search for solutions

Various ideas were tried to introduce improvements, with differing degrees of success. It is worth describing all of these even though certain innovations were abandoned either because they were not wholly satisfactory as solutions or because they introduced further complications. The successful innovations are discussed in more detail under "Conclusions and Recommendations", together with some suggestions for further development work that these point to.

(i) methods for improving pumping performance

One of the only complaints voiced consistently by the Gelebs was that the sail wind-mills did not pump enough water when the wind was low; they tended to set their standards by the performance of the Dempster factory-built wind-mills which would start in a very low wind as a result of being fitted with rather too small a diameter of pump for the low lift called for and being geared down. The Dempster mills are also on 25ft tall towers giving better access to the wind. One thing not apparent to the casual observer is that, through being geared down, the pumping rate of the Dempster is not as fast as a directly linked wind-mill.

Increased wheel sizes and double-acting pumps

Therefore an early objective was to modify a sail wind-mill so that it would clearly outpump a Dempster and start in similarly low winds. This was achieved by increasing the wheel diameter so that a greater cross-section of wind intercepted would compensate for other shortcomings. Hence a standard 11ft sail wind-wheel was enlarged to an overall diameter of 16ft by welding on extensions to the arms (see Fig 1). For convenience the same sails were used and the attachment hooks were moved outwards to allow for this. Therefore the full benefit of the enlargement was not completely realised as less of the centre of the swept disc was being exploited, although most of the power of a wind-mill is derived from the outer parts of the swept disc. The 2ft 6in increase in radius should provide an increase in starting torque (due to the extra "leverage" of the sails on the shaft) in proportion to the extension of radius, that is by a factor of $8/5\frac{1}{2}$ or about 45%. Similarly, an increase in power proportional to the increase in swept area is to be expected (power is proportional to area, see Appendix 3), and this works out at a ratio of 134:78 or 72%. This modification proved satisfactory in that the 16ft diameter sail wind-mill not only started in lower winds than the Dempster, but was capable of outpumping it at a rate approaching 2 to 1 (measured by strokes per minute of the identical diameter pumps). (See Appendix 5). One disadvantage was that the outer edge of the wheel was now only 5ft from the ground and proved to be a serious hazard should anyone accidentally walk into it, therefore it was decided to make 14ft diameter wheels as a compromise, although one 15ft diameter one was built. The 14ft and 15ft wheels give an improvement in starting torque of about 27% and 36% respectively, with power increases of 43% and 55% respectively when compared with the original 11ft wheels (and rather better than this compared to the earlier 10ft wheels).

A parallel experiment consisted of the building of a completely different wind-wheel with four large rectangular sails designed to be aerodynamically more efficient than the sail arrangement on Cretan mills, in other words an attempt to intercept more wind, more efficiently, (Fig 16). The sails on the experimental design were mounted on a metal frame which held them more rigid and gave the sail surface approximately the correct angle of attack to achieve reasonably efficient lift at all points along the radius; the characteristic twist common to all propellers. This wind-wheel was built to be 18ft in diameter and the inner ends of the sail surfaces were nearer the shaft to extract as much wind-energy from the swept-disc area as possible. This machine proved to be rather more powerful than the other mills, so much so that it was difficult to control or to pull out of the wind. The blades were mounted so that they could rotate about their axes in tubes radiating from the hub, and there were rubber loops fitted in the hub to provide control forces so that the blades would partially feather by going into a coarser pitch in high winds (Fig 17). The wheel disc was rather too large to be controlled by the standard wind-mill tail, so as an added innovation, this mill was run downward of the tower without a tail, and this worked reasonably well with the head displaying considerable sensitivity to changing wind-directions. This experimental wheel was later used in conjunction with a number of other innovations, to be described later, but it was later abandoned mainly because the 14 and 15ft Cretan wheels seemed to be quite adequate, and being braced with wire, they seemed stronger and less prone to get damaged and their sails were easier to fit or remove. Nevertheless this experiment did point to ways in which considerably more power might be extracted from the wind in areas with lower winds than Omo, or where higher pumping heads are required, although it should be stressed that further development of this design would be called for.

Fig 16. Experimental 18ft diameter four-sail wind-mill with feathering blades operating downwind of the tower.

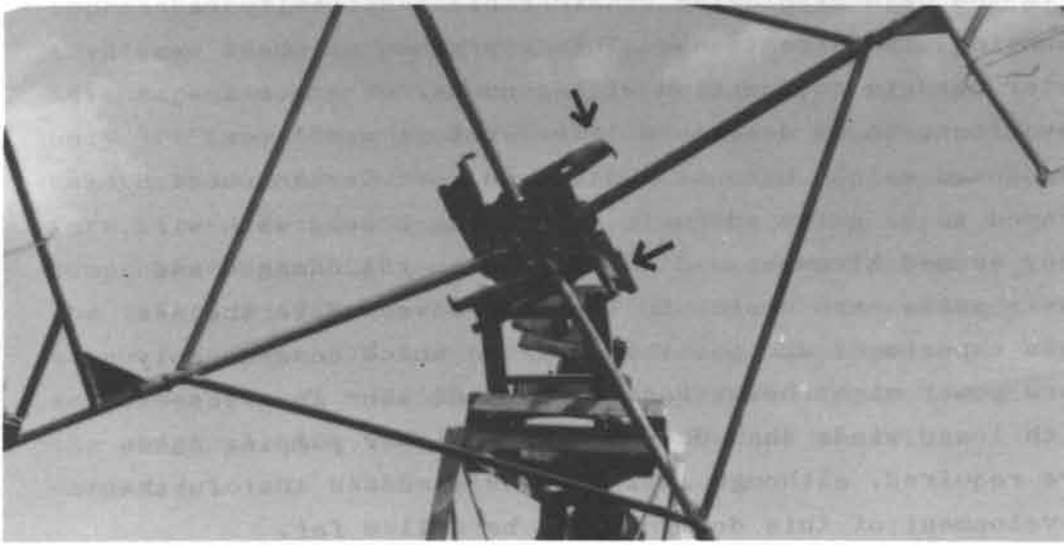


Fig 17. Rubber loops were used to restrain sails in feathering mechanism.

Another method of obtaining a considerable improvement in pumping performance is to use a double-acting rather than a single-acting pump, (i.e. arranged to deliver water on both the up and the down stroke). All the available pumps were single-acting and could not readily be modified to be double-acting with materials on hand, so this approach was simulated by mounting two single-acting pumps under a wind-mill, arranged in such a way that when one was on the up-stroke the other was on the down-stroke, using a rocking beam installed by Ted Pollock (Fig 18). As will be seen under the discussion of the test results, this mill was capable of delivering fully double the volume of water in a given wind using both pumps, compared with when one of the pumps was disconnected. In fact this mill achieved the best performance under any of the tests of just under 1300 gallons per hour against a static head of 9ft with a wind speed of $14\frac{1}{2}$ mph (using the experimental 16ft diameter wheel fitted with only four sails), (see Appendix 5).

Improving wind-wheel orientation

The high drag of a wind-wheel, particularly when carrying a lot of sail, tends to make it try and turn itself around to the rear of the tower; the function of the tail vane being to fight against this tendency. Directional stability was not completely satisfactory with the smaller 11ft diameter wheels, but the enlargement of wheel diameter just described rendered the previous tail design quite inadequate. With poor directional stability the wind-wheel could frequently only receive wind at some acute angle to its plane of rotation, thereby losing much of the advantage gained from increasing the diameter. Also, the 12ft towers are rather low and in not always ideally exposed situations, so the wind tends to veer and gust. Therefore it is important to have a machine capable of responding rapidly to changes in wind direction if the maximum efficiency is to be obtained from the wind-wheel.

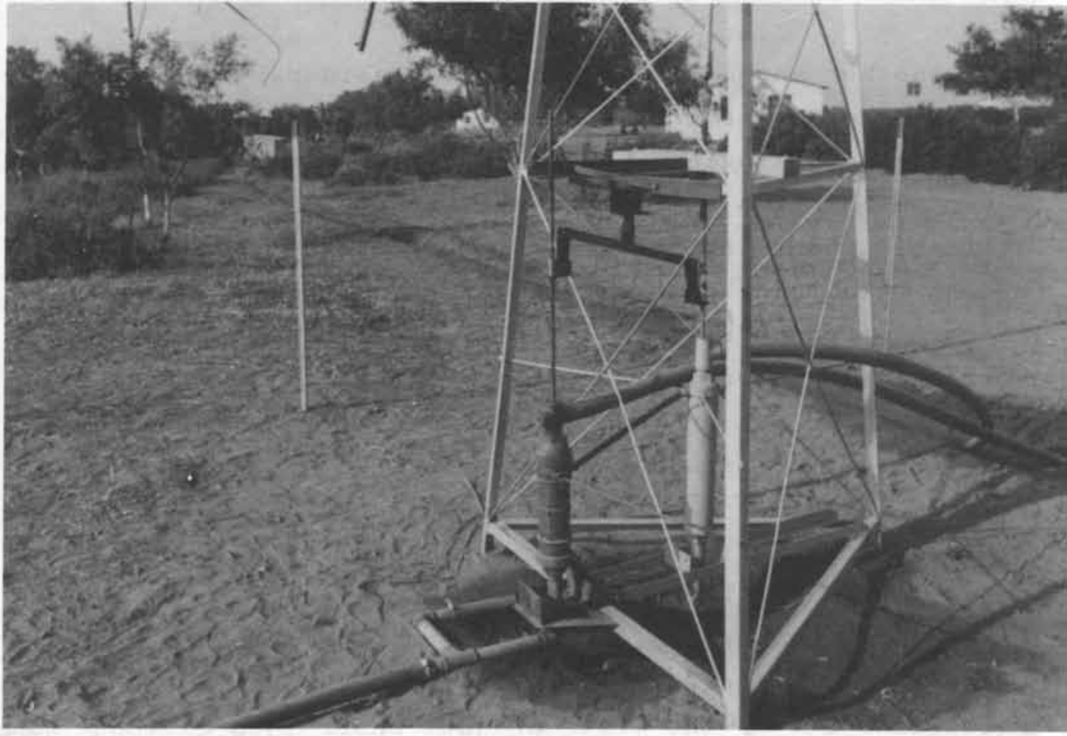


Fig 18. Double pump arrangement.

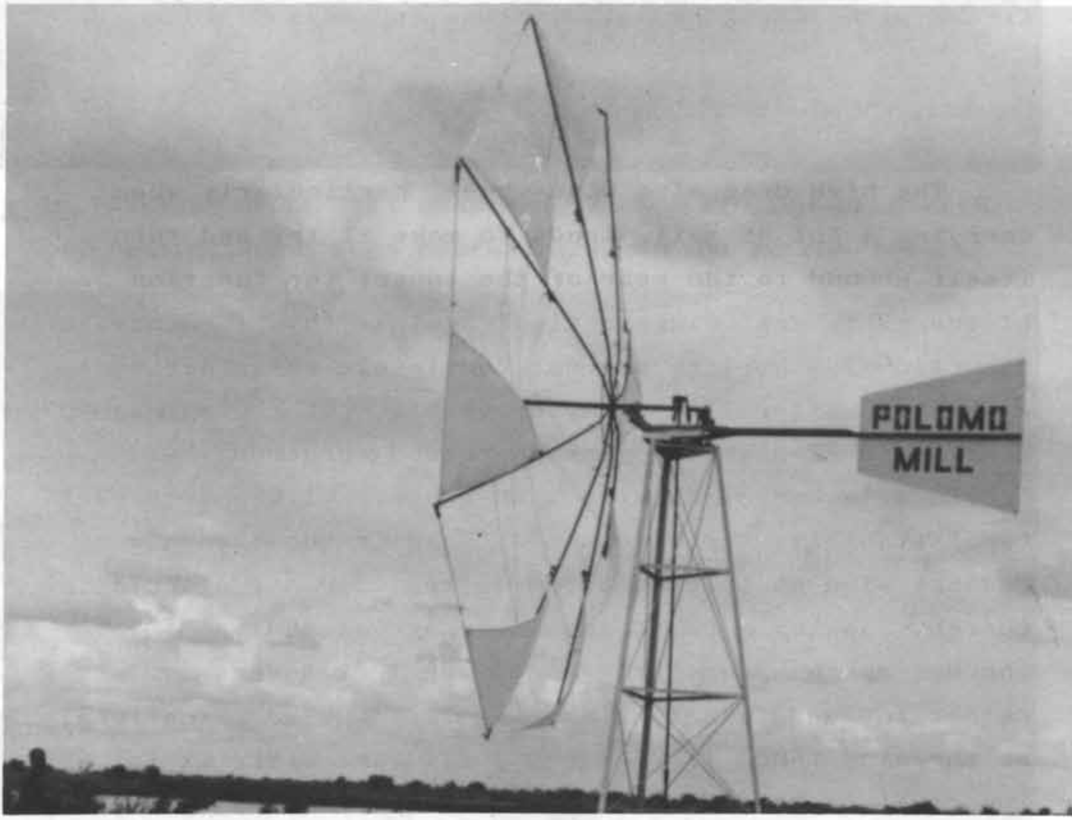


Fig 19. Interim extended tail.

Therefore the original tail was cut off and refitted on an extended tail-boom, to increase its effective leverage; the increased size of the wind-wheel at the other side of the turntable tended to compensate for the increased weight acting on the rear of the turntable. However, as this did not produce sufficient improvement, an additional area of metal was added to the rear of the tail to increase its surface area and to further increase its leverage slightly (Fig 25). This did improve the situation somewhat, but introduced a new problem in that the whole turn-table/head assembly was now too tail heavy, which caused the turntable to rock backwards and engage the front pair of hooks under the tower ring, thereby increasing the general friction at the turntable and reducing much of the effect of the improvement in tail leverage.

Because of this we scrapped the original tail design and built a new, larger rectangular tail vane, carried on a lighter and longer tail boom (Fig 20), this being fabricated from thinner-sectioned square tubing and triangulated to compensate for any loss of strength. This was introduced in conjunction with an improved design of turn-table bearing, allowing the head to run on rollers instead of either axled-wheels or straight metal-to-metal surfaces. The roller bearings (Fig 14) consisted of several short lengths of pipe guided by a light cage made from a ring of flat-bar with stub-axle guides for the rollers. As in this case the axles are not loaded by more than the weight of the cage, there is much less friction than when using flanged wheels, and this modification produced a marked improvement in response to changing wind conditions when used in conjunction with a 15ft diameter sail wind-wheel. This tail was built as a compromise using available materials, but as detailed later under the recommendations, it is suggested that its concept can be extended to obtain further improvements.

Fig 20. Recommended 15ft diameter wind-mill configuration with lightweight extended tail vane and head running on roller bearing (see Fig 14).

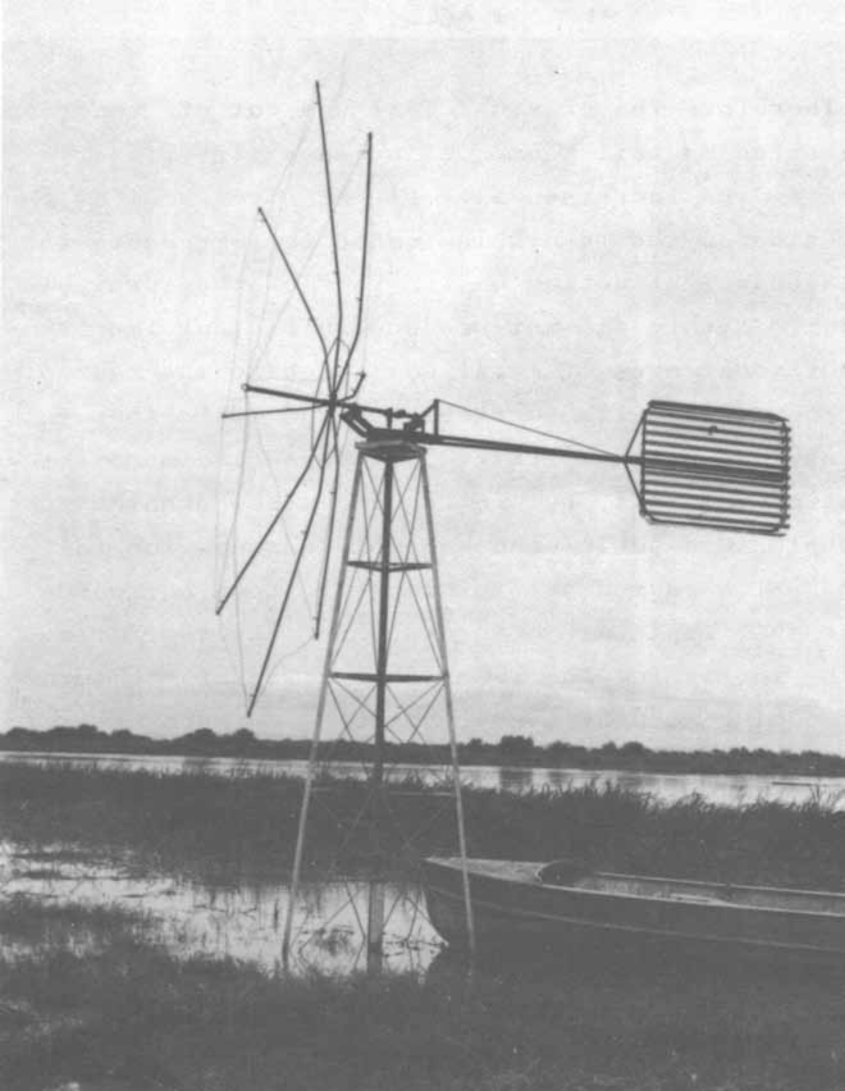
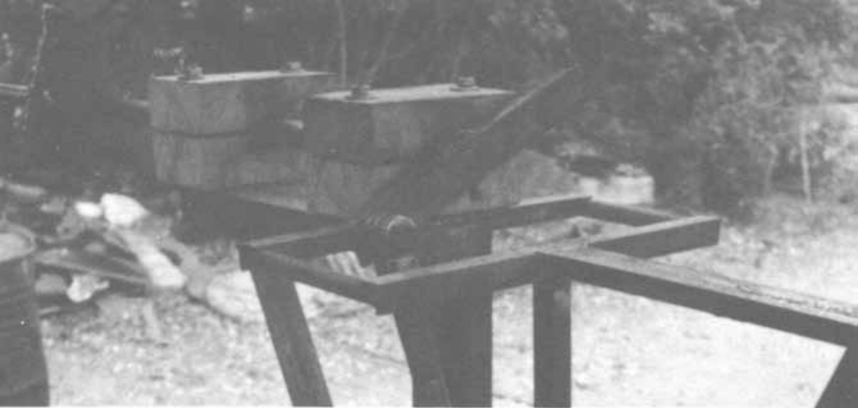
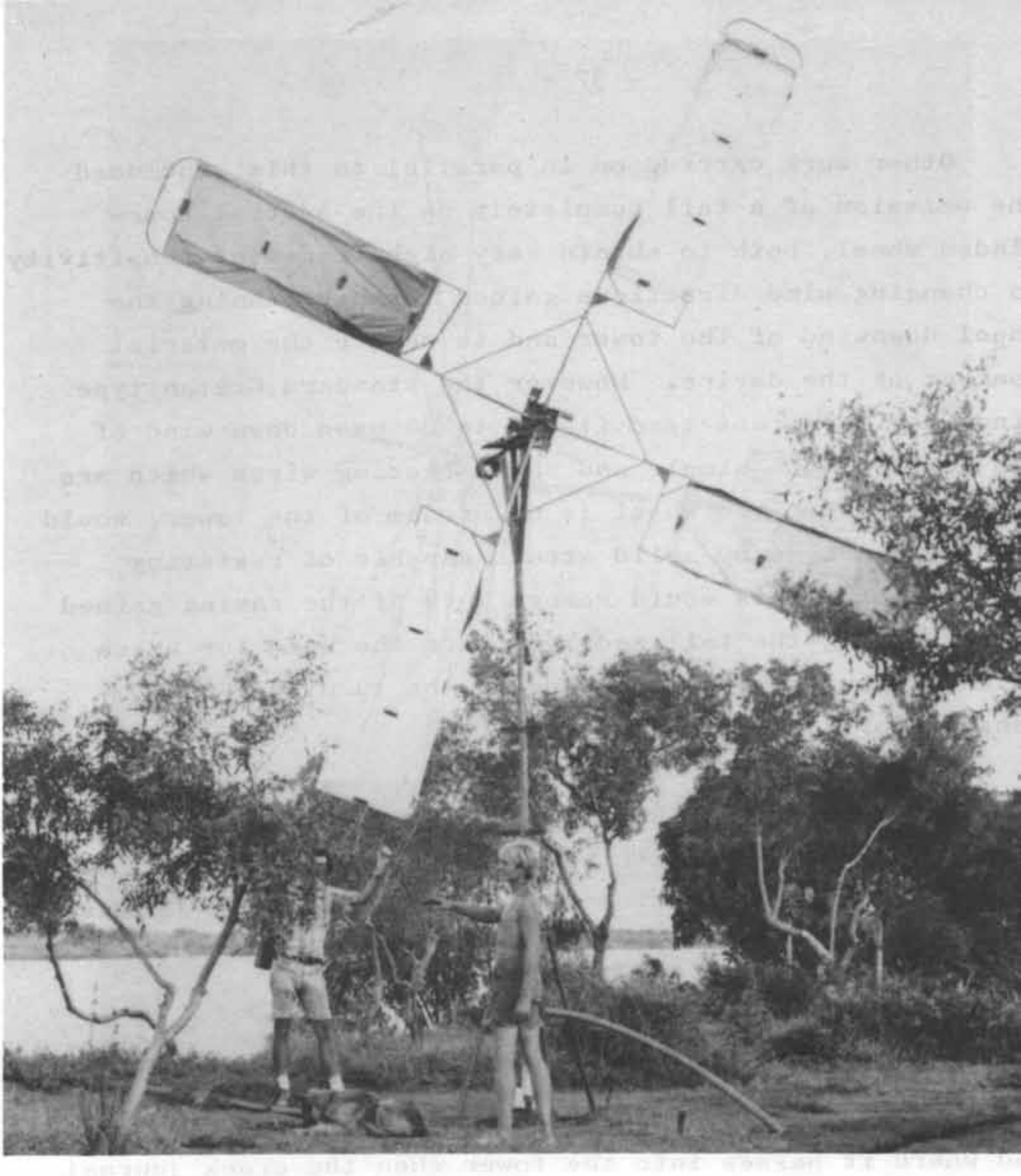


Fig 21. Transmission system for tubular tower wind-mill.



Other work carried on in parallel to this, included the omission of a tail completely on the special four-bladed wheel, both to obtain very high degree of sensitivity to changing wind directions gained through running the wheel downwind of the tower and to reduce the material content of the device. However the standard Cretan type wind-wheel does not lend itself to be used down-wind of the tower as the simple and cheap bracing wires which are in tension when the wheel is up-stream of the tower, would need replacement by solid struts capable of resisting compression. This would remove much of the saving gained from removing the tail and introduce the need for extra balancing on the opposite side of the turntable to compensate for the heavier wheel.

Another indirect approach to the problem was to tackle high turning resistance between the turntable and tower head by reducing the diameter of the head, because the friction resistance to rotation is proportional to the mean diameter of the support bearing. To do this involved a complete change in the tower and head design, as the large diameter is needed with the existing arrangement to allow clearance for the pump connecting rod where it passes into the tower when the crank journal reaches the lateral extremes of its throw. Therefore the opportunity was taken when developing a tubular tower (Fig 22) to include a redesigned transmission (Fig 21) involving the use of a much shorter connecting rod. This allowed a 3in diameter head bearing to be used, consisting of the bottom end of the turntable tube resting on a ring-shaped lead thrust block supported on the tube tower. Although the tower design was abandoned for reasons to be described, the small diameter turn-table turned very easily and was both low in material content and simple to build. But the successful later development of a roller bearing (previously described) removed the need for this other development and involved fewer changes in the existing and proven design, to which considerable volumes



<u>Fig 22</u>. Tubular tower wind-mill.

of ordered construction materials were committed.

Provision of adequate pump-rod seal

The wooden plug with a hole for the pump rod proved suitable in situations where the delivery water runs downwards through a short length of plastic hose directly into distribution channels, but it precludes the delivery of water against heads of more than about 1ft (30cm) as in such situations significant quantities of water fountain out around the pump plunger and are wasted. As a result, certain areas of reasonable soil to the south of the mission that offer potential future plots for irrigation could not be used as any wind-mills supplying them would need to lift water through a static head of some 6ft (2m) with an additional substantial dynamic head due to the need for delivery through some 50 to 100 yds (m) of pipe.

Commercially manufactured seals were available from the pump manufacturer, but are relatively expensive and possibly have excessive friction as they are designed to withstand much greater delivery heads than are ever experienced or needed for this project. Therefore two alternative sealing devices were improvised from available materials (see Fig 23). The first is a gland-packing utilising a short length of compressed rubber hose as a seal. This has the advantage of being adjustable to cater for increasing leakage after wear takes place. The second system depends on shaped washers; a leather cup washer with an aluminium backing washer, which offer less friction than a packing as the water pressure itself presses the sealing edge against the plunger shaft. Both appeared to work reasonably well, at least for the short term of the author's presence, but the packing appeared to be more leakproof than the cup washer. Further developments that might be considered to overcome this problem are outlined in the section on recommendations.

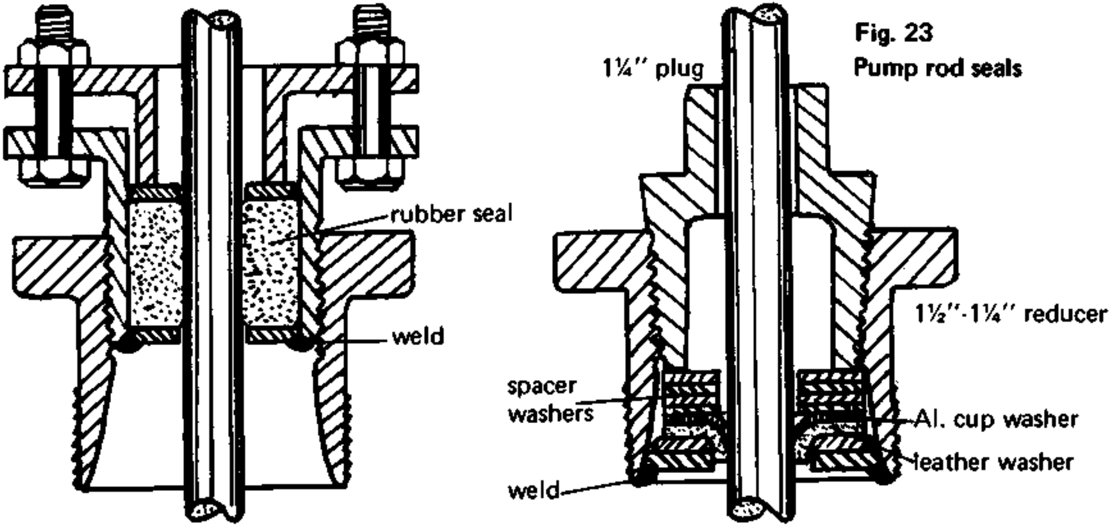


Fig 23. Alternative pump rod seals.

Methods for reducing costs

As wind-mill systems intended as development aid depend for their attractiveness on achieving a long life with low-running costs (i.e. high reliability), any reductions which conflict with these requirements could be counter-productive. Therefore it is the author's opinion that the best means for achieving "cost reduction" is to improve performance, that is although the capital cost of the system may even increase, the aim will be to minimise the cost per gallon of water lifted. Any improvement which produces an increase in cost may be justified if it produces a proportionately greater increase in water output and conversely any cost saving reductions must be questioned if they can cause reductions in water output through either reduced running performance or reduced reliability/life. A further important consideration with metal wind-mill structures is the fatigue strength of various components; although an item may be quite adequately designed to withstand the loadings over relatively few cycles of operation, a wind-mill must withstand many years of operation if it is to be viable and should therefore have exceptional reserves of strength to withstand metal-fatigue. To emphasise this point; a reliable commercial vehicle is considered to have performed well if it runs 500,000 miles between show-room and scrap-yard, that is just under 17,000 hours at an average of 30 mph. This is the equivalent of 4½ years of continuous operation for a wind-mill, which is a rather short period at least compared with life times of commercially manufactures water-lifting wind-mills, which are normally of the order of more than 10 years without major repairs.

These points are made because the author feels that small savings in capital cost that degrade the structural integrity of the design, as it has evolved, should generally be avoided. Having said that, a number of areas where savings could be sought are pointed to by the cost breakdown (Appendix 2), which are discussed in some detail under the recommendations which follow.

Two practical attempts at cost reduction were attempted under the work programme. As the lattice tower did not lend itself to reduction of metal content, (mainly because the lateral members are needed to allow the towers to be climbed), an attempt was made to produce a tubular tower braced with guy ropes (Fig 22). This also lent itself well to the application of a simpler, small diameter, thrust bearing to support the tower-head. The design philosophy was to minimise the structural weight and cost of the tower relative to the dynamic parts of the system such as the wheel and transmission. The tubular tower was in fact very much quicker to build and was also cheaper in that it used less steel, but it proved very vulnerable if the guy ropes were not perfectly tensioned and eventually failed for this reason. Although braided steel rope was available for guying the tower, it could not be used as it is extremely likely to be removed by local people during the night, being very highly prized for making crocodile harpoons. Therefore, ordinary fencing wire was used which was prone to stretch; also constant vibration from gusts of wind loosened the anchorages. Therefore it was concluded that although this design approach might be viable in situations where adequate guying (probably from concrete anchorages) is possible, it was not an appropriate method in this situation. Further considerations weighing against the tubular tower were that it was rather more difficult and dangerous to climb than a lattice tower and that there was a considerable commitment in terms of materials on hand and ordered for the lattice towers, which were functionally quite satisfactory.

The other area where practical work aimed at cost reduction was completed was a study of redundant components in the evolved design. It says much for the development skills of Messrs Swart and Pollock that there were few unnecessary components that had not already been eliminated. The main areas where savings can be effected is in increased ease of construction by the simplification of the head bearing already outlined together with the elimination of "balance weights" from the crank flanges. A number of towers were fitted with an unnecessary square top frame (a relic of the prototype tower design which, (copying those in Crete) was four-cornered); but these are no longer to be fitted now that the originally fabricated batch has been used up.

Consideration of alternative sails

The Dacron material, obtained free through the generosity of the manufacturers, has so far proved entirely satisfactory, (although a number of proposals for further development work on sail shapes and sizes are included in the recommendations). However, as conventional locally available fabrics had proved rather unsatisfactory in terms of durability, the author felt it was worth looking for alternatives in case either the supply of free Dacron were to dry up or if the system were to be tried elsewhere without the connection with the Dupont Corporation.

Therefore a pair of detachable aluminium sails were built, designed to be simply substituted for the existing design of Dacron sail on the standard wind-wheel (Fig 24). The sails needed to be removable to allow the same facility for adjusting the wind-mill to cope with different wind strengths. They were clipped to the wind-wheel at the front and were secured via polypropylene rope and rubber loops at the trailing edge and could readily be removed or fixed in place. The aluminium used was obtained by flattening some surplus aluminium roof cappings. This kind of material should be readily available and cheaper than Dacron in most areas. It would also be very much more durable than any locally available textile materials. In addition, we found that provided the aluminium sails were mounted correctly (to avoid too shallow an angle of attack) the two aluminium blades provided about the same water pumping output in a given wind as three Dacron sails (Appendix 5). Lack of time prevented further experiments with larger numbers of aluminium blades. This work is of primary interest for any applications of the Omo windmill design in other areas, in which case further development of the aluminium (or perhaps wood or galvanised sheet steel) blades would be justifiable.

Method for testing wind-mills

The results of the testing system that was evolved proved how unreliable subjective impressions based on general observation of performance can be; it is very difficult to judge water delivery simply by looking at the appearance of the jet of water being produced.

Because the wind very rarely blows steadily for more than a few seconds, but tends to gust, it was not practicable to try and build a dynamometer to measure the shaft power output of a wind-mill (which would of course vary continuously with the wind). Also it is not so much the shaft output, but the volume of water pumped in a given situation by the system as a whole that is of interest.

Therefore it was decided to bypass the problem of obtaining "instantaneous" values of power output to relate to wind-speed by measuring average values over short periods. This could readily be done by measuring the time taken to fill a 45 gallon oil barrel while simultaneously noting the wind-run over the same period, measured by the cup anemometer that was available for

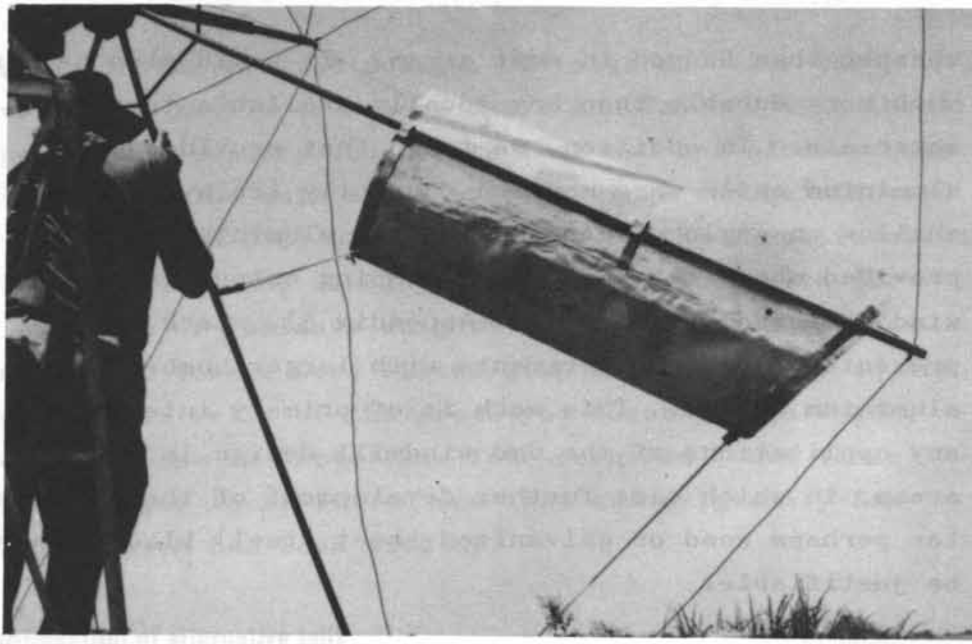


Fig 24. Windmill with experimental clip-on metal sails, beaten out of aluminium roof cappings.

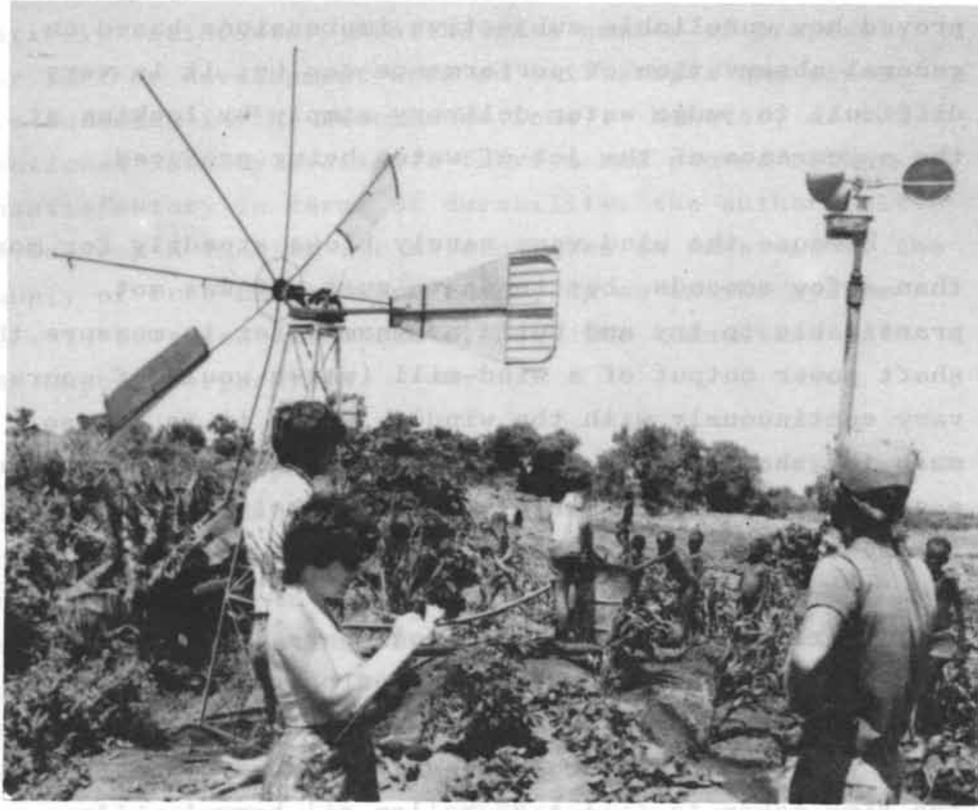


Fig 25. Windmill testing by filling a 45 gallon barrel (metal blades being evaluated).

the weather station (Fig 25). (A hand held wind-speed indicator was borrowed from the Missionary Aviation Fellowship, which gave instantaneous wind-readings, but this only served to show how variable the wind-conditions are, with the indicator marker continuously weaving up and down its scale).

The wind run (automatically integrated by the anemometer) divided by the time taken to pump 45 gallons gave the average wind-speed during the test, and the volume of water (45 gallons) divided by the time taken gives the average pumping rate. Hence values of performance in terms of water pumped in different wind-speeds were obtained for a number of permutations and combinations of wind-wheel size and numbers of sails, (see Appendix 5) From the knowledge of the volume of water pumped, the useful power output of the wind-mill can be computed by obtaining the total (manometric) head across the pump (this is the static head plus a dynamic head, the latter being estimated from standard tables) and multiplying by the weight of water pumped. By using appropriate units a dimensionless ratio, called the performance coefficient (see Appendix 3) can eventually be arrived at which provides a ready comparison for the efficiency of a wind-mill at converting wind energy into pumped water. This of course is efficiency in the technical sense; in the end the cost must also be considered and may make a technically inferior wind-mill have the economic edge over a more sophisticated technical design.

This testing system has the advantage of being simple to carry out and only requires a standard integrating cup-anemometer plus a 45 gallon (or other known volume) container. But it does pose problems of obtaining performance figures in very low winds, as, if the wind-wheel should stop during a test, the test becomes void because the anemometer usually continued to record wind-run while the wind-mill is stationary. Also, as low-wind tests take the longest there is a high chance of a lull in the wind during such a test. Therefore it may be justifiable to modify testing procedure as outlined under the recommendations in order to obtain results at low wind-speeds more readily. This is quite important, as one of the main problem areas is to obtain the best possible performance in low winds from wind-mills.

Operational problems

The problem of obtaining more irrigation land for non-land-owning potential mill-owners is being tackled by the project organisers. One way of helping towards this is to try and ensure that existing mill users achieve successful crop yields, which will serve to generate even greater interest from non-users. The use of a suitable pump-rod seal may permit water to be lifted to a higher area to the south of the mission which is suitable for cultivation and will therefore open up a new area of "no man's land" and also wind-mills are now being installed in areas further from the mission where they may well attract further interest.

Poor water distribution and failure to rotate crops is being tackled intensively by Mr Larry McAuley, who is spending some six months at Omo Station and who has learnt sufficient of the Geleb language to communicate in little more than a month and who seemed to have established an effective rapport with the mill-owners. This of course continues the efforts along similar lines by the Rev Bob Swart who also of course speaks the local language with fluency and has run a continuous educational effort through discussions and through the provision of tape-players with cassettes to reinforce his teachings (Fig 26).

The author's wife, who accompanied him during the project, conducted a series of interviews with mill-owners (using the good offices of the Rev Bob Swart as an interpreter) (Fig 27). This helped identify a number of cultural and social difficulties that had not previously been so clearly apparent. An outline of the findings from these interviews is included in Appendix 4 and it is suggested that occasional interviews might be organised from time to time in order to obtain a valuable feed-back from the mill users, both to identify new problems and to evaluate the effectiveness of attempts at solutions.

Although the author's prime task is to consider technical aspects of this project, the social and cultural side of applying this technology may be more critical in effecting the success of it than seeking technical perfection, and it also overlaps into the realm of the choice of technical approach. Therefore it is concluded that some of the more significant findings in this field are an important component of this report so far as understanding the complete perspective of the project is concerned.

5. CONCLUSIONS AND RECOMMENDATIONS

Some of the following conclusions became obvious during the course of the work programme and are already in the process of implementation. But for completeness these are included together with some ideas for further development which could be tested and introduced when the opportunity permits.

Wind-mill modifications

1. Increase wind-wheel size to 14ft (4.25m) diameter to improve starting and pumping performance. Further increases up to 20ft(6m)diameter might be tried, but accompanying increases in tower height will be needed, (such as indicated in Fig 28). (20ft diameter gives four times the power of a 10ft diameter mill).

2. If 14ft diameter (or larger) wind-wheels are used, it should be possible to build them with only six arms rather than eight and still achieve sufficient performance, so little (if any) extra material will be needed.

3. Further small gains in starting torque might be obtained by extending the inner end of the sails nearer to the wheel hub, (see Fig 29).

4. Starting performance might be slightly improved by sheeting the outer trailing edge of each sail less tightly so as to allow it to take up a steeper "angle of attack". Tests will be needed to check this in case it causes excessive sail flapping in higher winds.

5. The induced drag of the tail could be increased further by increasing its aspect ratio, (i.e. making it taller and narrower - see Fig 30). This would improve directional stability at no extra cost and permit a lighter tail on a longer boom to be used. Another improvement would be a swallow-tail arrangement (Fig 30) which should

be more sensitive to small changes in wind direction. Aluminium roof cappings, available at Omo, would be a suitable construction material for either of these types of tail.

6. A wire loop with a handle on the end of it could be attached to the tail to allow the wind-wheel to be turned out of the wind from ground level.

7. If directional stability problems persist, a wind-mill could be modified as shown in Fig 31 so as to operate down-wind of the tower. This would eliminate the need for a tail, but the other additions shown would be needed.

8. Initial tests indicated that a double-acting pump produces twice as much water as a single-acting one. Therefore a single-acting pump should be converted as indicated in Fig 32. The connecting rod will need stiffening to prevent it buckling on the down-stroke; a possible way of doing this is shown in Fig 33. If it proves difficult to convert single-acting pumps, it appears justifiable to use two single-acting pumps per wind-mill instead, as on the test installation.

9. Tests should be conducted to determine the best stroke when using either bigger wheel diameters or double-acting pumps. It is likely that a longer stroke could be used which would produce still higher pumping rates. The crank-shaft, bearings and wheel might have to be raised slightly to provide sufficient clearance between the pump rod and frame. These tests could be conducted either by making up several crank-shafts of different throws, or by making an adjustable stroke crankshaft such as that suggested in Fig 34.

10. An alternative way of fabricating crankshafts is indicated in Fig 35. The author is grateful to Marcus

Sherman of New Alchemy Institute for suggesting this means of obtaining correct alignment; apparently this is a method used in Greece. This would allow crank-shafts to be made at Omo instead of at Ghimeera.

11. Circular or hollow bar (thick-walled pipe) would be more suitable for shaft material than the hexagon bar previously used.

12. The balance weights added to crank-shaft webs are not necessary and could be left off in future.

13. Sealed metal ball-races seem satisfactory while free stocks last, but olive wood bearings appear equally good and would be a better choice if ball-bearings had to be bought, being cheaper. Fig 36 illustrates methods for the possible controlled lubrication of wooden bearings which would be worth testing over an extended period.

14. The flanged-wheel type of tower head bearing should be discontinued. Roller bearings made from bits of pipe are less difficult to build, no more expensive and offer much less friction. Future bearings should use thicker-walled pipe for rollers and three rollers would probably be better than four to prevent wobbles due to inaccuracies of alignment. Alternatively plain metal-to-metal contact is cheaper and no worse than the flanged-wheel arrangement.

15. Home-made or commercially manufactured pump-rod seals should be used if lifting water against heads of more than about 5ft; Fig 23 shows the two home-made types tested during the work programme. A few of each should be made and tested to establish which is easiest to make and how well they perform. Alternatively, the modification shown in Fig 37 would be useful for low lift situations and might be generally introduced with all future wind-mills. It will require some modifications

to the connecting rod arrangement, and should be tested before being generally applied.

16. Major cost savings might be possible in the suction line and float assembly. The following might be tried: reducing the length of suction hose by up to 50% in some cases; trying $1\frac{1}{4}$in diameter instead of $1\frac{1}{2}$in diameter suction hose (if it is available from Addis Ababa) - although to avoid increased friction losses the smaller pipe should only be used in shorter lengths than at present; a smaller foot-valve, if available, would allow the use of a smaller (and cheaper) styrafoam float. The foot valve might be supported from a steel frame lying on the bed of the river, instead of from a float (such as in Fig 38), which should be cheaper.

Testing procedure

1. It is recommended that a standardised wind-mill testing procedure, such as that described earlier in this report, be instituted to evaluate any modifications to the wind-mills.

2. Smaller containers than 45 Imp. Gallon drums might usefully be used for low wind tests as these would shorten the test period and reduce the chance of the wind-mill stopping during the test.

3. The following information should be recorded during a complete test:-

1) diameter of wind-wheel
2) number of sails
3) time for test
4) volume of water pumped during test (size of container filled)
5) wind-run measured during test
6) static head (height vertically from river level to

delivery hose outlet)

7) approximate length of suction + delivery hose and diameter of hose

8) special modifications or conditions

Items 6 and 7 may be omitted to obtain simpler comparative results on the same wind-mill, providing these tests take place without any change in river level or delivery hose outlet level.

The Intermediate Technology Development Group can undertake to evaluate and comment on any such test results taken in future, if required.

Meteorolgical station

1. The anemometer should ideally be located within the mission compound on or near the river bank, as clear of the trees as possible. Although this is not completely in accordance with weather station specifications, it is consistent with the typical positioning of most wind-mills and should allow wind data to be related to wind-mill performance.

2. The rest of the weather recording equipment would be better located at the south-west corner of the mission compound, where it will be unlikely to be affected by river seepage or flooding and will also be clear of shading by trees.

3. The system adopted for taking readings three times every 24 hours at 0700, 1300 and 1900 hours seems quite adequate for obtaining a meaningful record of the monthly variations in wind régime. It would provide a valuable extra information input if readings could be taken hourly, or even two hourly, from 0700 to about 1600 on about one day each month to gain some idea of hourly wind variations; a "typical" day should be chosen for this. Again, ITDG

would be prepared to evaluate the wind régime further with particular reference to wind-mill operation, after about one complete year's figures are available.

Use of Omo wind-mills in other places

1. These wind-mills are only really suitable for use in locations where there can be almost constant supervision when they are in operation, (i.e. for irrigation), so that sails can be removed or added if the wind changes.

2. They are comparatively low-powered devices so they are not suitable for lifting water through heights much greater than 30 to 40ft (10 or 12m) and they would in any case need different pumping arrangements to those used at Omo if working with suction lifts greater than about 20ft (6m). It would be possible to use these mills for even higher lifts, but volumes of water pumped would be quite small.

3. Care should be taken to relate the wind-regime at any other location with that at Omo Station before any conclusion as to wind-mill performance can be made.

4. The equipment required to build this kind of wind-mill (as used at Omo) consists of an electric arc-welding set, a light vertical drilling stand with a heavy-duty electric drill, a wood-lathe, plus a work-bench and hand tools. Plumber's pipe thread cutters are also necessary for assembling the inlet and outlet pipes.

Extension to tower required
if using an enlarged wind-wheel
greater than 14ft dia.
(Maximum size suggested 20ft dia.
requires a 3ft extension to the
tower)

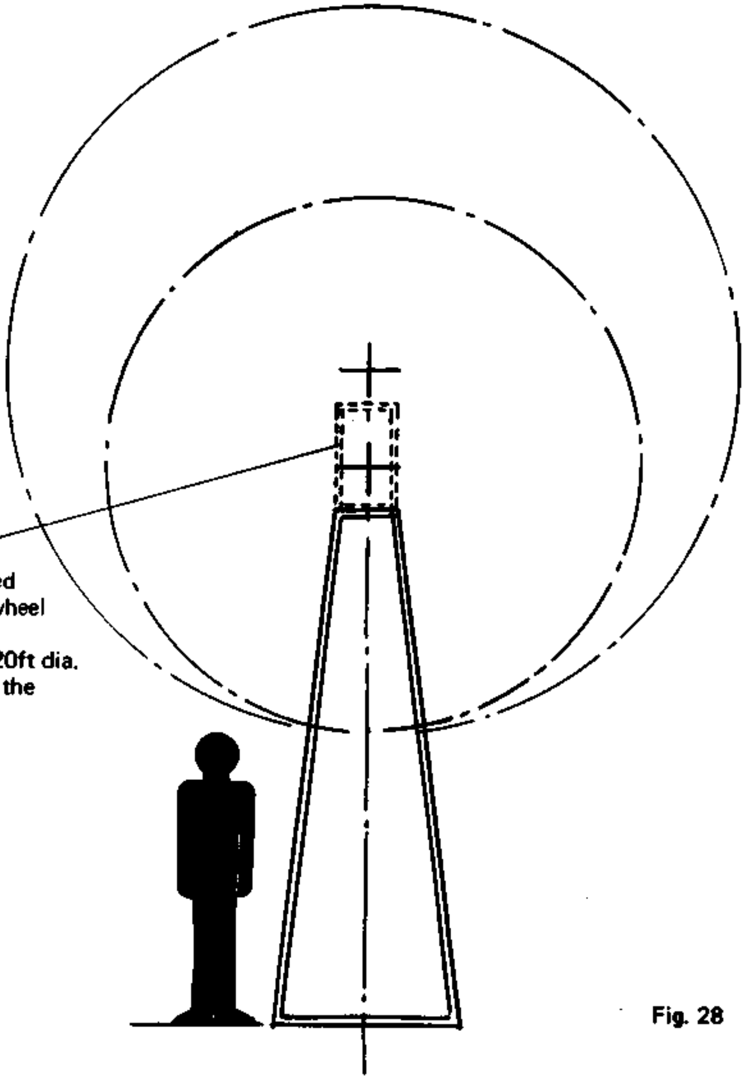


Fig. 28

Recommended six sail rotor with
sails extended as close to the hub
as possible. Existing sail as used
on smaller wind-wheels is shown
dotted.

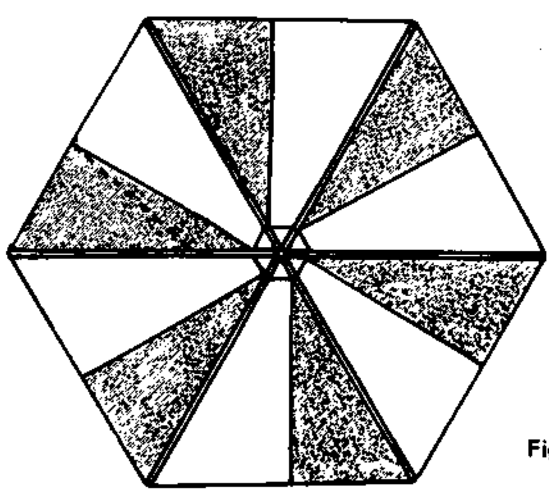
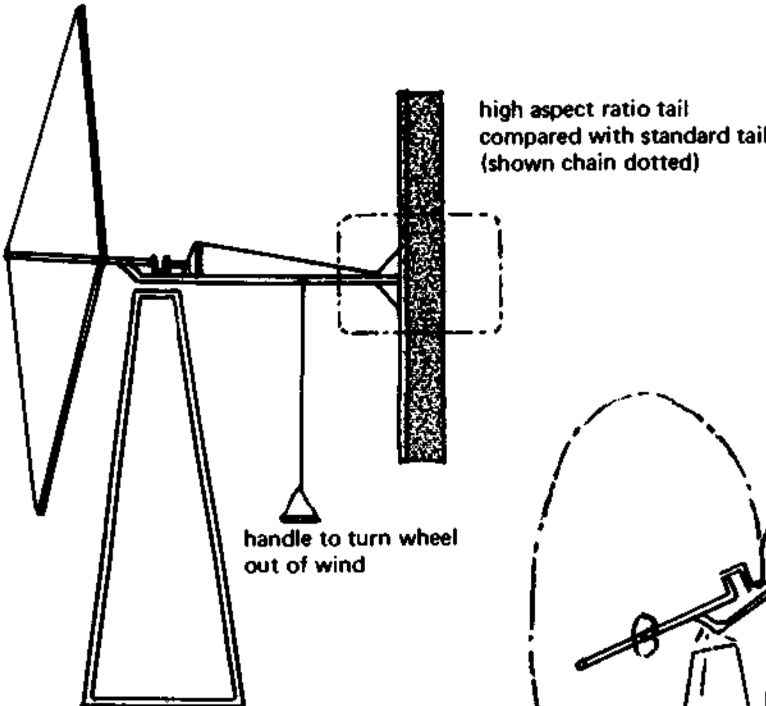
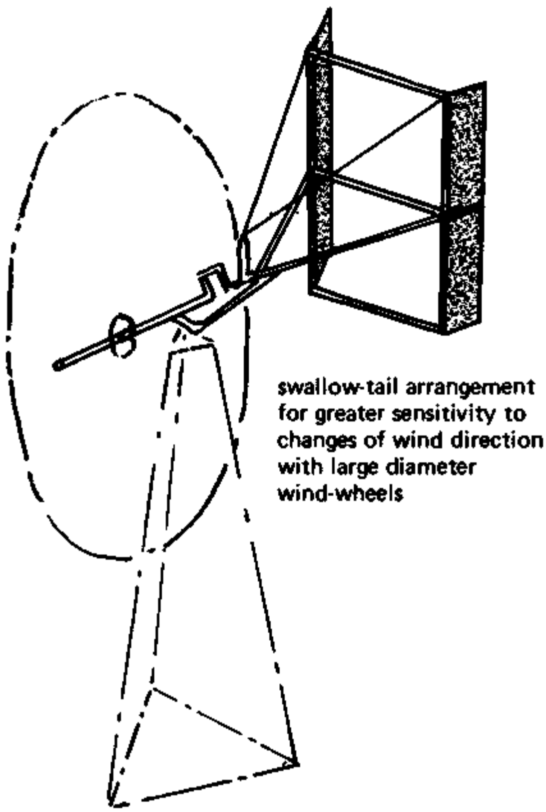
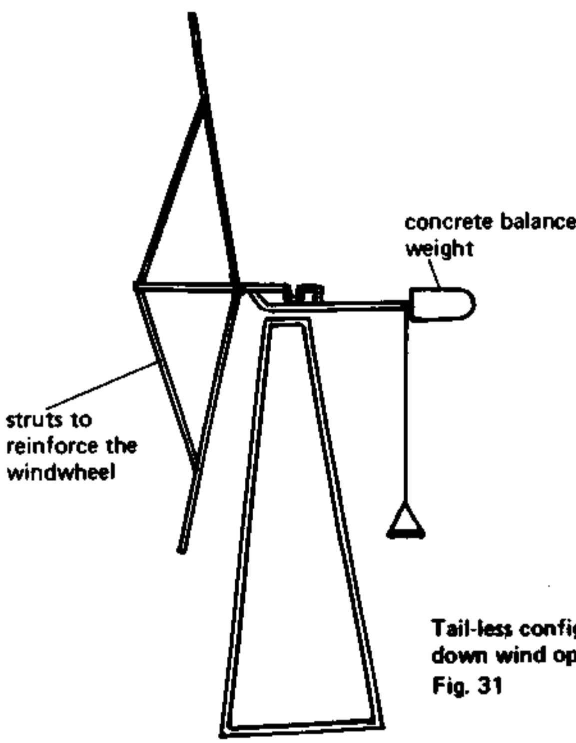


Fig. 29





High aspect ratio tails
Fig. 30



Tail-less configuration for down wind operation
Fig. 31

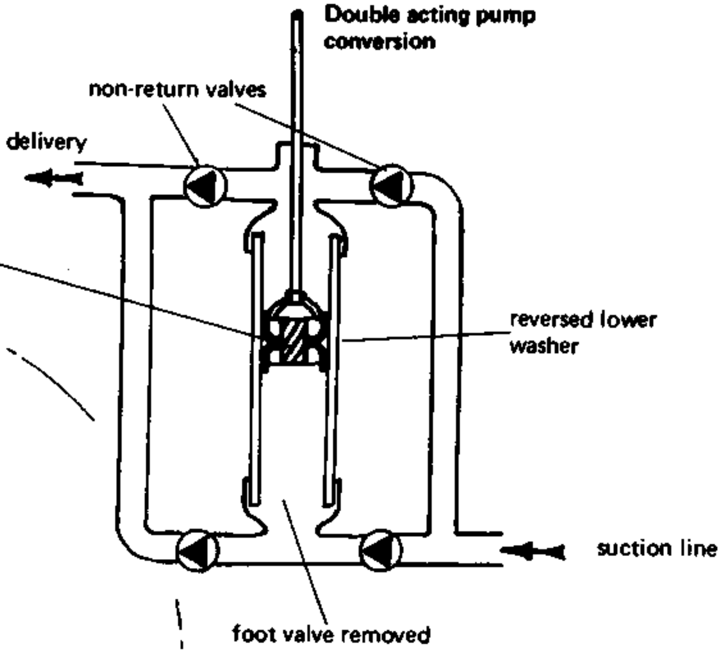


Fig. 32
Double acting pump conversion

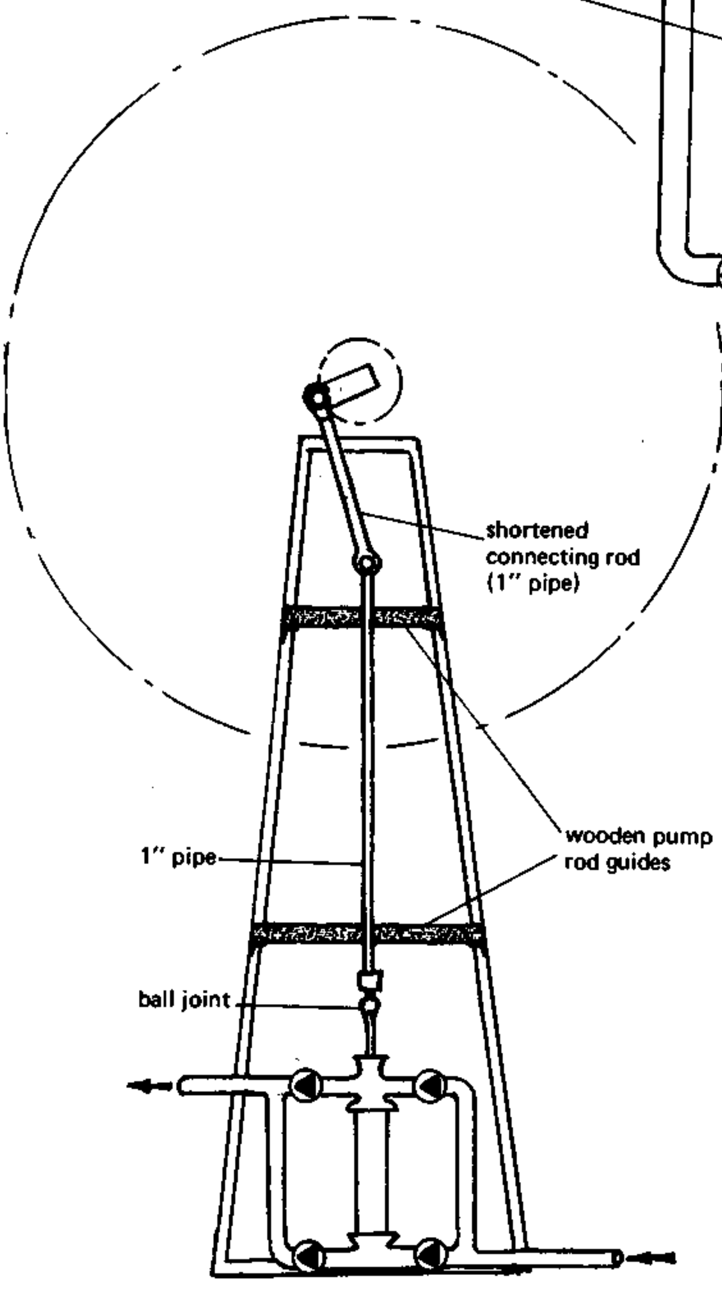


Fig. 33
Stiffened transmission for double-acting pump

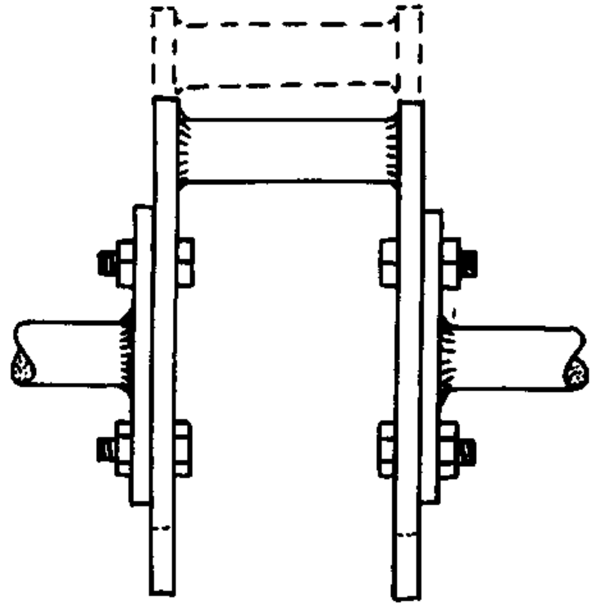
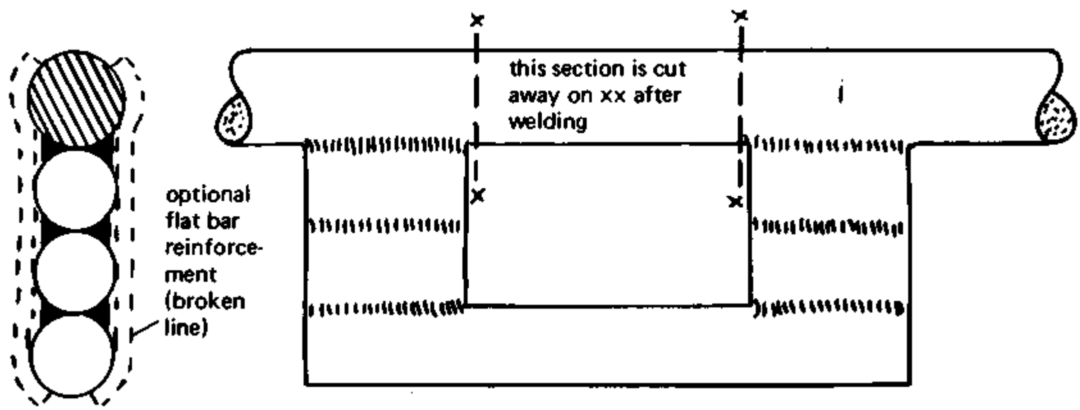


Fig. 34 Adjustable throw crank

Fig. 35 Method for fabricating crank to ensure correct shaft alignment after welding



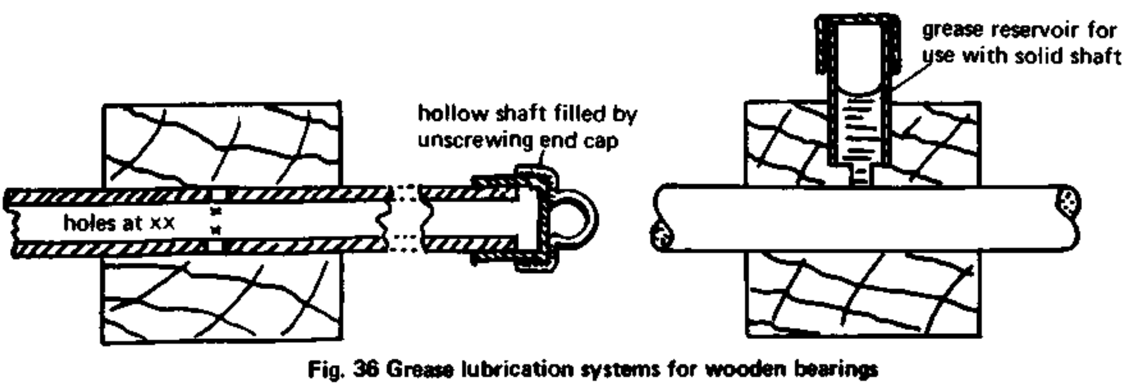


Fig. 36 Grease lubrication systems for wooden bearings

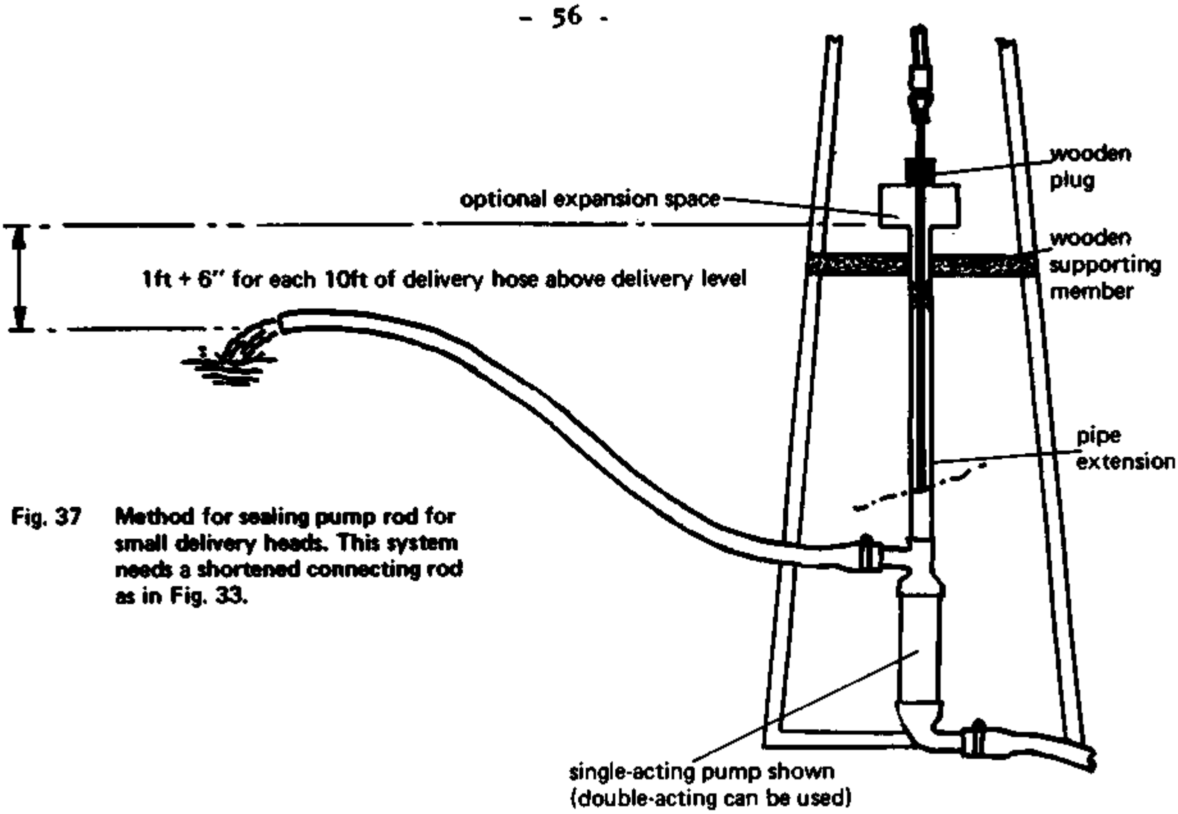
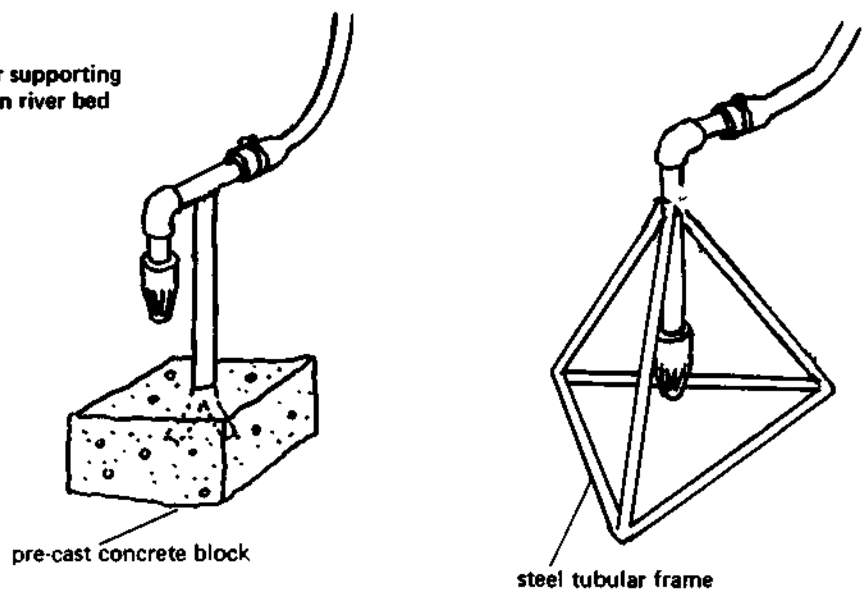


Fig. 37 Method for sealing pump rod for small delivery heads. This system needs a shortened connecting rod as in Fig. 33.

Fig. 38 Methods for supporting foot-valve on river bed



APPENDIX 1 : Wind-mill construction to mid-August 1975

1. Wind-mills in use by Geleb farmers.

1	April 1974	Dempster (imported from USA)
2	June 1974	10ft sail
3	June 1974	10ft sail (removed July 1975)
4	June 1974	10ft sail
5	August 1974	10ft sail (modified to 14ft diameter in July 1975)
6	January 1975	Savonius rotor
7	January 1975	10ft sail
8	March 1975	10ft sail
9	March 1975	10ft sail
10	March 1975	Dempster
11	March 1975	10ft sail
12	April 1975	10ft sail
13	April 1975	10ft sail
14	April 1975	Savonius rotor
15	April 1975	Savonius rotor
16	May 1975	Savonius rotor
17	May 1975	11ft sail
18	June 1975	11ft sail
19	July 1975	11ft sail
20	August 1975	11ft sail

2. Wind-mills in use in mission compound (commissioning dates not available)

2 x Dempster (for irrigation and water supply)

2 x 10ft sail(for instructional purposes at farmers' classes)

1 x Savonius (for medical dresser's family water supply and garden)

3 x various (for experimental work)

3. <u>Completed and awaiting commissioning</u>

11 x 11ft sail (most were due to be modified to 14ft diameter)

4. <u>Materials on hand or on order</u>

For approximately 20 further wind-mills.

APPENDIX 2 : Cost breakdown on wind-mills

There is no completely precise means of estimating the cost of wind-mills as there are a number of different variations in the design, materials are cut with varying efficiencies in terms of minimising off-cuts, and due to inflation and/or different supply sources, various materials vary in price depending on when and where they were ordered. In addition, certain components were manufactured at Ghimeera and the cost of these was unavailable at Omo, so an estimate for these items has been made. Once a standard design is finalised more precise cost estimates will be possible, but nevertheless, the figures arrived at either from mission accounts giving actual expenditure or from a breakdown of a mill by components gives reasonably consistent results amounting to around Ethiopian \$700 per mill (note: Eth \$2.07 = US \$1.00) for materials plus a nominal sum to cover indirect expenditure and capital investments.

1. <u>Estimate for OXFAM funding</u> Eth \$700 per mill (Ca. £160)

2. <u>Cost derived from "Food for Wind" accounts 1974 and 1975</u>.

Total expenditure 1974 accounts*	Eth \$ 20,899
Total expenditure 1975 accounts*	\$ 12,950
	\$ 33,849

Of which indirect expenditure on capital equipment (tools, etc.), casette recorders, etc., accounted for..	\$ 8,664
Leaving direct expenditure on materials	\$ 25,185

* (no labour costs included and excluding costs of pumps and heads produced under different budget at Ghimeera for about ∅80 per pump plus ∅40 per head).

Therefore ...	mills erected (various types but excl. Dempsters)	24
	mills completed and awaiting commissioning	11
	materials paid for and not yet used for approx.	15
	Total mills paid for under this budget	50

Hence ... cost per mill $\frac{\text{∅}25{,}185}{50}$ plus ∅120 for head & pump

gives total material cost per mill of ∅623.70

If capital expenditure of ∅8,664 is also included for the 50 mills, we arrive at

material costs + capital expenses ∅796.98

It should additionally be noted that various components were obtained free or at a special discount (sail material free, pumps at 50% discount) but against this high transport costs are involved from Addis Ababa to Omo Station which probably more than cancel out the free or cheap items. The 50 mills include such experimental units as the Savonius rotors, which probably cost more than the sail wind-mills. Because labour is not specially paid for on this project, it has not been costed and neither on the other hand is there any credit included for the nominal payments of ∅5.00 per year paid by Geleb farmers.

3. Breakdown of cost by component for 11ft sail wind-mill

Steel costs were derived by weight of actual components at the rate Eth ∅1.50 per kg + ∅0.35 for transport (i.e. not including any wastage from off-cuts). Total weight of steel components 113 kg.

steel	$ 209.05	foot valve	$ 12.85
pump	$ 80.00	sail fixings	$ 7.00
paint	$ 10.00	float drum	$ 10.00
nuts & bolts	$ 4.15	welding rods	$ 4.00
sails	$ 0.00	pipe fittings	$ 9.00
pvc suction pipe	$ 100.00	electricity	$ 10.00
Styrofoam float	$ 12.50	head assembly	$ 40.00
		TOTAL :-	$508.55
		plus tax 7%	$ 35.60
		NET TOTAL MATERIALS	$544.15

This of course allows for no wastage (off-cuts) and the cost arrived at under paragraph 2 above from mission accounts allows for experimentation and trial and error (including the Savonius Rotor wind-mills which probably cost rather more in terms of materials). It is also based on steel prices applicable in Addis Ababa in 1974 when materials were last ordered. Therefore, it is likely that the figure of $700 will probably barely cover material costs per wind-mill in future material purchases.

4. Relative cost of importing factory-built Dempster wind-mills

These cost around Eth $2,000 each, landed at Omo station and would probably cost at least 10 to 15% more at the time of writing following steel and transport cost increases. The modified sail wind-mills are capable of lifting similar or greater quantities of water than the Dempsters and do not rely on imported spare parts or regular lubrication. The Dempster is one of the least expensive factory-built wind-mills available; a Southern Cross 21ft wind-mill (from Australia), which is much bigger than the 8ft diameter Dempster of course, was quoted at Eth $\not{S}$19,000 landed at Addis Ababa in September 1975. It would of course pump much more than the little sail wind-mills, but probably not 27 times as much - this being their relative costs!

APPENDIX 3 : Some principles of wind energy conversion

1. Power from the wind

Power $P = k.C_p.A.v^3$ where: k is a constant dependent on the system of units being used

C_p is the Coefficient of Performance, which is a measure of the efficiency of energy conversion

A is the cross-section of air stream being used (area of wind-wheel)

V is the speed of the wind

If P is in horsepower, A in ft^2 and v in miles/hour, this becomes:-

$$P = 0.0000071\ C_pAv^3$$

or if P is in kilowatts, with A in m^2 and v in m/s, it is:-

$$P = 0.00064\ C_pAv^3$$

These formulae, which are commonly quoted in the literature on wind-power, assume that the air is at a density appropriate to sea level and 15°C. Higher altitudes and temperatures rarify the air and consequently cause a lower power output. For the purposes of the graphs which follow (Appendix 5) the effect of altitude and temperature has been ignored, implying therefore that the wind-mills are potentially slightly more efficient than might appear from the figures, if they were used at sea level under cooler conditions. Also, it is normal to take the entire disc area of the wind-wheel as being A in the formula, but as rather small sails were used on the larger diameter wheels, the area swept by the sails has been taken. This has been applied for all wind-wheel sizes to achieve consistency for purposes of comparison.

2. <u>Starting torque</u>

A certain minimum torque (or twisting force on the wind-mill shaft) is needed to overcome the static friction in any wind-mill system and allow pumping to begin. The torque produced by the wind-wheel is a function of the tangential turning forces on each sail, the number of sails and the average radius (or leverage) that these forces act on the shaft from the tangential turning forces are approximately proportional to the square of the wind-speed.

Therefore, torque will be proportional to the radius of the wind-wheel and to the square of the wind-speed. The bigger the wind-wheel diameter, the lower the wind-speed needed for starting.

3. <u>Power requirement for water lifting</u>

The net power output of a water lifting wind-mill will move water at a rate such that the power output is directly proportional to the product of flow rate and the pressure difference across the pump (or resistance to flow).

The pressure difference across the pump is a combination of the static head of water being lifted, which is the vertical height from the surface of the river to the outlet of the discharge pipe, and frictional resistance to flow which is generally called the dynamic head. The dynamic head is a function of flow rate and the length, diameter and condition of the pipe system. The more water is pumped through a given system, the higher is the frictional resistance to flow and the greater the dynamic head. An estimate of the dynamic head for the Omo wind-mills can be made from the following table which considers 100ft of $1\frac{1}{2}$in and of $1\frac{1}{4}$in diameter pipe (the two options discussed in the text). Friction or dynamic heads for other lengths can be estimated on a pro rata basis, i.e. 80ft of pipe would produce 0.8 times or 80% of the head that 100ft produoes. An additional amount, say a nominal 25%, should be added to allow for the extra resistance caused by bends, the foot-valve and pump valves.

flow rate:	200	600	1000	1400	1800	imperial gallons/hr
dynamic friction head in ft. water						
100ft $1\frac{1}{4}$in pipe	0.6	4.5	11.0	20.0	33.0	
100ft $1\frac{1}{2}$in pipe	0.3	1.8	4.8	9.0	14.0	

This indicates how shortening the suction line as advocated in the text could not only reduce costs but can also reduce the dynamic head thereby producing an increased flow. If smaller diameter pipe is used to save cost, then shortening it too is important to avoid unacceptable increases in head.

The total net power output of the system, as defined for the graphs in Appendix 5, consists of:-

$$P_{hydraulic} = K\,(h_{static} + h_{dynamic}) x (\text{weight water/sec})$$

(where K is a suitable constant dependent on the units used)

4. **Coefficient of Performance** C_p

This has been defined for the purposes of Appendix 5 as:-

$$P_{hydraulic} = C_p \cdot P_{wind}$$

$$\text{i.e.} \quad C_p = K \frac{(\text{Total head}) \times (\text{weight of water/second})}{(\text{Area of wind-wheel}) \times (\text{wind speed})^3}$$

where K is the appropriate conversion constant

In other words, C_p is taken as an overall system efficiency for the combined wind-mill and pump installation.

It can be shown that the maximum theoretical rate of wind energy conversion by a wind-mill is 59.3% of the total kinetic energy of the wind. Therefore the efficiency as a fraction of what is theoretically attainable will be rather better than the value of C_p by a factor of 1/0.593 or 1.686. For example the value of C_p of 0.1 represents nearly 17% conversion of available wind kinetic energy.

APPENDIX 4 Interview with Geleb farmers

I am indebted to my wife for collecting the material from which these notes have been condensed during a series of interviews with various Geleb farmers. We are also grateful to both the Rev Bob Swart and to Mr Thompson Gac, the mission medical dresser, for their services as interpreters.

1. Koriye

He is one of the original pioneers. Began with a hand-pump having admired Thompson Gac's clinic garden which was similarly irrigated. Then obtained first Dempster in April 1974 (Fig 4). Has grown cabbages, corn, peanuts and beans and now has a variety of fruiting trees including paw paw, mango, lime, guava, grapefruit, fig, banana and tangerine. Sells cabbages, limes and mangoes to police at Kelem. His wife and five children help with the work and also help maintain a traditional flood-land garden where he grows millet, maize, beans and tobacco. Eldest daughter generally looks after flock of sheep and goats. His one cow is in the care of a friend. He finds it a problem to look after both wind-mills and cattle and says this is a general problem for other mill-owners too. He has no land problem as he has the rights to the land he is farming, but he has suffered from theft of crops by what he calls "hyenas" (meaning other people).

Koriye, who is in his thirties, is very willing to try new ideas despite having had no education at all. He is talking of using a plough, which would be a radical change in this area where animals are never used in agriculture. He thinks solutions can be found to most of the problems faced by mill-owners; cattle can be left in the care of relatives or friends; he has fenced parts of his plantation to guard against theft. His crops are particularly vulnerable as he lives the other side of the river due to mosquitoes on the east bank;

he says he would move if he could build a mosquito-proof hut.

He says his family have not been hungry since he has worked with the wind-mill, and he had obtained five harvests up to August 1975.

2. Natakan

Koriye's Dempster provides more water than he can use, so he allows three other men to cultivate adjacent plots of his land. Two, who are not relations, pay a small rent to him, the third is his cousin, Natakan, who works his plot free. He grows maize, tomatoes and ground nuts, but no fruit trees and has had three harvests so far. First two were good but the latest spoiled by hyenas (not specified whether this was a euphemism or not) and water buck. He also cultivates flood land. Younger brother is responsible for his few cows, goats and sheep, but he occasionally leaves his cultivation in his wife's care for a few days to go and see how his animals are, particularly when they are grazing far away. He sees two advantages in cultivation; it ensures his family always has food and he claims it enables him to buy more cattle.

3. Lohkwar

He was the first to operate a sail wind-mill and also is the only wind-mill farmer to give up his mill. He spent two years at the mission school and started wind-mill farming much younger than the others, at the age of 20 (approximately). He had no land, but a cousin of Koriye (qv) gave him a plot to use for nothing. This plot proved to be difficult for him, in that it is a bit sandier than most and soaks up water quickly. At first Lohkwar and the owner of the land worked the plot together, but the owner soon lost interest and left Lohkwar to work it on his own. He grew gound nuts and maize, but only got a small gound-nut crop and he allowed the maize to dry out and lost the lot. Although other farmers have worked equally difficult plots, Lohkwar was discouraged and tried to find another plot; he was offered one at an exorbitant rent. He left his difficult plot in the charge of a small boy and neglected it and then finally gave it up completely. He now has a job as a helper at the mission clinic, but says he would try wind-mill cultivation again if he could find a better plot of land. His wife cultivates a small plot of flood land, in the meantime, which yields one small annual crop of millet. They have no cattle, but own a few goats and sheep which his younger brother looks after.

4. Igogor

There are ten wind-mills on a single large plot of land about 1 mile downstream of the mission. The land belongs to Igogor, an older (probably late 40s) and more senior man than most of the other mill owners. His wind-mill installed in August 1974 was the first on the site and he has used it continuously except for a gap of one month when he once did not replant straight away after a harvest, but took his cattle to some distant grazing. He stays with his cattle when they are far away and delegates the wind-mill cultivation to one of his two wives, (his children are all very young in spite of his age). Men with mills on neighbouring plots help her with putting the sails on for watering when Igogor is away, but he always prepares the plots for planting. He has had five maize harvests and has also grown millet, sugar cane, peanuts, paw paws, sweet potatoes, guavas, mangoes, tobacco and water melons. He tried pigeon peas but they failed. He likes his mill and sewed up tears in the sails himself before getting the stronger Dacron sails. He is critical about the volume of water pumped by his mill (having seen the diesel pump at Rati on the EPID irrigation scheme). Therefore his mill was modified as quickly as possible to the new 14ft diameter to improve its low wind performance. (The diesel scheme has several times been in serious trouble with engine failures and there is a continuous worry about fuel shortages - the wind-mill workshop has twice provided tools when the US Peace Corps worker in charge of the diesel irrigation scheme had inadequate facilities of his own to repair the engines; unfortunately the Gelebs do not appreciate the problems and expense of diesel engine maintenance in such remote areas).

Igogor, being enthusuastic about wind-mills, readily releases large areas of land he has rights to for other people to cultivate with wind-mills. He has had problems with soil depletion and insect pests due to his failure to rotate crops properly (he is now being helped to remedy these problems). But he claims his family are no longer hungry as they used to be at certain times of the year.

5. <u>Korass</u>

Unlike Igogor, Korass is poor and has no land rights. However a younger cousin, Natade, who has a suitable plot permitted him to cultivate it, without any payment. Korass obtained his mill in June 1974, and as he had no money, he paid for it by collecting firewood for the mission. The soil was poor at the first place he tried, so after a while the mill was moved a little way along the river bank. Again the soil was poor and the mill was moved a second time (one good reason for not needing permanent foundations!). Since then Korass has had two good maize harvests and one poor one. He has also grown soya beans, sweet potatoes, tomatoes, bananas and has young paw paw, lime and fig trees. His pigeon peas also failed. He also grows millet and tobacco on flood lands, and his wife grows beans. His wife helps him with the main plot. He has no cattle; only a few goats. He has a daughter approaching marriagable age and hopes for cattle from the family of whoever marries her.

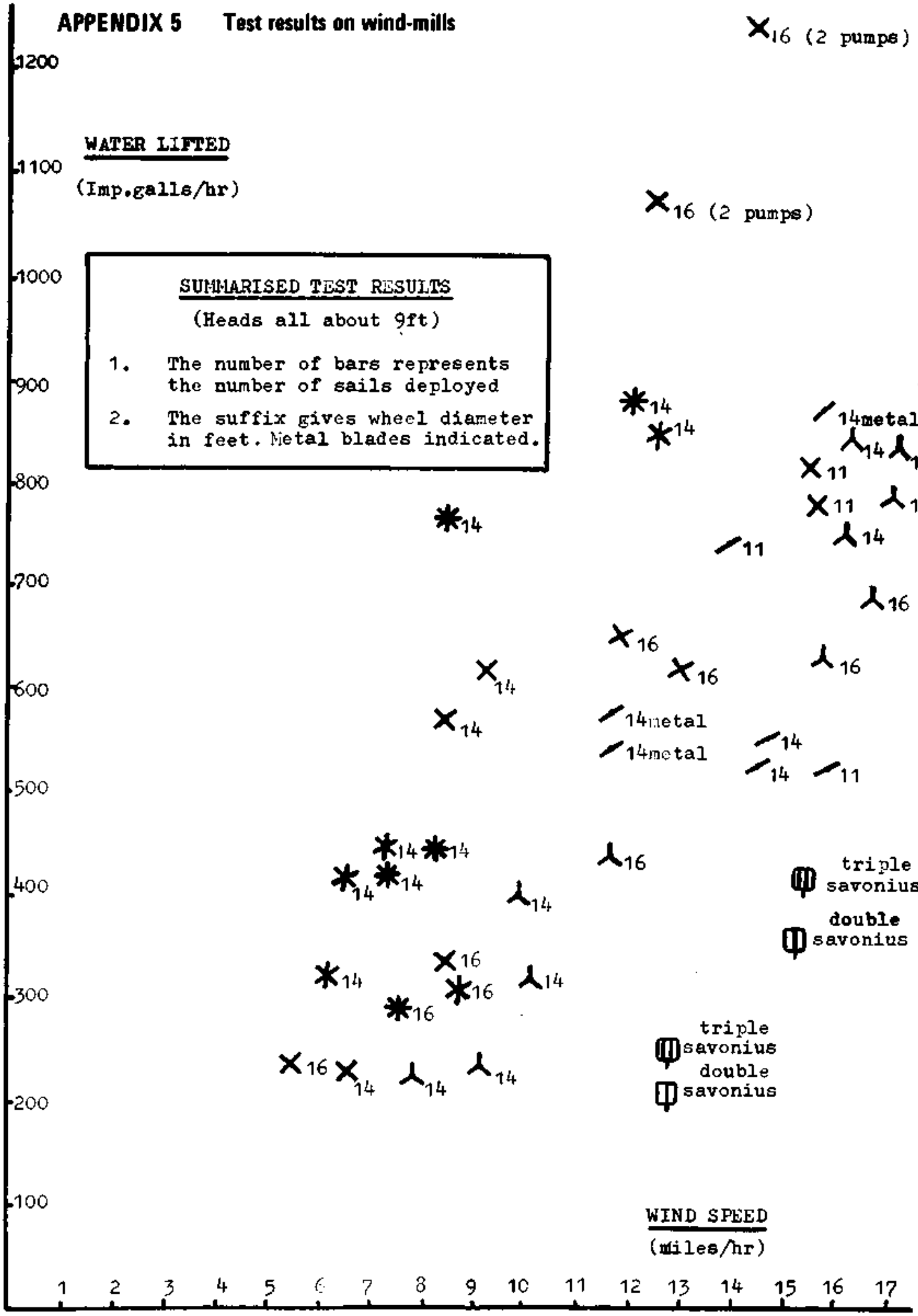
Korass, like Lohkwar, is easily discouraged by crop failure and needs encouragement, but he does recognise the value of his wind-mill and claims that a man with a wind-mill who works well need never be hungry.

6. Achao

Achao is the mission's handy man (and he happens to be Korass's younger brother). He has had no schooling, but has worked closely with Bob Swart for several years and learns quickly, so he is well able to assemble and paint wind-mills and he can dismantle and over-haul the pumps. He also helps new mill owners and as explained earlier, recorded the special cassettes they got. He has no wind-mill of his own, preferring his regular handy-man job, but his wife grows flood-land crops. He has a few sheep and goats and is buying a cow by instalments from Bob Swart.

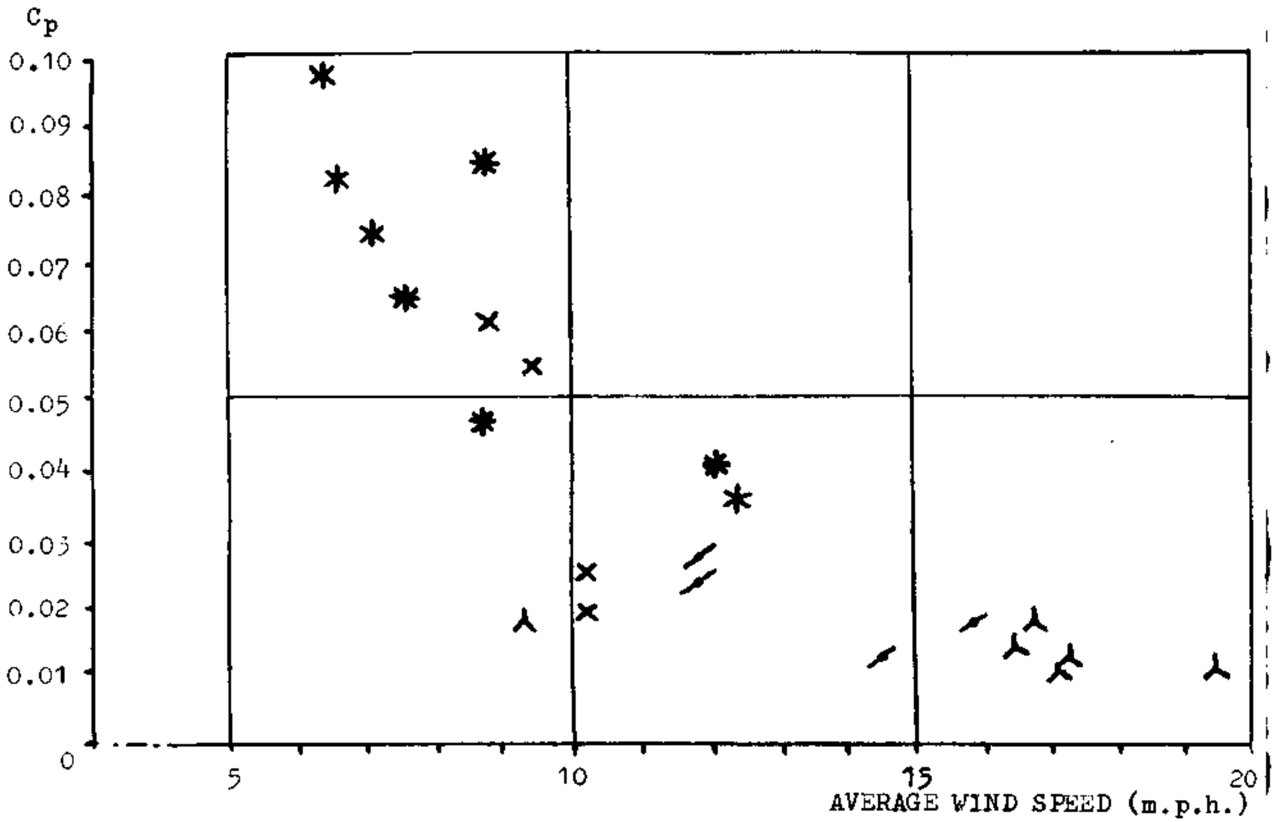
The graph on the right indicates the comparative pumping ability of various windmills of different diameters with different numbers of sails deployed. Also included are the results of tests on two and three-bladed Savonius Rotor windmills which demonstrate the poor performance of this type of device. The 16ft diameter mill driving twin pumps clearly out-performs everything else. The static head in all cases is quite low, being about 9 ft (2.75m). If these windmills were used for lifting water to a greater height, then the delivery would be proportionately less.

APPENDIX 5 Test results on wind-mills



VARIATION OF THE COEFFICIENT OF PERFORMANCE FOR 14ft WIND-MILL

Each star on the graph gives a measure of the overall system efficiency at a given average wind speed. The number of points on a star indicates the number of sails fitted for the test.



This graph suggests that the C_p (coefficient of performance) is influenced more by the wind speed than by the number of sails fitted - provided sufficient sails are fitted to give reliable operation.

The indications from this are that the following numbers of sails are appropriate with this size of wind-wheel (14ft):-

no.of sails	wind range
6 or 8	6 - 12 m.p.h.
4	8 - 16 m.p.h.
3	12 - 20 m.p.h.
2	16 - 30 m.p.h.

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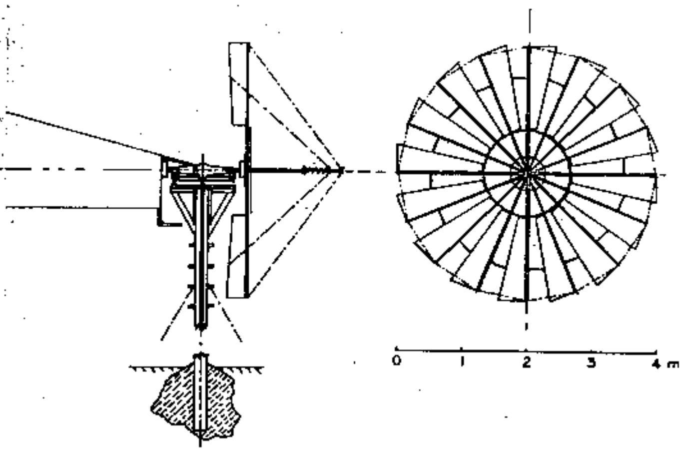
HOW TO BUILD A 'CRETAN SAIL' WINDPUMP

R.D.Mann



Low-cost Windmill for Developing Nations

multi-vane fan type HARTMUT BOSSEL

a VITA publication

HOW TO BUILD A 'CRETAN SAIL' WIND-PUMP

for use in low-speed wind conditions

by
R.D. Mann, A.I. Agr.E., M.L. Biol.,
Agricultural Officer
Gambia Christian Council
West Africa

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CONTENTS

List of plates *Page*

List of illustrations and tables

Introduction

At the end of 1974, the Gambia Christian Council started a small-scale village-level agricultural programme. The rains in the Gambia occur from mid-July to mid-October, and during the nine-month dry season there can be no field cropping without irrigation. The drought conditions from 1968 to 1977, when average rainfall decreased from 51.6 inches to 35.8 inches per year, caused a shortage in domestic food supply, and any method of producing food or cash crops in the dry season is of considerable value to the rural community.

The G.C.C. agricultural programme has consisted of introducing vegetable production on a planned basis, involving the use of livestock-proof fencing and the sinking of 4′ diameter concrete-lined wells at the rate of two wells per acre. The wells range in depth from 15′ to 35′, and all water extraction is by bucket and rope, the water being carried by hand to the vegetable plots. Each village project is planned for an area of one to two acres under vegetables each season, one acre being sufficient for 25 families.

At their current stage of development, this labour-intensive method of irrigation by hand is not a limiting factor to the success of these projects as the availability of water from October to May, together with improved methods of crop husbandry, are the most important inputs.

However, when one considers future development possibilities, and in particular the present need for tree-planting in all Sahelian and near-Sahelian countries, a mechanical means of water lifting could have far-reaching results in making such schemes feasible, and this has been the background thinking which prompted the development of the Gambia Christian Council Wind-Pump.

Meteorological Considerations

With reference to the wind frequencies given for three stations in The Gambia in Tables 1, 3 and 4, it will be seen that there is no wind for 27% to 36% of the time, wind speeds of over 12 miles per hour occur for only 3% to 9% of the year, and the balance of 61% to 64% of the time has wind speeds up to 12 miles per hour.

So for any practical use to be made of wind power, a windmill design is required which can start and operate in low wind speeds varying from 5 to 10 miles per hour.

Hydrological considerations

The river Gambia is tidal for a distance of 150 miles or more from the coast, and therefore water for irrigation can only be taken from the upper reaches of the river. The ground water level varies from 15′ to 80′, the deeper wells being mainly in the eastern end of the country.

Most dry-season vegetable growing areas are low-lying with water tables varying from 15′ to 25′, but their location would require a high windmill tower of 50′ to 60′ in order to reach the available wind. However, there are some areas, suitable for dry-season cropping, with a water table of no more than 20′ depth at the end of the dry season, and it was decided to build a windmill to operate a simple piston lift-pump.

Wind-pump design

The design was based on the information given in the ITDG publication, ***Food from Windmills,*** and from practical advice given by Mr Peter Fraenkel, ITDG Power Project Engineer, in September 1976. The design of the 'Omo' windmill, developed by the American Presbyterian Mission in Ethiopia, was studied in detail. The 'Omo' windmill worked mainly in a wind regime of speeds from 8 to 15 miles per hour, and it had problems associated with turntable rotation and directional stability of the wind-wheel into the wind. Since our winds are much lighter than those of the Ethiopian situation, it was decided to make the wind-wheel 16′ in diameter and with six arms to permit the use of two, three, four or six sails as required.

With reference to drawings A and B (given in Part 2) the drive shaft turns in three bearings, two of oil-impregnated hardwood, the rear bearing being a self-aligning ball-bearing which also takes the axial thrust. The adjustable crank permits pump strokes of 5⅞″, 7″ and 8⅛″ to be used. The pump is the same as used on the 'Omo' windmills; it is a 3″ diameter piston operating in a 16′ p.v.c. cylinder, and it is connected to the crankshaft via a universal joint. The turntable is fitted with four sealed roller-bearing units, which run on a ½″ wide, 12″ diameter bearing track.

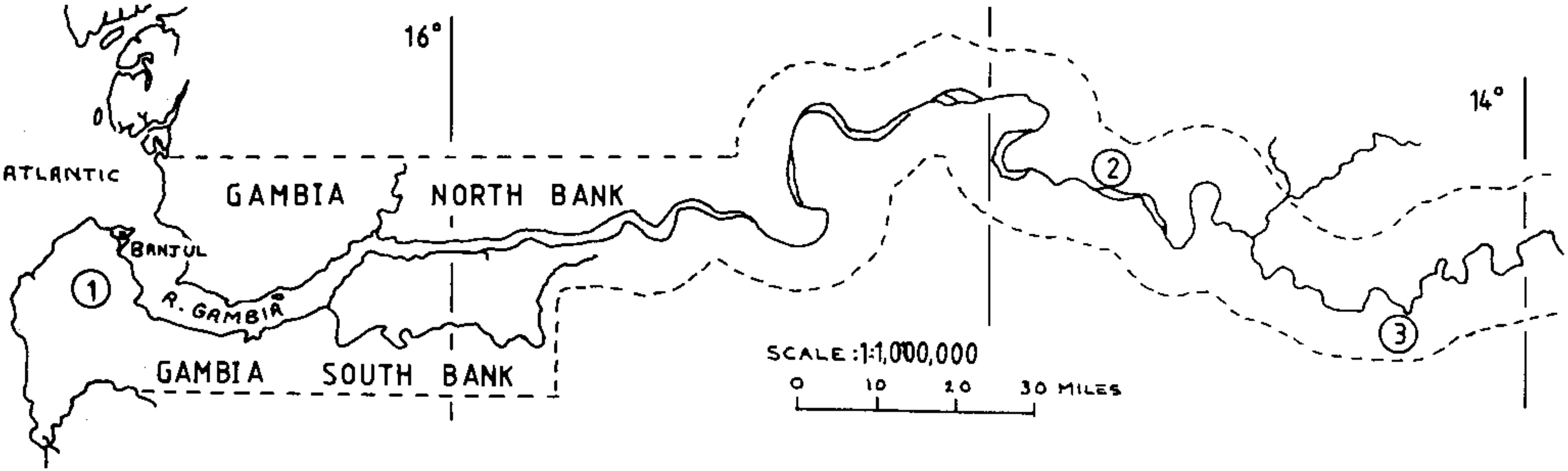


Table 1 Wind frequencies for site 1 at Yundum

WIND SPEED	J	F	M	A	M	J	J	A	S	O	N	D	Average
Calm	22	17	13	10	12	20	30	33	41	48	48	28	22%
1-12 miles per hour	70	71	71	72	73	66	61	59	55	50	50	66	64%
12-24 miles per hour	8	12	16	18	15	14	9	8	4	2	2	6	9%
Over 24 miles per hour	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 2 G.C.C. Wind-pump output on four selected days

Date:	Wind:	Test period	Less stops:	Net period	Height lifted:	Wind-run:	Gallons pumped
4.4.78	NE-NW	0830-1500	5 mins	6 hrs 25 mins	13' 4"	33 miles	1162 galls
5.4.78	NE-NW	0830-1804	67 mins	8 hrs 27 mins	13' 4"	49 miles	1937 galls
6.4.78	NW-NE	0830-1800	11 mins	9 hrs 19 mins	13' 4"	62 miles	3861 galls
7.4.78	NW	0830-1800	5 mins	9 hrs 25 mins	13' 4"	64 miles	3342 galls

Table 3 Wind frequencies for site 2 at Georgetown

WIND SPEED	J	F	M	A	M	J	J	A	S	O	N	D	Average
Calm	35	34	35	32	24	20	27	33	38	46	50	42	35%
1-12 miles per hour	58	61	60	65	71	75	70	64	60	53	49	53	61%
12-24 miles per hour	7	5	5	3	5	5	3	3	2	1	1	5	4%

Table 4 Wind frequencies for site 3 at Basse

WIND SPEED	J	F	M	A	M	J	J	A	S	O	N	D	Average
Calm	–	39	29	25	18	15	28	33	50	47	55	55	36%
1-12 miles per hour	–	55	66	73	78	80	70	64	49	52	43	41	61%
12-24 miles per hour	–	6	5	2	4	5	2	3	1	1	2	4	3%

The tail-fin has been built high in relation to its width to obtain maximum leverage in the wind-stream. The tail unit is of articulated design, with control ropes operated below the wheel to put the wheel into or out of the wind. The position of the tail-fin can be adjusted on the tail boom to obtain balance across the turntable bearings and so provide the best response to changes in wind direction.

The tower is three-cornered and made in three sections for ease of transport and erection. The tower feet have plates welded on to the bottom of the legs, and are sunk into the ground to a depth of 4'. When erecting the tower, a spirit level is held across the bearing track at the top, the position of the legs being adjusted in turn until the track is precisely level in all directions, and the holes are then filled in with tightly packed soil. The height of the tower is 23' from ground level to the bearing track.

The 'main' sails are made of heavy-duty marine canvas, and the 'starter' sails are lightweight cotton. The inner and outer sail corners are fitted with rubber loops (details of which are given in the construction data in Part 2), and it takes about six minutes to either fit or remove the sails.

The wind-wheel is provided with struts and perimeter-wire tension adjusters so that the wheel can be made quite taut, and thus any tendency of the wheel arms to flex during gusting winds is avoided.

As will be seen in the construction drawings in Part 2, the various windmill components can all be unbolted to allow for easy maintenance and modifications. After completing the workshop construction, all the mild steel parts are coated with a marine anti-corrosive paint to give long-term rust protection.

The construction of this prototype machine was carried out on a part-time basis, as and when other field duties permitted, in the Ministry of Agriculture engineering workshop at Yundum Experimental Station. The construction commenced in March 1977 and was completed by the end of September 1977.

Field testing

To facilitate testing, the wind-pump was sited adjacent to a 7½' deep concrete water reservoir tank at Abuko, 2½ miles from Yundum. The top of the tank was at ground level, and the total lift could be kept constant, the water lifted being measured in drums and then drained back into the reservoir.

There were a few scattered trees of up to 35' in height, but none within 100 yards of the wind-pump, and at 150 yards and beyond the tree-line was mainly oil-palm. The obstruction to wind-flow caused by this vegetation was considered to be fairly typical of that which would be found at other suitable pumping sites. Initial field trials were carried out in November and December 1977.

The wheel was first fitted with six large sails, all the same size, with the outer sail corners (corner C shown in drawing U) held by tight rubber loops to the outer sail hooks on the perimeter wires. With this arrangement there was no directional stability in wind speeds of 8 m.p.h. and above. The sail pattern was changed to three large sails, corners fitted as before, and this provided better wind-wheel stability and less sail-flapping.

During these first trials, the arms of the wind-wheel were not fitted with support struts. It was soon found that the wind-wheel was too flexible in gusting winds, and struts were then fitted to each arm which solved this mechanical problem and made the wheel completely rigid.

The tail boom design was also changed. The initial tail boom was made of 1" x 1" angle iron, 59" total length, but this allowed twisting of the boom and caused the tail-fin to shake under wind pressure. A new tubular tail boom was designed (as shown in drawing Q), and to counter-balance the extra weight of the struts on the wheel it was then possible to fit the tail-fin a further 7" away from the turntable.

The result of these alterations to the wheel and tail, together with the use of three large sails, was improved sensitivity to changes in wind direction, but there was still some sail flapping and the wheel would tend to over-run at wind speeds above 9 m.p.h. During sudden high-speed gusts, the back of the sails would occasionally hit the tower legs, and there was still the tendency for the wheel to move to the right-hand side around the tower as the speed of the wind and the wheel increased.

The large sails provided adequate sail area to drive the wheel, but during light winds the starting performance was poor. To provide more starting torque, three small-size sails were designed with a no-load 'angle of attack' to the wind of approximately 19°.

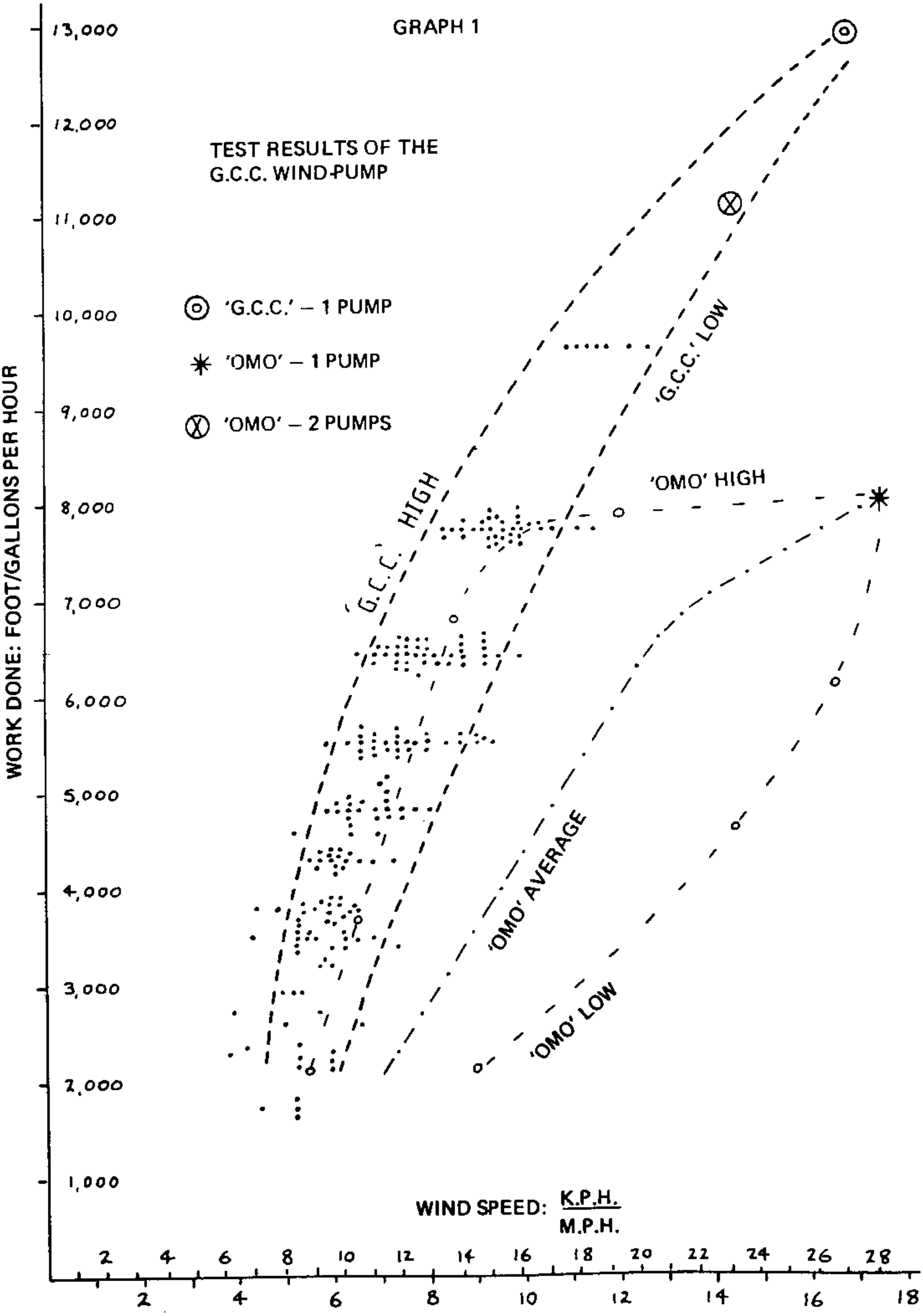
During uniform wind conditions, in February and March 1978, the sail arrangements of 3 'main' sails, 2 'main' sails and 2 'starter' sails, and 3 'main' sails with 3 'starter' sails were compared, and it was found that for a wind speed range of 5 to 10 m.p.h. the best overall performance was obtained with 3 'main' sails and 3 'starter' sails.

After further trials, it was found that sail flapping and any tendency of the main sail to hit the tower legs, could be completely eliminated by tying the leading edges of the sails tightly against the wheel arms, and a further considerable improvement in wheel rotation and pumping output was obtained by fitting lengths of rubber from the preceding wheel arms to the outer sail corners, full details of which are given in Part 2 under the section entitled 'Sails'. This provision of an elasticated connection on each sail trailing edge also had the effect of governing the wheel speed during high gusts, and thus prevented the wheel from over-running.

The final improvement involved counteracting the tendency of the wheel to swing to the right-hand side around the tower as the wheel-rotation speed increased. To do this, the boom catch (see drawing P) was released, and in the first instance the tail boom was tied in a position 10° to the left (looking forwards to the wheel). The tendency was now for the wheel to move progressively around the tower to the left-hand side; a final position of about 7½° to the left was then found to give the best directional stability of the wheel, and the boom was fixed in this position for the remainder of the trials.

For the pumping tests, two drums (each of 48.4 gallons capacity) with screw-type outlets at the bottom were placed on the reservoir wall. The pump inlet was connected via a 1½" diameter p.v.c. pipe to a 1¼" factory-made brass foot-valve placed in the water tank. The pump outlet was taken by a 1½" diameter p.v.c. pipe to the drums. Wind-run was measured by an integrating cup anemometer mounted on a pole at a height of 6½'.

With reference to Graph 1, the wind-speed was calculated from the time taken to fill a drum and the wind-run as shown by the anemometer at the commencement and completion of each drum-filling period. On some of the test days, the total lift (measured from the water reservoir surface to the pump outlet, vertically) was 13' 4", and on others it was 14' 1", so all output figures have been equated to foot-gallons for ease of comparison. The work done in foot-gallons per hour was calculated by noting the time required to fill each drum. As one drum was filled to the top, the


GRAPH 1
TEST RESULTS OF THE G.C.C. WIND-PUMP
'G.C.C.' – 1 PUMP
'OMO' – 1 PUMP
'OMO' – 2 PUMPS
WORK DONE: FOOT/GALLONS PER HOUR
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
'G.C.C.' HIGH
'G.C.C.' LOW
'OMO' HIGH
'OMO' AVERAGE
'OMO' LOW
WIND SPEED: K.P.H. / M.P.H.
2 4 6 8 10 12 14 16 18 20 22 24 26 28
2 4 6 8 10 12 14 16 18

outlet pipe was transferred to the other drum, the first drum being drained back into the tank, so that continuous recording could be carried out. Since it was intended to obtain a realistic picture of the pumping capability, the recording was not interrupted if the wind-wheel stopped turning for short periods during variable light winds, and all meaningful recorded figures have been included in the graphs.

Again with reference to Graph 1, a total of 196 separate drum-filling measurements have been plotted, together with 19 various-quantity output readings taken specifically to indicate performance at low wind speeds. The pump stroke used during these tests was $8^1/_8$''. The sail arrangement was changed for brief periods during the trials, but the majority of readings were taken using three 'main' sails and three 'starter' sails.

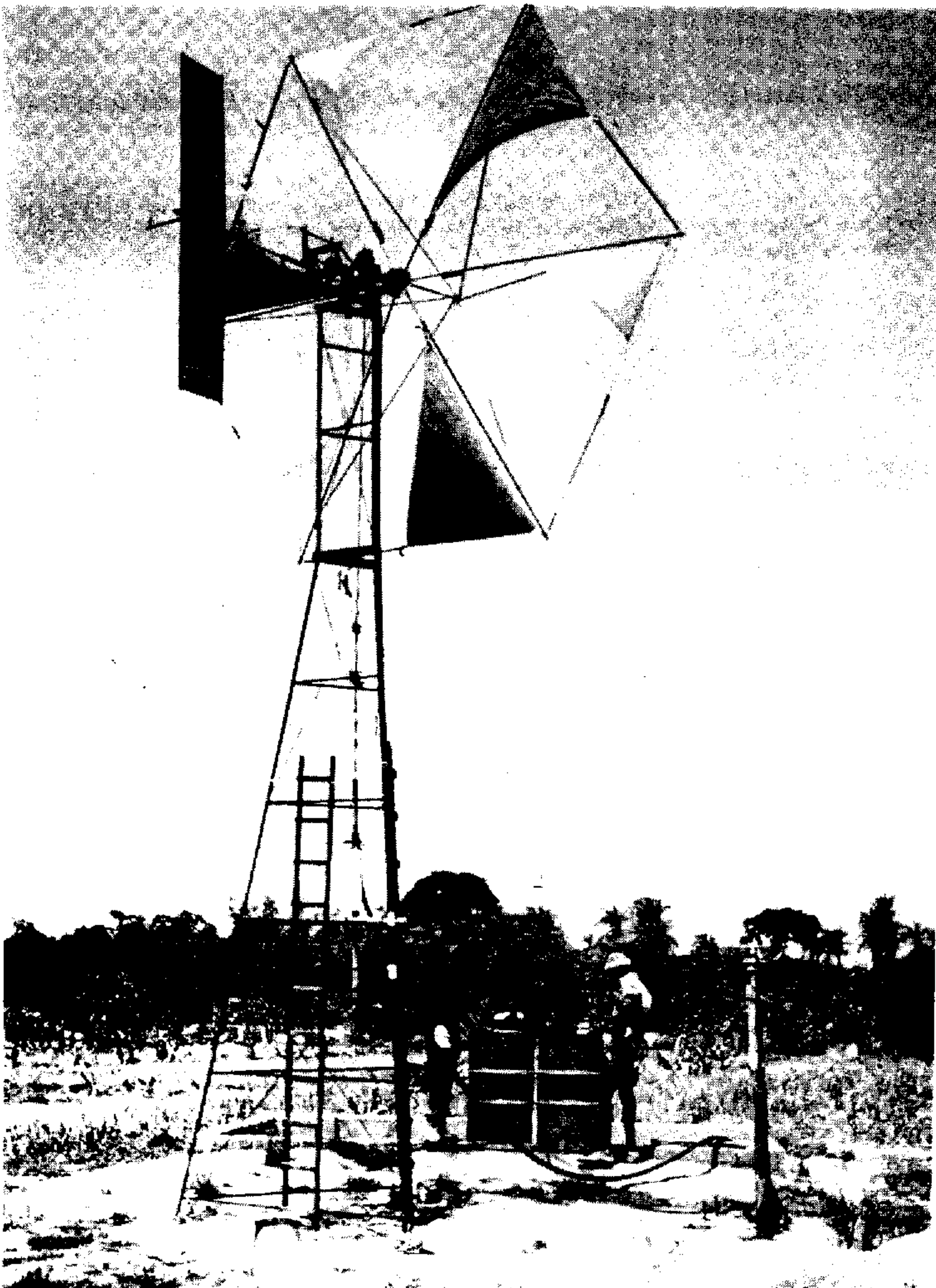
The pumping output of the 'Omo' windmills, as given in the publication ***Food from Windmills,*** has been put on the same graph for ease of reference, and it will be seen that the highest recording of the G.C.C. wind-pump (with a single pump) is greater than the output of the 'Omo' windmill fitted with two pumps.

The wind speed required to start the G.C.C. wind-pump from rest was calculated to be between 5.2 and 5.6 m.p.h., and once started the wind-wheel continued to run in a steady wind down to 4.5 m.p.h. The usual wind-speed range at Abuko was found to be 0 to 10 m.p.h., and the highest recorded wind-speed during the trials was 16.9 m.p.h.

The output obtained on four selected days is shown in Table 2, the 'net period' and 'wind-run' figures being inclusive of those periods when no pumping occurred due to insufficient wind.

Conclusions

1. The design arrived at in the G.C.C. wind-pump has produced a good pumping output under specific low-lift conditions at sea-level.
2. There is no visible adverse wear in the turntable bearings or on the bearing track after a period of 10 months.
3. Very little wear has occurred in the oil-impregnated shaft and big-end wood-block bearings, which appear to be both durable and suited to local construction.
4. The universal-joint design appears to be mechanically sound; providing it is lubricated properly it should last for a while.
5. The safety straps and rollers which were subjected to buffeting during initial sail trials, show no signs of distortion.
6. The track guides function well in facilitating turntable rotation, but in future models they should be located on the other side of the bearings to slide round the inner track ring, so that wear will occur only on the easily replaceable inner ring.
7. Four bearings for the turntable are not required, three being quite sufficient, placed 120° apart, and the bearing load will then be equalised. This modification should be made on all future machines.
8. The $1^3/_8$'' diameter drive shaft has shown no sign of fracture or bending, but it would be better to use a 1½'' diameter shaft for this size of wind-wheel.
9. The marine canvas and light-weight cotton used for the sails have not shown serious wear so far, but these materials will not last very long and the sails should be made of a yacht-sail material such as 'Dacron' to provide a good life under constant use.
10. The articulating tail boom design is not essential when the sails can be easily fitted and removed each day, and it is considered better for economy if this complex mechanism is omitted. Future designs should allow the boom angle to be adjusted while tests are carried out to obtain the best directional stability, following which the boom can be bolted in position and a rope left hanging down from the boom to pull the wind-wheel out of the wind when removing the sails.
11. The total cost to build this prototype wind-pump amounted to D2,400-00 for materials. (Note: D4-00 = £1.00.) On a local production basis, the cost of labour might be about D600-00, which would give a total of D3000-00 per machine. This figure compares favourably with the price of approximately D10,000-00 to import a comparable wind-mill from the U.K.
12. The G.C.C. wind-pump has so far lifted water a height of only 14 feet. The maximum height that water can be raised using a lift-pump is not much more than 21 feet, and this limits the use of a lift-pump to riverside pumping and those few places with ground water near the surface.
13. In view of the point made in 12, above, further testing of the G.C.C. wind-pump will include trials with a force-pump to see if it can lift water to a height of 45 feet, and if this is possible it may have a wider application for village level development.



The erected wind-pump in action.

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We also remember, with appreciation, Rev. C. Awotwi Pratt, Chairman of the Methodist Mission, who gave approval for expenditure of Mission funds at the commencement of the project, and are also grateful for subsequent contributions towards the project costs by the Ministry of Economic Planning in Banjul and the Commonwealth Secretariat in London.

R.D. Mann, A.L. Agr. E., M.I. Biol.
Agricultural Officer,
Gambia Christian Council.

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CONSTRUCTION DETAILS

INDEX

Notes

i. In the attached drawings, adequate construction detail is provided of all the wind-pump components, but it must be noted that certain items are omitted from particular drawing views, where clarity of the described part is required.

ii. All angle iron referred to in the construction description is of ¼" web thickness except where otherwise stated.

Note: The item numbers referred to throughout the following text are shown as circled numbers on the drawings attached.

A.1. Turntable Frame

Refer to drawings C,D,E, and O.

1. Cut 2 lengths of 1½" x 1½" angle, item 1, 36¾" long. Drill ½" diameter (9/16") holes, items 2a, at one end of each frame side piece, remembering that one is left-hand and the other right-hand, and also drill the bearing-box bolt-holes 3/8" diameter (7/16"), item 3.

   At a point 9½" from the other ends of item 1 cut 'V' notches of 47°, bend upwards, and weld each at 45° angle.
2. Cut 2 pieces of 1½" x 1½" angle, item 4, 10¾" long, and drill the bearing-box bolt-holes 3/8" diameter (7/16"), item 5, in each.
3. Weld items 4 to items 1 to form the frame bed.
4. Cut 2 pieces of 1½" x 1½" angle, item 6, 4" long, as legs for the rear bearing support.
5. Cut 2 pieces of 1½" x 1½" angle, item 7, 6" long, as legs for the middle bearing support.
6. Cut 1 piece of 1½" x 1½" angle, item 8, 10¾" long, and 2 pieces of 1½" x 1½" angle, items 9 and 10, 11¼" long, these pieces to be slightly oversize in length to provide a jam-fit assembly to facilitate welding.

   In the rear bearing support, item 10, drill holes of diameter and spacing to suit the rear bearing selected. ***Note: for this prototype wind-pump, a self-aligning ball-bearing complete with grease-packed housing was used.*** In the downwards leg of the angle, item 10, three holes of ½" diameter, item 11, must also be drilled for the tail boom control ropes to pass through. In the middle and front bearing supports, items 9 and 8, drill ½" diameter (9/16") holes, item 12, 4" apart.
7. Weld the rear legs, item 6, in place; then jam-fit item 10 between the rear legs with upper surface of the angle at 2¼" from upper edge of main frame sides and inclined upwards/forwards at 5° as shown in drawing C. Weld in position.

   Note: a 5° inclination is obtained by a 1" vertical rise over a length of 12".
8. Weld the middle legs, item 7, to the main frame sides. Jam-fit item 9 between the middle legs, also inclined at 5° upwards/forwards in line with the upper surface of the rear bearing support, item 10, and weld in place.

   Similarly, jam-fit item 8 between the foremost part of the frame side pieces, at 5° inclined upwards/forwards with its upper surface in line with the rear and middle bearing supports, and weld in position. ***Note: the drive shaft is inclined upwards at 5° to ensure that the wind-wheel and sails have adequate clearance from the tower.***

A.2. Turntable Bearings

Refer to drawings, F, J, and K.

1. Cut a piece of 2″ x ¼″ flat mild steel, item 13, 6″ long, and drill bolt holes, item 14, $^3/_8$″ diameter.
2. Cut a piece of 2½″ x 1½″ box section, item 15, cut away both sides at one end by ½″ depth as shown, and drill a $^5/_8$″ diameter hole through the box to take the bearing bolt, item 16.
3. Weld the box, item 15, to the flat plate, item 13.
4. Cut a piece of 1¼″ x ¼″ flat mild steel, item 17, 2¼″ long and drill a $^5/_8$″ diameter hole in it for the bearing bolt. ***Note: this piece acts as a guide to prevent the bearings moving sideways off the turntable bearing track.***
5. For this prototype machine, a sealed bearing, item 18, was used, of 2″ outer diameter, $^9/_{16}$″ wide, with $^{13}/_{16}$″ inner bore diameter.

   The bearing was fitted on to the $^5/_8$″ diameter bearing bolt, item 16, on a pipe sleeve, item 19, with distance piece, item 20, made of pipe, and distance washers, items 21 and 22, either side of the track guide, item 17.

Notes:

(a) the actual thickness and position selected for the washers and distance piece must be such as to locate all four turntable bearings precisely on the ½″ wide turntable bearing track within an accuracy of plus or minus $^1/_{16}$″ sideways.

(b) the turntable safety straps and rollers, which bolt on beside each turntable bearing, are discussed in the tower head section below as they are related to the safety ring fitted in the tower.

A.3. Wind-wheel Drive Shaft

Refer to drawings C and G.

1. The crankshaft is made in 3 sections, the front shaft, item 23, the crank, item 24, and the rear shaft, item 25. All three parts are made of ¾" inner diameter galvanised steel pipe of such outer diameter that it can be lightly force-fitted, using a heavy wooden mallet, inside 1" inner diameter galvanised steel pipe, the result being a thick-walled hollow shaft and crank journal of 1³/₈" outer diameter.
2. Cut the front shaft, item 23, to a length of 17¾".
3. Cut the rear shaft, item 25, to a length of 12¼".
4. Cut the crank journal, item 24, to a length of 5".
5. Cut 2 pieces of 2" x ¼" flat mild steel, item 26, 7" long; drill the two ½" diameter holes accurately; mark and punch the centre of each piece and scribe a circle round the centre of 1½" diameter to facilitate alignment during welding.
6. Make up a jig out of angle iron to support both the front shaft, item 23, and the rear shaft, item 25; bolt the crank-bolt plates, item 26, together, with the scribed circles facing outwards; draw the front and rear shafts together to butt against both sides of the bolted plates, and having aligned the shaft ends within the scribed circles, weld the shafts to the crank-bolt plates.
7. Cut 2 pieces of 2" x ¼" flat mild steel, item 27, 9" long; drill the six ½" diameter holes, item 28, accurately in each piece; mark and punch the centres where the crank journal is to be welded and scribe a circle 1½" diameter around each centre point.
8. A big-end bearing of 1½" width and 1½" diameter was selected for this machine, and to ensure its correct location on the journal, 4 flat washers, item 30, and a phosphur-bronze bush, item 31, were fitted on to the journal with ¹/₈" diameter split pins provided behind the outer washers.
9. Using the same jig as referred to in 6 above, bolt the crank-bolt plates with shafts, item 26/25 and item 26/23, to the crank arms, item 27; position the crank journal item 24, complete with fittings, accurately within the scribed circles (a large G-clamp is useful to clamp the pieces together) and weld the crank journal to the crank arms.

Notes:

(a) alignment of the shafts is not easy, but the jig will help together with careful welding, and the alignment between front and rear bearings should be accurate to within ¹/₁₆".

(b) the front shaft flange is discussed in the section on the wind-wheel as it is related to the wheel hub.

A.4. Crankshaft Bearings

With reference to drawings C and H, the front and middle crankshaft bearings are made as follows:

1. Obtain a hardwood, remembering that the greater the density the better the bearing life (bearings on this machine were made of 'Mampato', a West African tree harder than 'African Mahogany').
2. For each bearing, cut 2 blocks, item 32, each 2" x 3" x 6" but oversize by 1/16" in 3" to allow for shrinkage.
3. Clamp the blocks together in pairs; drill the shaft hole, item 33, 1 7/16" diameter (to allow for shrinkage), and holes 9/16" diameter for the securing bolts, item 34; punch mark the blocks in pairs on adjacent faces before unclamping.
4. Half fill a 5 gallon drum with used engine oil. Place the wooden blocks in the oil with a weight on top to keep them submerged. Heat the oil steadily, observing the moisture release from the blocks indicated by the air bubbles rising to the oil surface. When the bubbles have reduced in size to that of a pin-head, remove the fire, and leave the oil and blocks to cool overnight. Remove the blocks after 24 hours when they will have absorbed all the oil they can hold.
5. Make the bearing bottom plate, item 35, of 6" x 3" x ¼" mild steel; drill bolt holes 9/16" diameter. The bearing top plate, item 36, is of 6" x 3" x 1/8" mild steel, drilled with two 9/16" bolt holes and a central hole for fitting the screw-type grease-cup, item 37. Drill a grease hole 1/8" diameter in the upper bearing block leading to the bearing surface.
6. The grease-cup can be welded on to the top plate, item 36, or threaded into the upper bearing block. When fitting the wood-block bearings on to the shaft, use shims between the blocks for initial running-in rather than trying to enlarge the bearing surface if it is found to be tight.

Note: The rear shaft bearing, item 38, is a factory-made self-aligning ball-bearing, complete with grease-packed housing, and it is levelled with the shaft by inserting distance pieces and/or shims between the housing and support. This bearing is of 1½" internal diameter and is locked on to the 1 3/8" shaft by a tapered screw-sleeve, which then takes the axial thrust from the wind-wheel.

B.1. Tower Head

Refer to drawings I, J and K.

1. Cut 3 pieces of 1½" x 1½" angle, item 39, 24" long with 30° angles at each end, and weld together to form an equilateral triangle.
2. Make two circles from 1" x ¼" flat mild steel, one of 12" inner diameter, item 40, the other of 12½" inner diameter, item 41, so they will fit one inside the other to provide a ½" wide bearing track of 13" outer diameter. When joining the ends of the 1" x ¼" mild steel, they must be cut to make 'V' notches on both sides, welded accurately, and then filed smooth on all surfaces.
3. Place the track, item 40/41, centrally on top of the triangular frame, and take measurements for cutting the 3 track support struts, item 42, from 2" x ¼" flat mild steel, such that these struts will project inwards beyond the inner edge of the track by not more than 3/8" (to ensure that safety straps do not touch the struts as the turntable rotates). Weld the struts, item 42, in place with their upper surfaces level with the upper surface of the triangular frame.
4. Cut 9 pieces of 1¼" x 1" x ¼" mild steel, item 43, and drill a hole of 3/8" diameter centrally in each. Place these pieces symetrically around the track with 3 of them central on the support struts and the other 6 equidistant at 60° apart as shown in drawing I. Weld all 9 pieces, item 43, to the outside face of the outer track ring, item 41.
5. Punch mark centrally through each of the 3/8" diameter holes in the track legs, item 43, on to the triangular frame and the support struts; remove the track and drill each point to 7/16" diameter.
6. Weld 3/8" diameter studs, item 44, into each of the track legs, item 43, and the track can now be bolted down on the frame.
7. Make another circle from 1" x ¼" flat mild steel, of 12" inner diameter, for the safety ring, item 45.
8. Cut 3 safety ring support legs, item 46, of 1¾" x 1¼" x ¼", and drill each with a 7/16" diameter hole.
9. Cut 6 distance pieces of 1" x 1¼" x 3/8", item 47, and 3 distance pieces of 1¾" x 1¼" x 1/8", item 48; drill 3/8" diameter holes in the latter.
10. Turn the head-frame upside down, bolt the legs, item 46, and the distance pieces, item 48, on the support strut studs; place the distance pieces, item 47, symetrically on the head-frame sides, and accurately position the safety ring, item 45, in line vertically with the inner track ring, item 40. Weld the safety ring on to the 3 legs and 6 distance pieces.
11. The safety straps with rollers, item 49 are made and fitted as follows: Assemble the turntable and bearings, and place this unit on the turntable track. Make 4 roller units, each consisting of a 1½" length of ¾" outer diameter galvanised pipe placed on a ½" diameter bolt, the end of the latter being welded on the 1½" x 1¾" x ¼" roller plate as illustrated in drawing K. Make 4 safety-strap legs of 1" x 3/16" flat mild steel, drilled to fit on the bearing-box bolt, bent at 90°, ensuring that the legs are sufficiently far out not to catch on the head frame as the turntable rotates. Bolt each safety leg on one side of each bearing box; clamp the roller unit on to the lower end of the leg, leaving 1/8" clearance between the roller and safety ring, and weld together.

B.2. Tower Upper Section

Refer to drawings A and L.

1. Cut 3 pieces of 1½'' x 1½'' angle, item 50, 78'' long, for the tower upper-section legs.
2. Cut 6 pieces of 1½'' x 1½'' angle, item 51, 24'' long, with 30° angles at each end, and weld up 2 triangular frames; one frame is used as the tower upper-section, 'bottom frame', the other as the 'top frame' of the tower middle section. Clamp these two frames together face to face, and drill 6 holes, $^{9}/_{16}$'' diameter at the spacing shown, for the attachment bolts.
3. Cut 3 pieces of 1'' x 1'' angle for lateral reinforcement, item 52.
4. Place the legs, item 50, at right angles inside the corners of the head frame, item 39, and the 'bottom frame', item 51, and weld all round. Weld the lateral members, item 52, inside the tower legs. On each of the 3 sides of the tower, ¼'' diameter reinforcement rod, item 53, is welded on to the outside of the frames and the lateral members to provide diagonal strength.

B.3. Tower Middle Section

Refer to drawings L,M and N.

1. Cut 3 lengths of 1½" x 1½" angle, item 54, 120½" long, for the middle-section legs, and 3 lengths of 1½" x 1½" angle, item 55, 130½" long, for the lower-section tower legs. Drill $^9/_{16}$" diameter holes on alternative sides of each leg for the ½" diameter attachment bolts (i.e. 2 bolts per leg) at the spacing shown, so that the middle-section legs overlap outside the lower-section legs when bolted together.
2. Place 2 middle-section legs, item 54, inside 2 corners of the 'top frame' (already constructed in B.2. 2. above) with the legs 55¼" apart measured between inside corners of the angle at the lower ends. Support the 'top frame' in a position of 7° away from perpendicular to the common plane of the two legs (to obtain the right inclination of the tower legs), then weld the legs to the frame.
3. Cut 3 lateral members, items 56a, 56b and 56c, of 1" x 1" angle, of the length required to fit in the positions indicated, and weld them inside the legs.
4. Complete the other two sides of the tower by welding the 3rd tower leg inside the 'top frame', with the other two lateral members, item 56c, in position to obtain the correct inclination of the tower leg, followed by welding the other lateral members, items 56a and 56b inside the angle legs.
5. Diagonal strength is obtained by welding ¼" diameter reinforcing rod, item 53, to the outside of the 'top frame' legs, and lateral members, on all three sides, in the positions shown.

B.4. Tower Lower Section

Refer to drawings M and N.

1. Lay the middle-section of the tower on its side, with blocks to hold it off the ground throughout its length by 2".
2. On to the middle-section legs, bolt 2 of the lower-section legs, item 55.
3. Fit a piece of 1" x 1" angle for the bottom lateral member, item 57a, between and inside the legs so that the outer width measurement at this point is 76".

   Note: the legs of the lower-section are splayed outwards by 2" each at the bottom to provide additional tower stability, and the bottom lateral must be fitted first.

4. Weld lateral member, item 57a, in position first, then fit and weld lateral members, items 57b and 57c.
5. Bolt the 3rd lower-section leg on to the middle-section. Cut 2 more bottom lateral members, item 57a, and weld in position, followed by the remaining lateral members, items 57b and 57c.
6. Unbolt the lower-section from the middle section; weld on to the legs and the lateral members ¼" diameter reinforcement rod, item 53, for diagonal bracing, in the positions shown, on all 3 sides.

   Note: the upper ends of the diagonal bracing must be welded inside the legs.

7. Weld a piece of 4" x 4" angle, 12" long, item 58, on to the bottom of each lower-section leg. This will allow the wind-pump tower to be erected in compacted soil without any need for concrete tower footings.

C. Tail Unit

Refer to drawings O,P,Q and R.

Note: The actual method of fabricating the tail unit is not critical, but the construction detail for this unit is given in full, since from this description many alternative designs will become apparent. The important points are:

- i. to make the tail boom last as long as possible, without causing imbalance of the turntable unit, to obtain maximum leverage,
- ii. to make the tail of lightweight material to allow the use of a long boom,
- iii. to make the tail fin high in relation to its width, so that it confronts a greater cross-section of the wind-power for leverage, and,
- iv. to provide some means of varying the horizontal angle between the tail fin and the wind-wheel to allow for experiment during trials to obtain the best directional stability.

With reference to the drawings provided, the tail unit on this machine is designed with a pivoting boom, operated by control ropes which lead down within the tower frame, for pulling the wind-wheel into and out of the wind. It is constructed as follows.

1. Make up a rectangular pivot-frame, item 59, of 1½" x 1½" and 1" x 1" angle, with attachment legs, item 60, of 1½" x 1½" angle, and brace pieces, item 61, 1" x ¼" flat mild steel. The braces, item 61, are attached with ⅜" diameter bolts at their upper ends on to the pivot-frame, and their lower ends are held by the left- and right-hand bearing bolts. The legs, item 60, are attached with ½" diameter bolts, item 2b, through the bolt holes, item 2a, at the back of the turntable frame, item 1.
2. Two pairs of ½" diameter pivot holes are drilled in the top and bottom members of the pivot-frame, one pair on the centre line and the other pair 3" offset to the right. ***Note: only the pair of offset holes were used for the boom pivot in these trials.*** Additional pivot-pin bearing-support surface is provided by welding drilled support pieces, item 62, of ¼" thick mild steel, inside the upper and lower angle members. Before assembly, a ⅜" diameter hole is drilled in the right-hand leg to take the boom stop-arm bolt, item 63; and the right-hand end of the lower angle is cut away as shown at 64a. The pivot-frame and legs are then welded together.
3. The boom stop-arm, item 64b, is made of 1" x 1" angle, 15" long. It carries the 'starting' pulley and its bracket, item 65a, the boom-stop, item 66a, and spring-loaded boom-catch, item 66b. The 'stop' pulley, item 65b, is bolted to the left-hand vertical member of the pivot-frame. The pulley attachment bolts are ¼" diameter. The tail control-ropes roller, item 66c, is fabricated of ½" galvanised pipe with washer-flanges brazed on each end, running on a ⅜" diameter bolt, and with legs, of ¾" or ⅛" mild steel attached on the turntable rear-bearing bolts. A rope guard, item 66e of ¼" diameter steel rod is welded across the roller arms to keep the ropes in place.
4. The holes, item 11, through the rear crank-shaft bearing-support, item 10, have pieces of rubber pipe inserted into them to prevent undue wear on the control ropes. Rubber, ⅛" thick, is wrapped around the contact surface of the boom-stop, item 66a, to provide a cushioned effect for the catch mechanism.
5. The tail control ropes, item 66d, are made of 3/16" diameter nylon. The boom-catch rope is attached at the end of the catch. Both the 'start' and 'stop' ropes are tied onto the boom-frame vertical member, item 67a, just below the catch position. A strong strip of vehicle-tyre inner tube, of 2" x ⅛" section, is wrapped several times around the left-hand ends of the upper and lower angle members of the pivot-frame, item 59, to act as a stop for the boom-frame when the wind-wheel is put out of the wind.
6. The tail-boom, item 68a, is made of 1" outer diameter galvanised pipe, 69½" long. To facilitate the attachment of the tail fin and boom-frame, thin-wall (1/32") square-section mild-steel box pieces, items 68b and 68c, of 1" x 1" internal measurement, are coated inside with anti-rust paint, then push-fitted over each end of the boom pipe, and brazed in place.
7. The foot of the boom-frame vertical member, item 67a, of 1" x 1" angle, is attached by a ⅜" diameter, item 67b, of 1" x 1" angle, has a bracket, item 67c, also of 1" x 1" angle, welded at the rear end, to take the ¼" diameter tension bolt, item 67d, for the ⅛" diameter galvanised brace-wire, item 67e. A hole is drilled into the top of the boom, 11½" from the end, to take the ¼" diameter anchor-hook, item 67f, for the brace-wire.
8. The horizontal member, item 67b, and the front end of the boom, item 68c, are drilled in line to take the ½" diameter pivot-pin, item 67g, the latter being provided with washers and split-pins top and bottom. The horizontal member, item 67b, and the vertical member, item 67a, are joined by welding, and a drilled support-piece, item 67h, is welded on top of the horizontal member (with the pivot-pin in place for alignment) to give added bearing surface against the pivot-pin at this point. Washers are also placed on the pivot-pin between the pivot-frame and the boom-frame.
9. A ½" diameter coil-spring, item 69a, of suitable strength, is held at its front end by the leg, item 69b, attached to the right-hand pivot-frame bolt, item 2b, and at the other end to the leg, item 69c, bolted to the boom. This spring provides an over-centre action to assist the boom in its travel towards the boom-catch when the 'start' rope is pulled.
10. Tail fin position-adjustment holes of ⅜" diameter, at 2" spacing, are drilled in the boom end, item 68b. The tail fin, item 70a, made of 3/16" thick plywood, 96" tall by 18" wide is attached by 3/32" diameter bolts within the frame, item 70b, of ½" x ½" x 1/16" mild steel angle, the latter being brazed together. Cross-pieces, item 70c, each made of 2 pieces of ½" x ½" x 1/16" angle, are brazed inside the other (after first coating internal surfaces with anti-rust paint) for added strength, and each cross-piece is brazed to the side of the frame.
11. Four pieces of ½" inner diameter lightweight pipe, item 70d, each ½" long, are brazed one to each corner of the frame; these pipe rings facilitate attachment of the 1/16" diameter galvanised bracing wires, and have rubber inserts to prevent wear on the wire at these points. Metal hooks, item 70e, of ¼" diameter reinforcing rod, are brazed to the outer ends of the cross-pieces, to take the bracing wires, item 70f, fitted from top and bottom of the tail fin, and also the bracing wires, item 70g, fitted across and diagonally between the cross-pieces.

    To obtain sufficient tension on the bracing wires, item 70f, simple tension adjusters, item 70h, are made with a 3/16" diameter eye-bolt and a foot-piece of ½" x ⅛" section mild steel as illustrated.
12. To give extra rigidity to the connection between the tail fin and the boom, support pieces, item 70i, of 1" x ¼" flat mild steel, are placed both sides of the tail fin and bolted together through the plywood with ¼" diameter bolts; the two support pieces on the right-hand side (those illustrated in the side view in drawing Q) are 8" long, and those on the other side are 23" long.

    The boom is connected to the tail fin assembly by two ⅜" diameter bolts, item 70j, which pass through the centre points of the supports pieces, item 70i.

D. The Wind-wheel

Refer to drawings S,T and U.

1. Cut 2 pieces of ¼" thick mild steel plate with 6 sides, 8" across flats; drill 12 bolt holes of 7/16" diameter at the spacing indicated, clamping the plates together to ensure alignment, and a ¾" diameter hole through the centre of both plates. One of these plates is the shaft flange, item 71a, and the other plate is the wheel hub, item 72a.
2. A ¾" length of ¾" outer diameter galvanised pipe, item 71b, is pushed into the centre hole, and welded flush with the rear surface, of the shaft flange, item 71a; this acts as a location stub when fitting the wind-wheel in place. The shaft flange, item 71a, is then welded centrally on the end of the front shaft, item 23.
3. Shaft flange reinforcement is provided by 6 triangular webs, item 71c, of 1½" x 2" x ¼" mild steel; a 1½" long piece of mild steel pipe is first cut lengthwise into two halves, placed together on the front shaft behind the flange and welded tightly along the lengthwise joints and at the front edge to the flange rear face; the 6 webs are then welded to the pipe sleeve and to the flange, with light tack welds to reduce distortion.
4. Weld a 1" length of 1" inner diameter galvanised pipe, item 72b, centrally on the front of the wheel hub, item 72a.
5. The wheel centre-shaft, item 72c, is made of galvanised pipe; an 18" length of ½" inner diameter pipe is force fitted a distance of 7" inside a 22" length of ¾" inner diameter pipe, the end of the latter pipe being inserted into the socket, item 72b, and both these joints welded.
6. The strut adjuster, item 72d, made of ¾" inner diameter pipe, 2½" long, is made to slide fit on the front end of the wheel centre-shaft, and is secured by a ¼" diameter split-pin through one of the 5 adjustment holes provided in the shaft at ¾" spacing. Six eyes of ¼" diameter reinforcing rod are welded around the strut adjuster.
7. The 6 wheel arms, item 72e, and the 6 wheel struts, item 72f, are made of 5/8" inner diameter thin-wall galvanised conduit pipe. Each wheel arm, item 72e, is flattened at the inner end over a distance of 4" to 5", bent at this point by 3° forward, and drilled with two 3/8" diameter holes for the attachment bolts, item 72g.
8. The outer end of each arm is threaded, and carries a ½" length of pipe coupling, on to which a loop of ¼" diameter reinforcing rod is welded to form an anchor, item 72h, for the wheel perimeter-wire, item 72i. Each arm also carries 4 hooks, 2 for sail attachment, one for brace-wire attachment, and the other to take the wheel strut. All hooks are of the same design, being made of ¼" diameter steel rod, welded on to a 1 1/8" length of thick-wall mild steel pipe of such diameter to be a slide fit on the wheel arm. Each hook unit is fastened by a 3/32" diameter steel pin through the hook pipe and wheel arm. The sail corner and inner hooks project sideways from the arm, while the strut and brace-wire hooks project forward from the arm.

***Note:** to facilitate bolting the struts to the arms, the strut hooks should be in the form of an eye.*

9. Between the corner sail-hook, item 72j, and the perimeter-wire anchor, item 72h, a ¼" diameter hole is drilled sideways through each arm to take a ¼" diameter steel adjuster-hook, item 72k, complete with lock nuts. The end of each perimeter-wire is attached to its own adjuster-hook on the preceding arm.
10. A wheel strut, item 72f, is provided on each of the 6 wheel arms. Each end of the strut is slotted and drilled to take 3/16" diameter bolts to secure it to the strut hook on the wheel arm and to its corresponding eye on the strut adjuster.
11. The 6 wheel perimeter-wires, item 72i, are made of 1/8" diameter galvanised mild steel wire. The outer sail hooks, item 72l, are made of ¼" diameter reinforcing rod with an eye at one end through which the perimeter-wire passes in the form of a loop to hold the hook securely. The outer sail hooks are positioned 56" from the anchor loop to the bend of the hook, and the hook shank is bound to the perimeter-wire with 1/16" diameter galvanised wire to hold it rigid.
12. When the perimeter-wires have all been fitted to their anchor points and to the adjuster hooks, the adjuster nuts are progressively tightened in turn around the wheel until all slack in the strut connections is taken up and the perimeter-wires are quite taut. After tightening, the wheel arms should be approximately 3° forward of the plane of the wheel hub. The brace-wire, item 72m, also of 1/8" diameter galvanised mild steel wire, is then wound around each brace-wire hook, item 72n, from one arm to the next, tightened by hand, to prevent sideways movement of the arms.

E. Sails

Refer to drawings B and U.

1. The 'main' sails, item 73, are made from heavy-duty marine canvas, with a 1" wide hem, in which 3/16" diameter nylon rope is placed, on all three sides. These ropes are tied tightly through the edge of the canvas at each corner, so that the sail cloth cannot slide back on the ropes under wind pressure. If the cloth corners are not secured to the ropes in this way, the sail shape will alter under wind-load, thus reducing the efficiency of the sails and the pumping output will be reduced.
2. Corner A of the main sail has a short loop of rope to go on the corner sail hook. Corner B has a tight loop of rubber (lorry type inner tube) of ¾" x 1/8" section to fit on the inner sail hook. Two rope ties, of 1/8" diameter cotton rope, passing through the sail canvas hem behind the hem rope, tie the leading edge close to the wheel arm. These latter ties are very important for correct sail operation.
3. During initial field trials, the outer sail corner C was tied to the outer sail hook, item 72I, on the perimeter-wire by a tight rubber loop, but this arrangement caused the wheel to over-run accompanied by sail-flapping during gusting wind conditions. A long rubber loop of ¾" x 1/8" section was then tied from the outer sail corner C to the perimeter-wire anchor on the preceding arm, and this arrangement provided progressive governing of the wheel speed as the wind speed increased and eliminated flapping of the sails.

Note: the side dimensions of the main sails are such that in the no-load position, i.e. with the sail corners fitted by insufficient wind to turn the wheel, the 'angle of attack' at mid-point of the trailing edge is approximately 7½°.

4. The 'starter' sails, item 74, are made of light-weight cotton, locally known as 'greyball' and used for sails on fishing boats. As will be seen from the dimensions of the 3 sides, the starter sails provide a greater 'angle of attack' to the wind of about 19° at the mid-point of the trailing edge at no-load. These sails, fitted on alternative arms around the wheel, are provided specifically to assist in starting at low wind speed, and they also help to maintain wheel rotation between gusts in light wind conditions.
5. The starter sails also have a 1" wide hem, through which a 3/16" diameter nylon rope passes on all 3 sides, all rope ends being tied tightly through the material at the sail corners as on the main sails.
6. The hem rope is brought out in a short loop at corner A of the starter sail to go on the corner sail hook. The rope running inside the sail edge A to B extends to a tight rubber loop of ¾" x 1/8" section to fit on the inner sail hook. The rope running inside the sail edge A to C extends 15" alongside the perimeter-wire and is then tied to a simple strand of ½" to 1/8" section rubber with its end looped over the perimeter-wire anchor on the preceding arm. A 1/8" diameter cotton-rope tie is passed through the sail material behind the hem rope at corner B to keep the leading edge of the starter sail against the wheel arm.

Notes:

(a) a short length of rubber tube is pushed on to the inner and corner sail hooks to avoid rapid wear of the sail attachment loops.

(b) in steady winds of 6.8 m.p.h. (11 k.p.h.) and above, the starter sails need not be used, but they are required where winds are variable and light.

F. Pump and Connecting Rod

Refer to drawings M, V, W, X, and H.

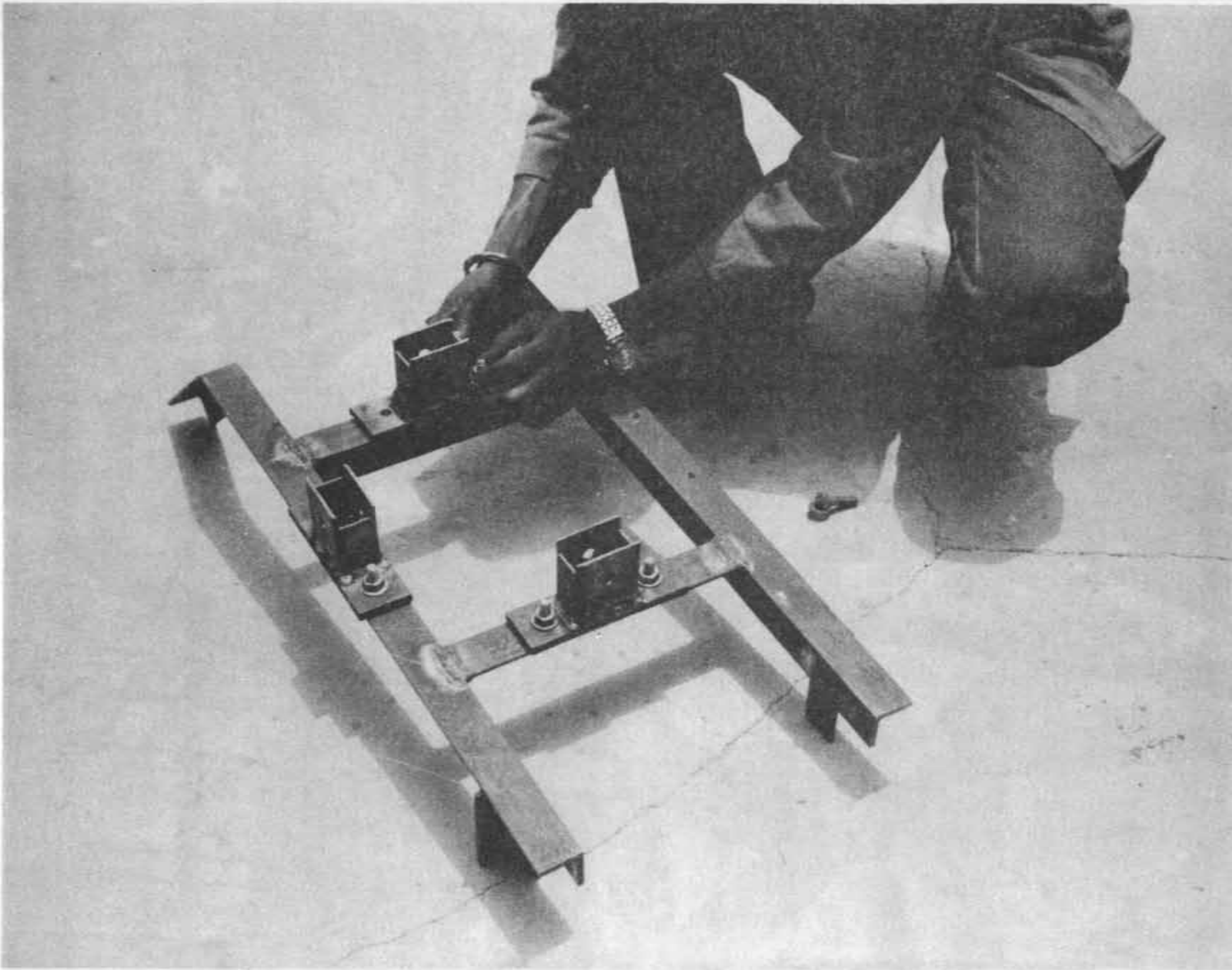
1. The pump, item 75a, is a 'Dempster' 3" inner diameter p.v.c. cylinder pump with two leather piston washers. The bucket and valve components are of gun-metal, and the top and bottom of the cylinder are threaded for 1¼" diameter inlet and outlet. The cylinder is 16" in length.
2. The pump inlet, item 75b, is 1¼" diameter galvanised steel pipe, proceeding via a gentle 90° pipe bend (not shown) to a 1¼"/1½" socket into which is threaded a 1½" diameter thick-walled p.v.c. suction pipe. The end of the suction pipe is fitted with a 1½"/1¼" socket to take a factory-made brass foot-valve.
3. The outlet, item 75c, is via a standard pipe 'T' fitting, above which a further pipe extension, item 75d, is fitted to take a 'Dempster' brass stuffing-box, item 75e.

   The outlet pipe is also 1¼" diameter galvanised pipe, and to facilitate the wind-pump testing was connected via a 1¼"/1½" socket to a length of 1½" thick-walled p.v.c. pipe to reach the drums used for measuring the output.
4. The pump foot mounting consists of a socket, item 75f, with legs welded each side and fixed with ½" diameter bolts inside two pieces of 1¼" x 1¼" galvanised steel angle, item 75g, the latter being held by four ¼" diameter 'J' hook bolts across the lateral members, item 56c.
5. The pump top is held centrally by a fabricated clamp-ring, item 75h, made of ¾" x 1/8" section mild steel, with 3 legs, item 75i, each of which takes a ¼" diameter 'J' hook bolt, item 75j. Each hook bolt passes through a tension-adjuster leg, item 75k, which in turn is connected by ¼" diameter reinforcing rod to one of the tower legs, item 54.
6. The pump is held down in the socket, item 75f, by means of two 1/8" diameter galvanised wires, item 75l, attached to ¼" diameter 'J' hook bolts, item 75m, which pass through the angle supports, item 75g.
7. The pump connecting rod, item 76a, is fabricated of 5/8" outer diameter conduit pipe, as illustrated in drawing W, and joined to the pump rod, item 76b, by a connecting link, item 76c, made up of 2 pieces of 1" x ¼" mild steel and two nuts.
8. The connecting rod is kept in alignment by a cross-head, item 77a, of 2" x 1" timber, held by 2 plates, item 77b, of 1" x ¼" mild steel, and four ¼" diameter 'J' hook bolts, item 77c, across the lateral members, item 56a. A 1" diameter hole is drilled centrally through the cross-head, item 77a, and an easily replaceable guide block, item 77d, provided with a 5/8" diameter clearance-hole, is screwed on top of the cross-head. Both pieces of timber are hardwood.
9. The adjustable crank journal, item 24, can be bolted in 3 different positions to give a piston stroke of 5 7/8", 7", and 8 1/8" respectively, and the length of the connecting rod, item 76a, is calculated accordingly.
10. A universal joint, item 78, shown in detail in drawing X, joins the connecting rod, item 76a, to the crank rod, item 79a. The replaceable wearing parts of the universal joint are the loose washers at top and bottom of the pipe guide, and a bush, made of conduit pipe, which fits inside the pipe sleeve bearing.
11. The crank rod, item 79a, is also made of 5/8" outer diameter conduit pipe, connected top and bottom by pipe couplings which are tack-welded at one end, and fitted with 3/32" diameter retaining pins at the other end to facilitate disconnection when necessary.
12. The construction of the big-end bearing is shown in drawing H. The blocks, item 80a, of this split wood-block bearing are oil-impregnated in the same way as the front and middle crank-shaft bearings, and they are held together by two 3/8" diameter bolts through top and bottom plates, item 80b, each of 1½" x 1¼" mild steel.

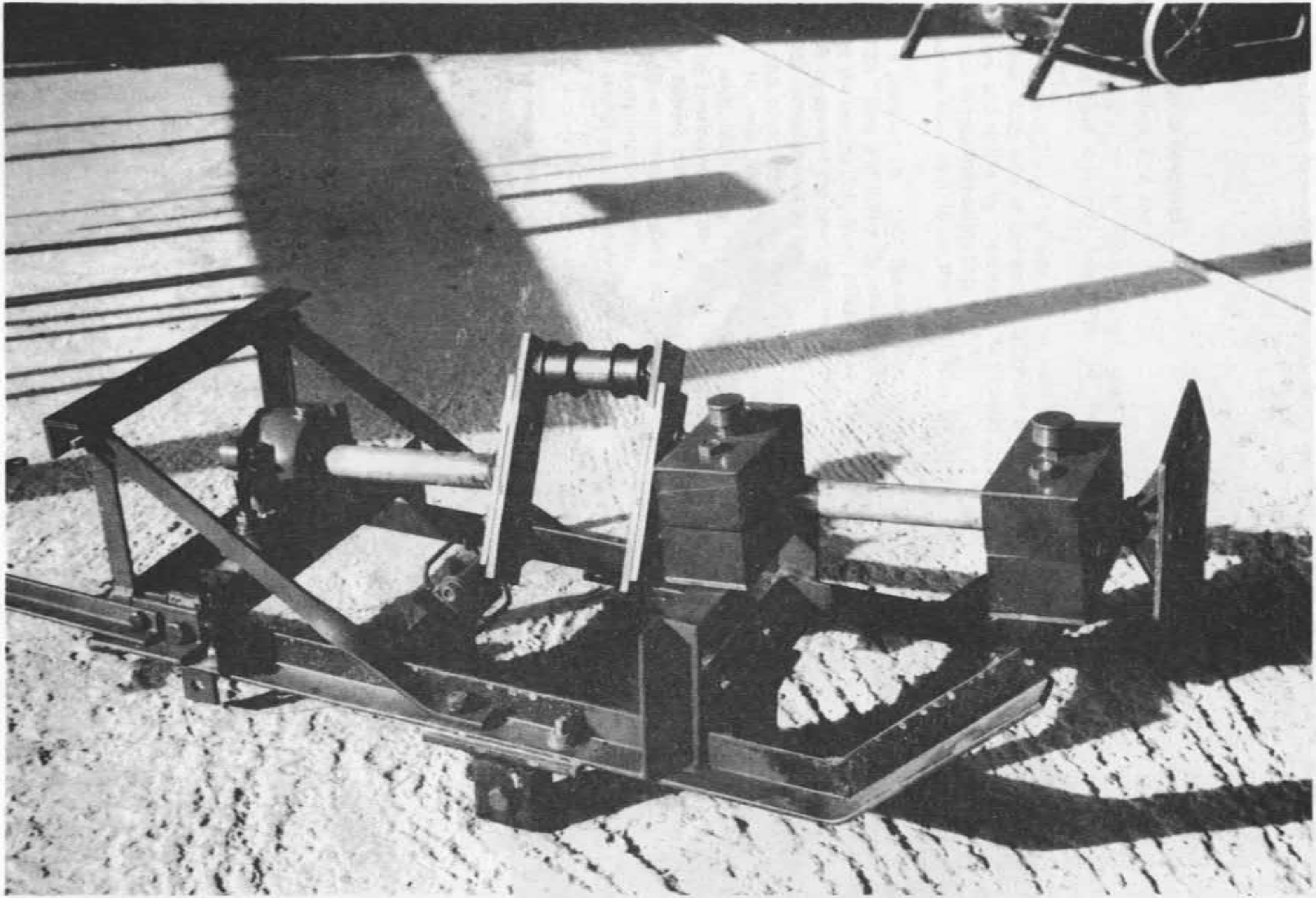
    The top plate is drilled and threaded to take a screw-type grease-cup, item 80c.

    A ½" diameter mild steel rod, item 80d, is welded to the bottom plate at a 5° angle to the bearing face to match the crankshaft inclination and triangular ¼" thick reinforcement webs are welded each side of the rod to provide adequate strength.

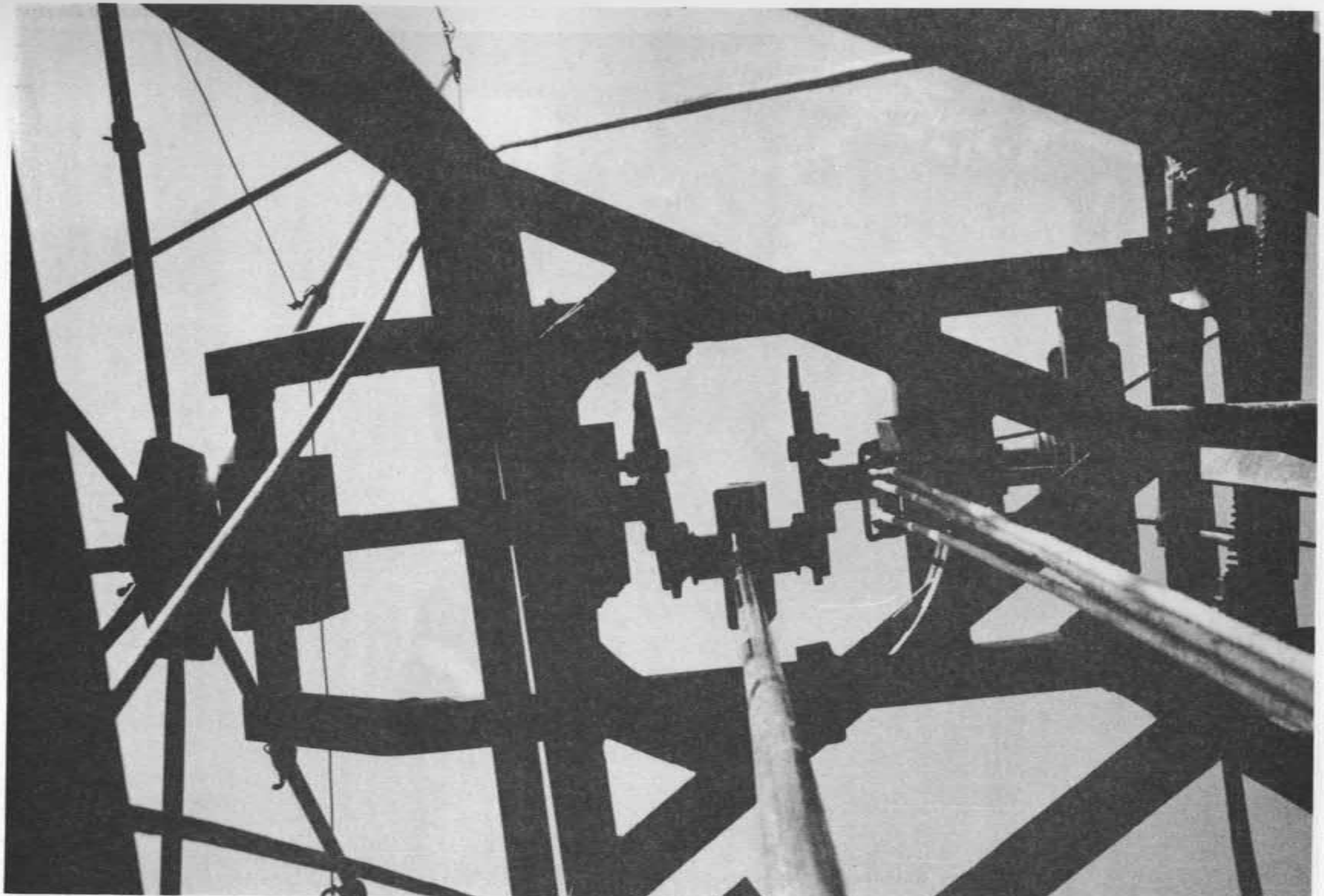
    The rod, item 80d, is welded inside a piece of 5/8" outer diameter conduit pipe, which then connects with the crank rod, item 79a, via the coupling, item 79b.



Underneath view of turntable frame showing bearing boxes.

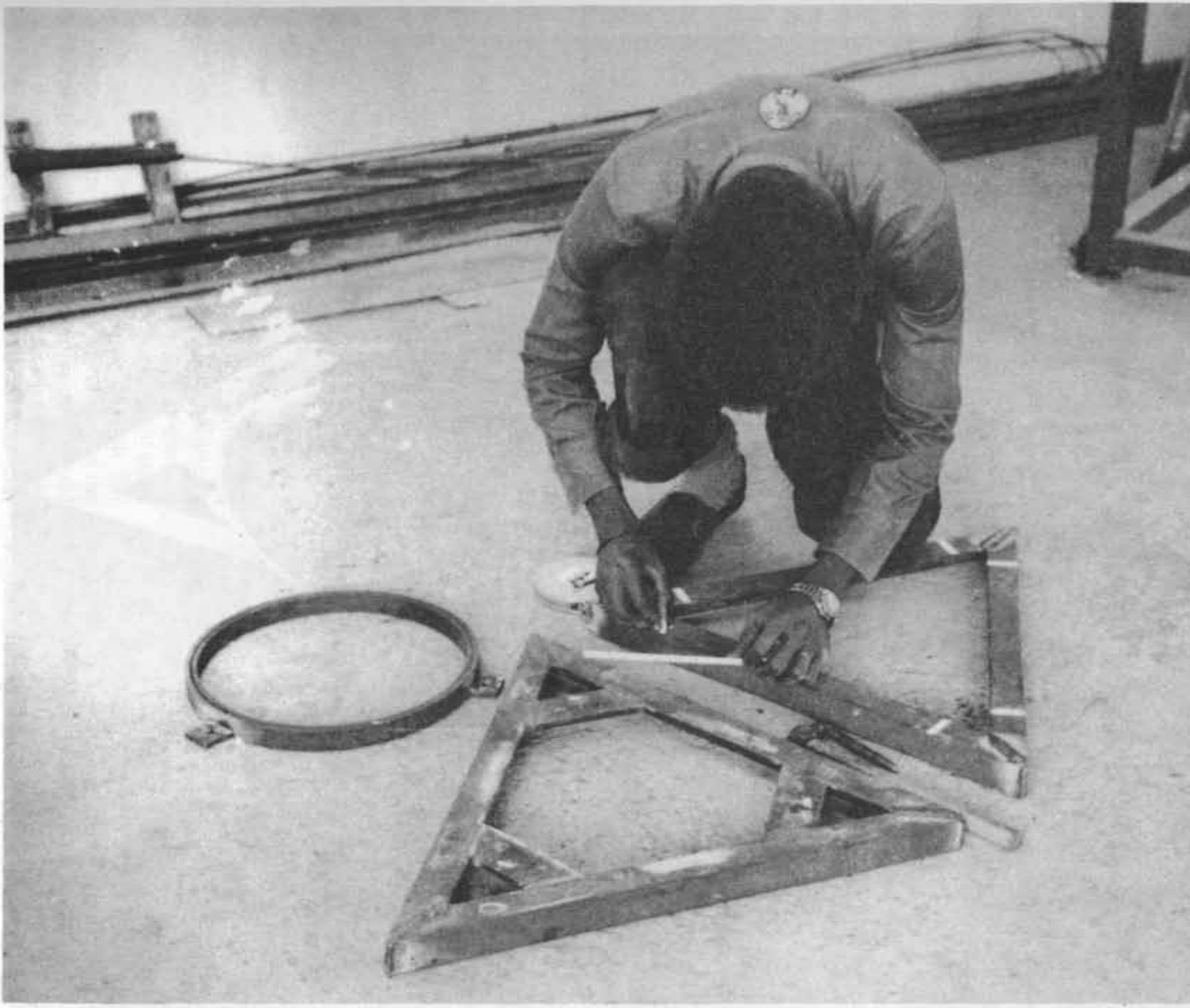


A view of the turntable.



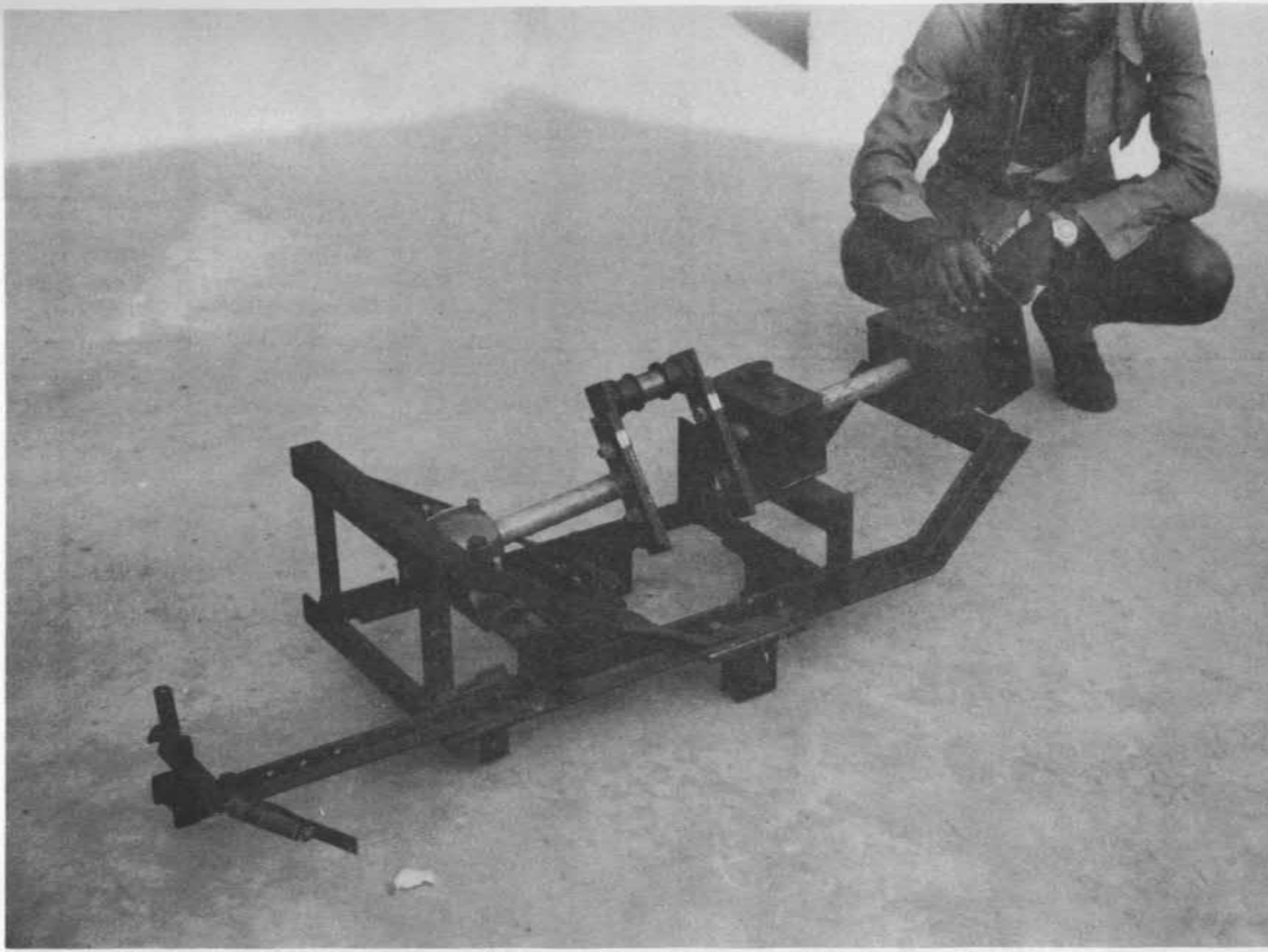
Turntable in operation on tower.

Making a turntable bearing track.

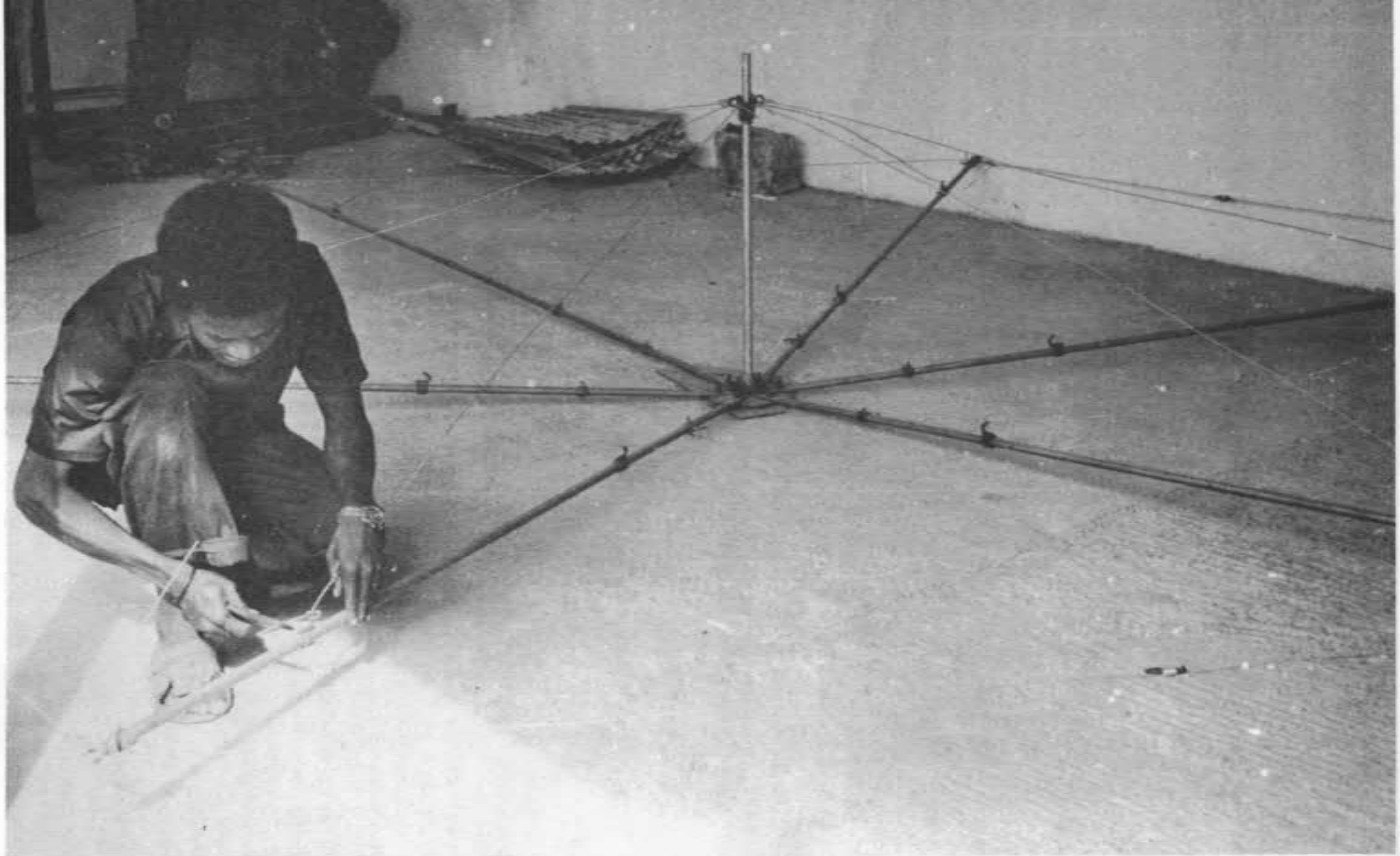


Making upper tower section frame.

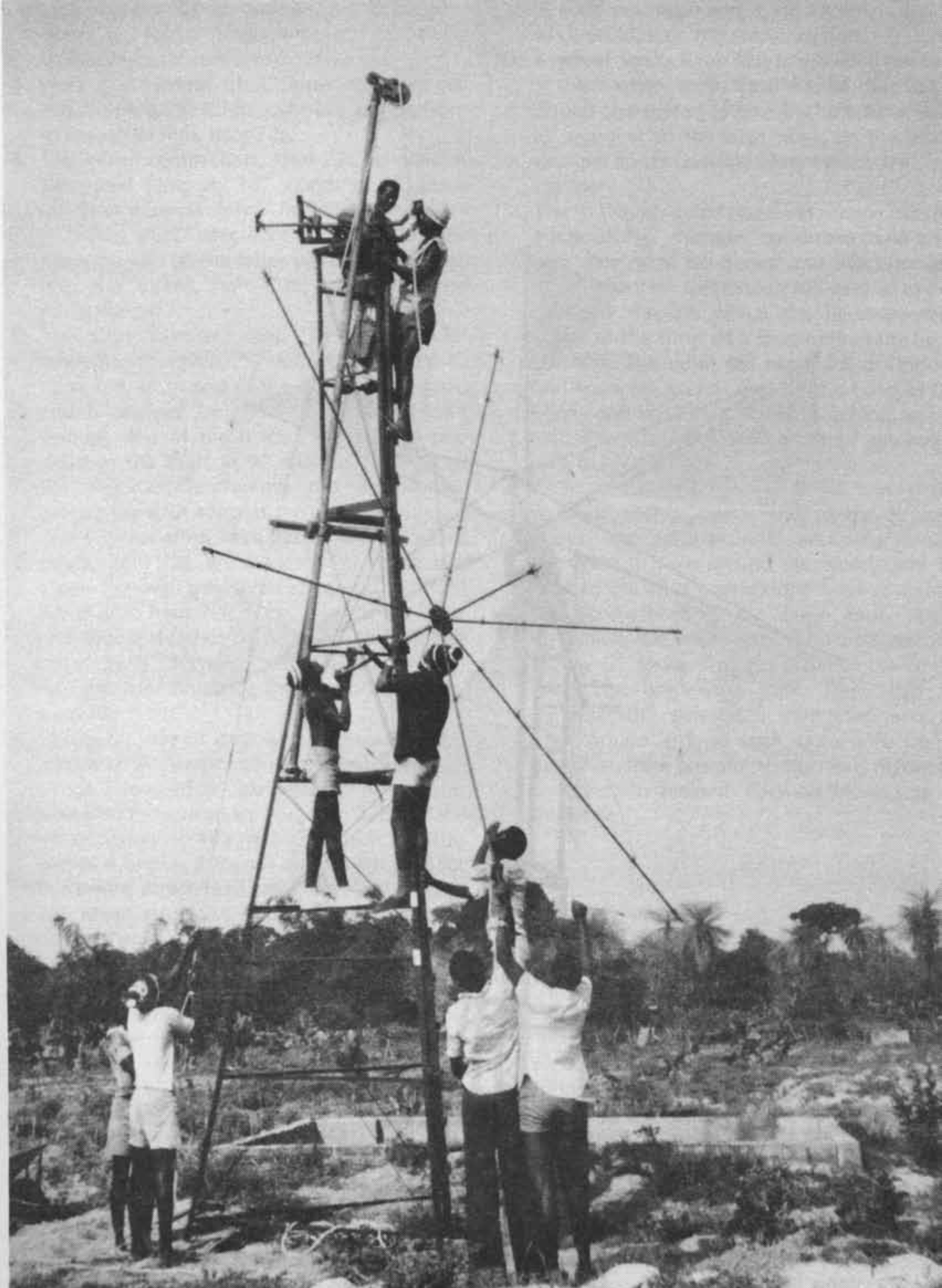
Fitting bearing track on head frame.



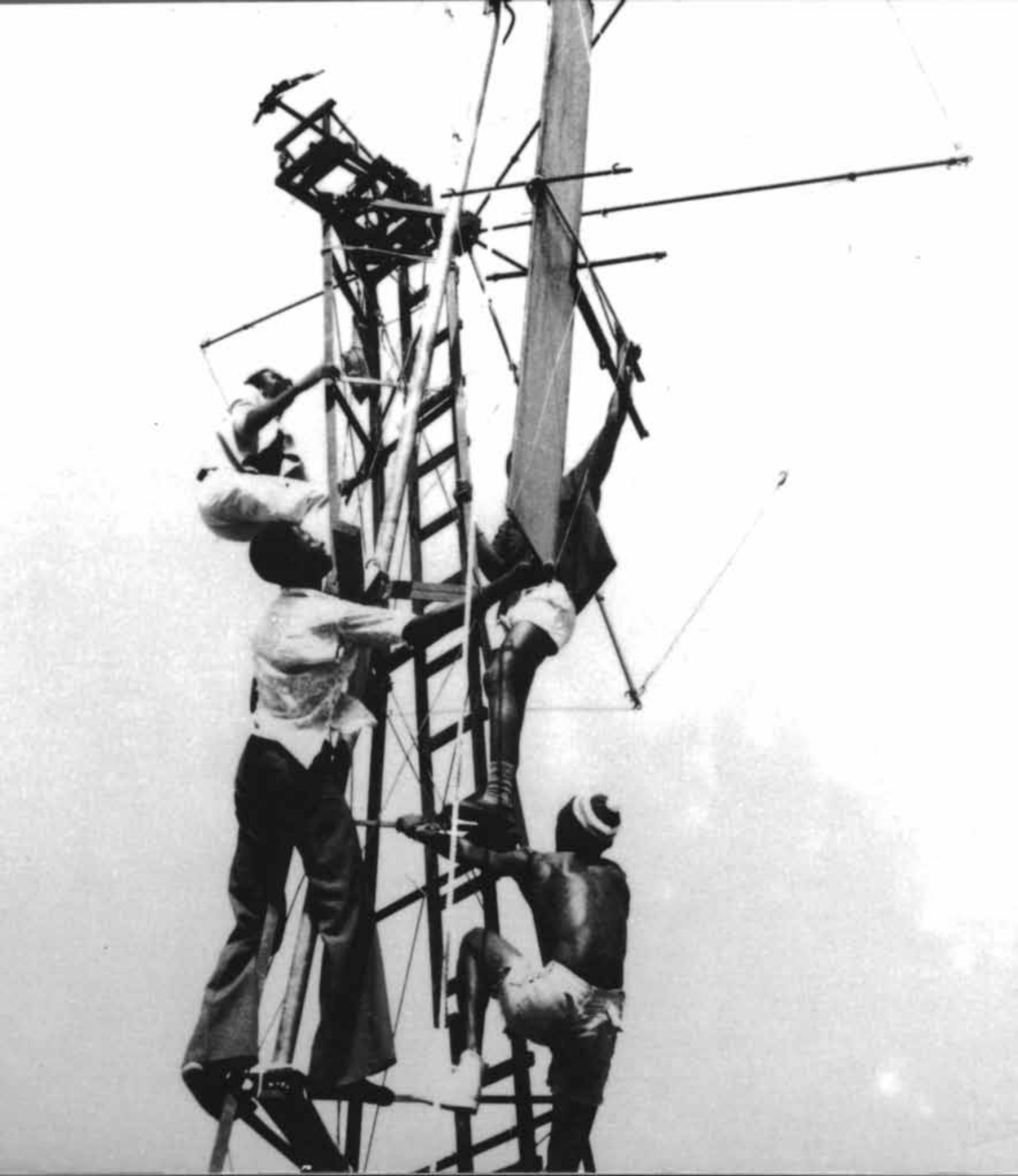
Back view of the turntable showing, on the far left, the bolt holes to which the legs of the tail unit are attached.

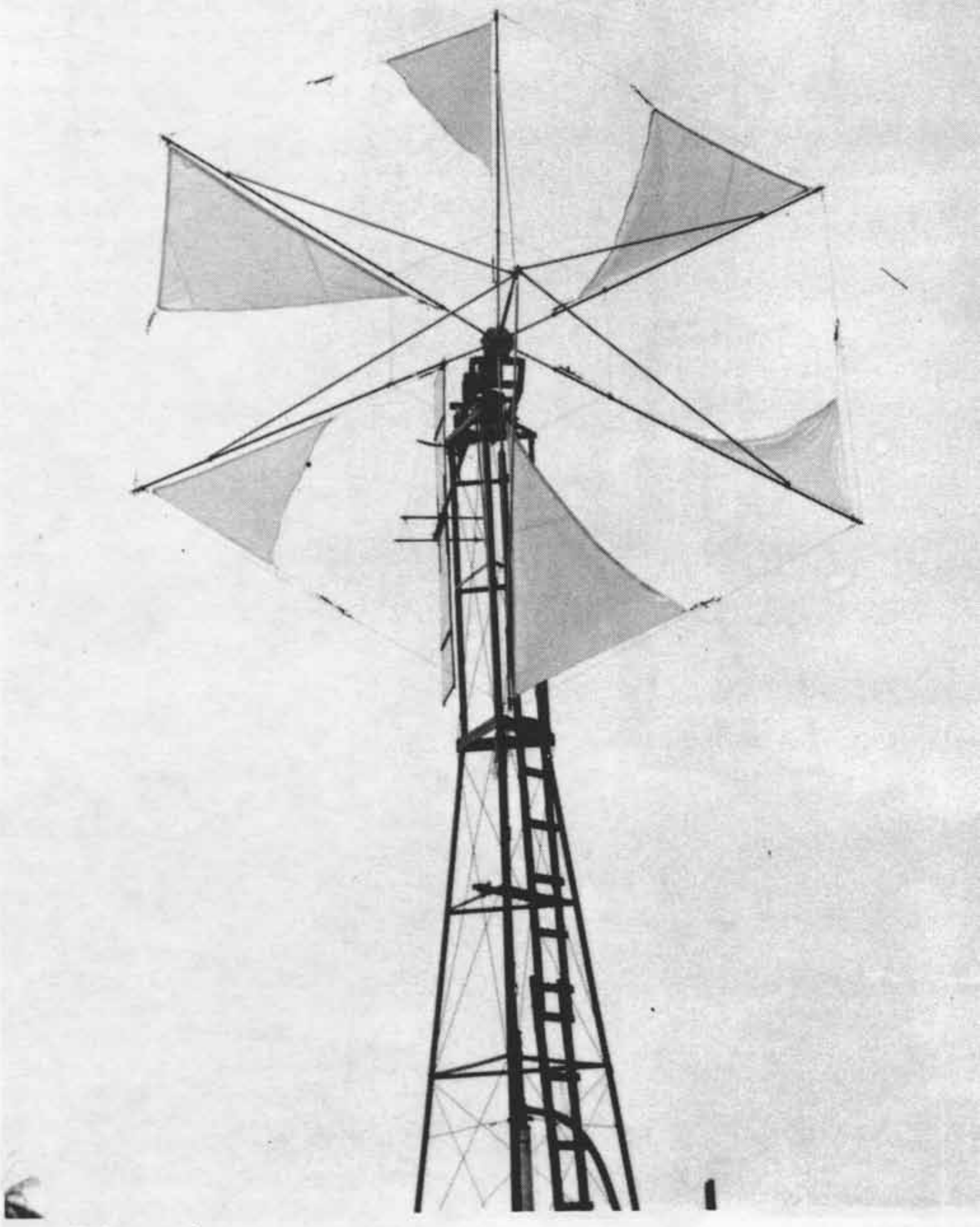


Assembly of wind wheel.

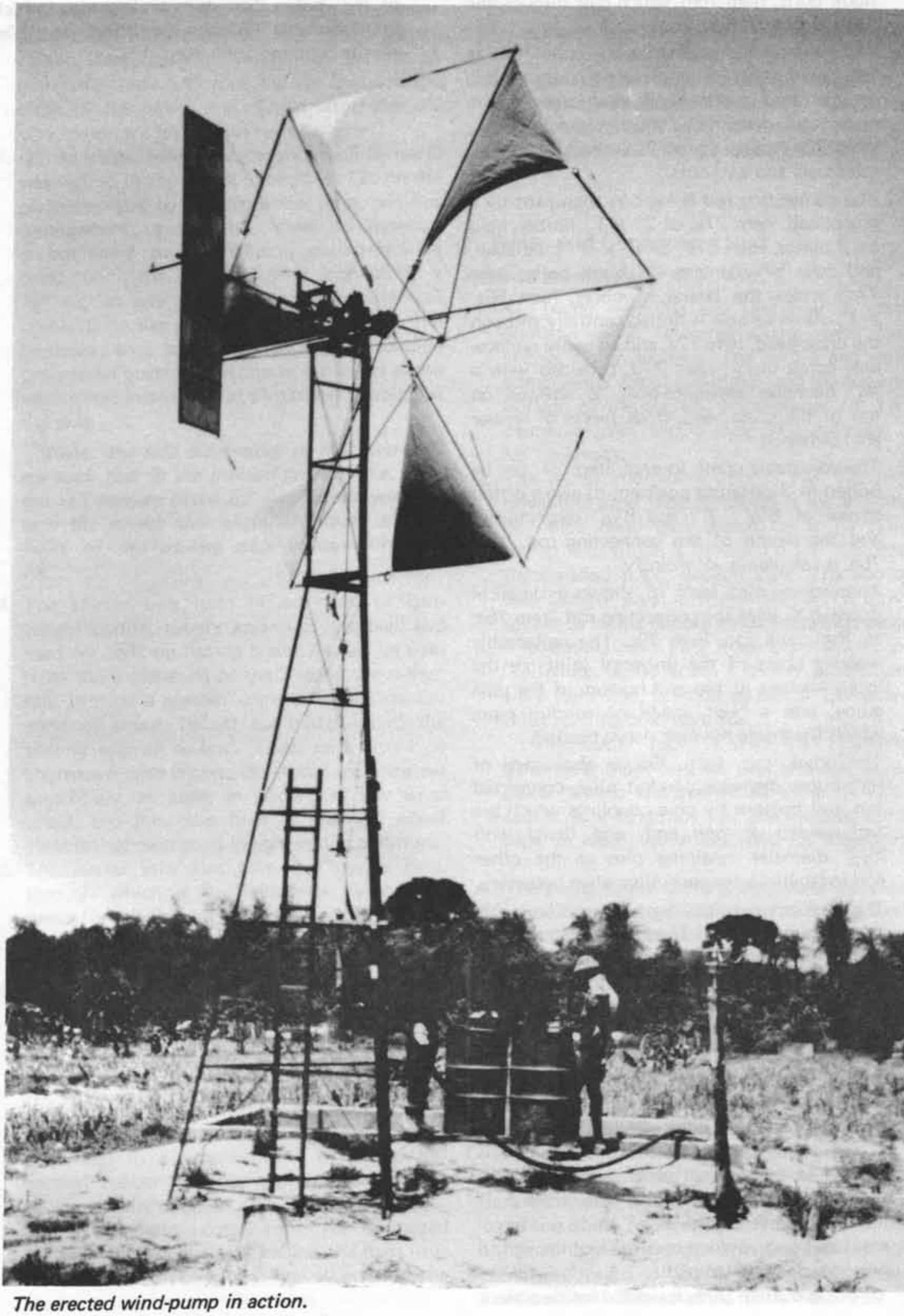


Fitting the wind wheel.

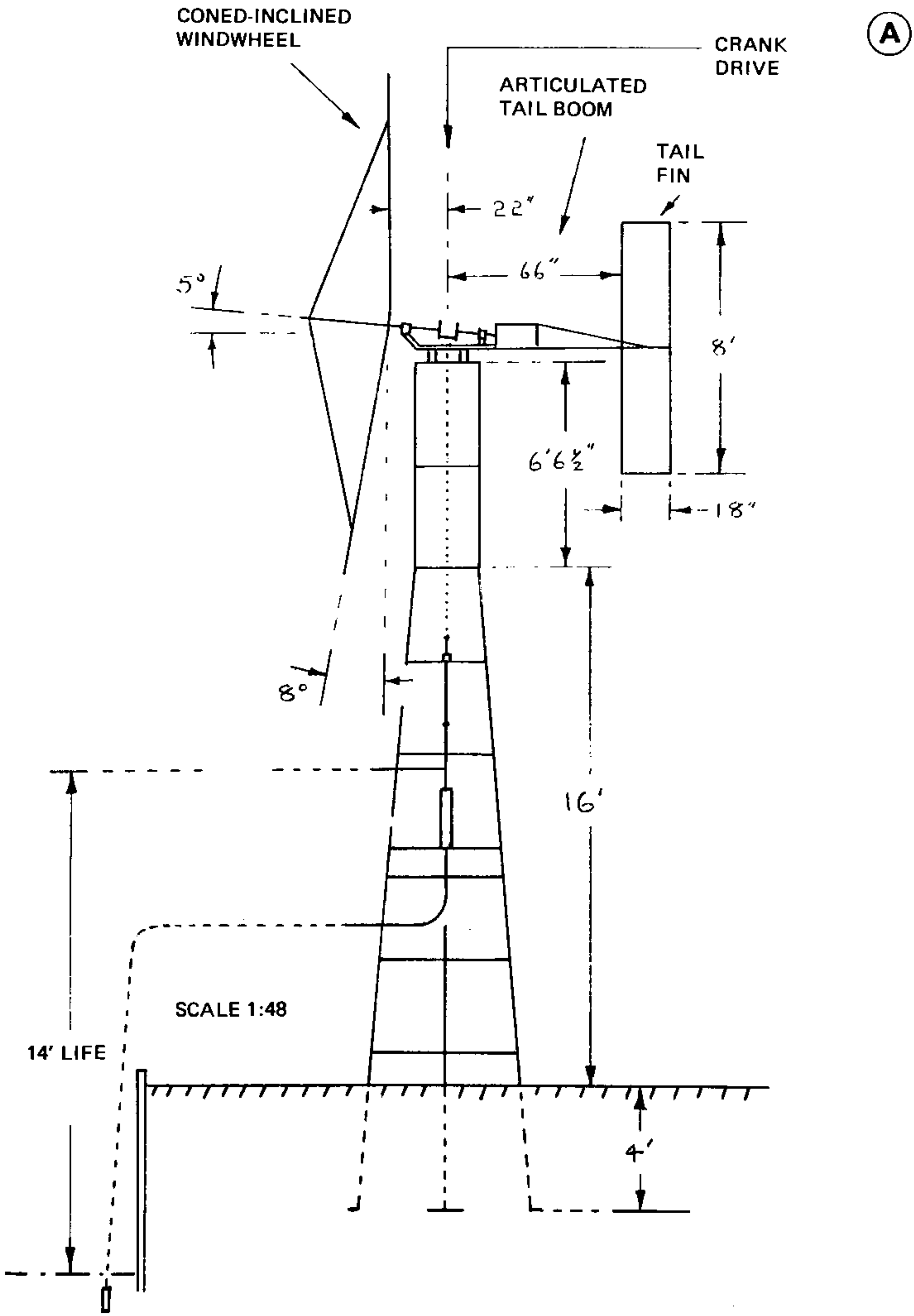




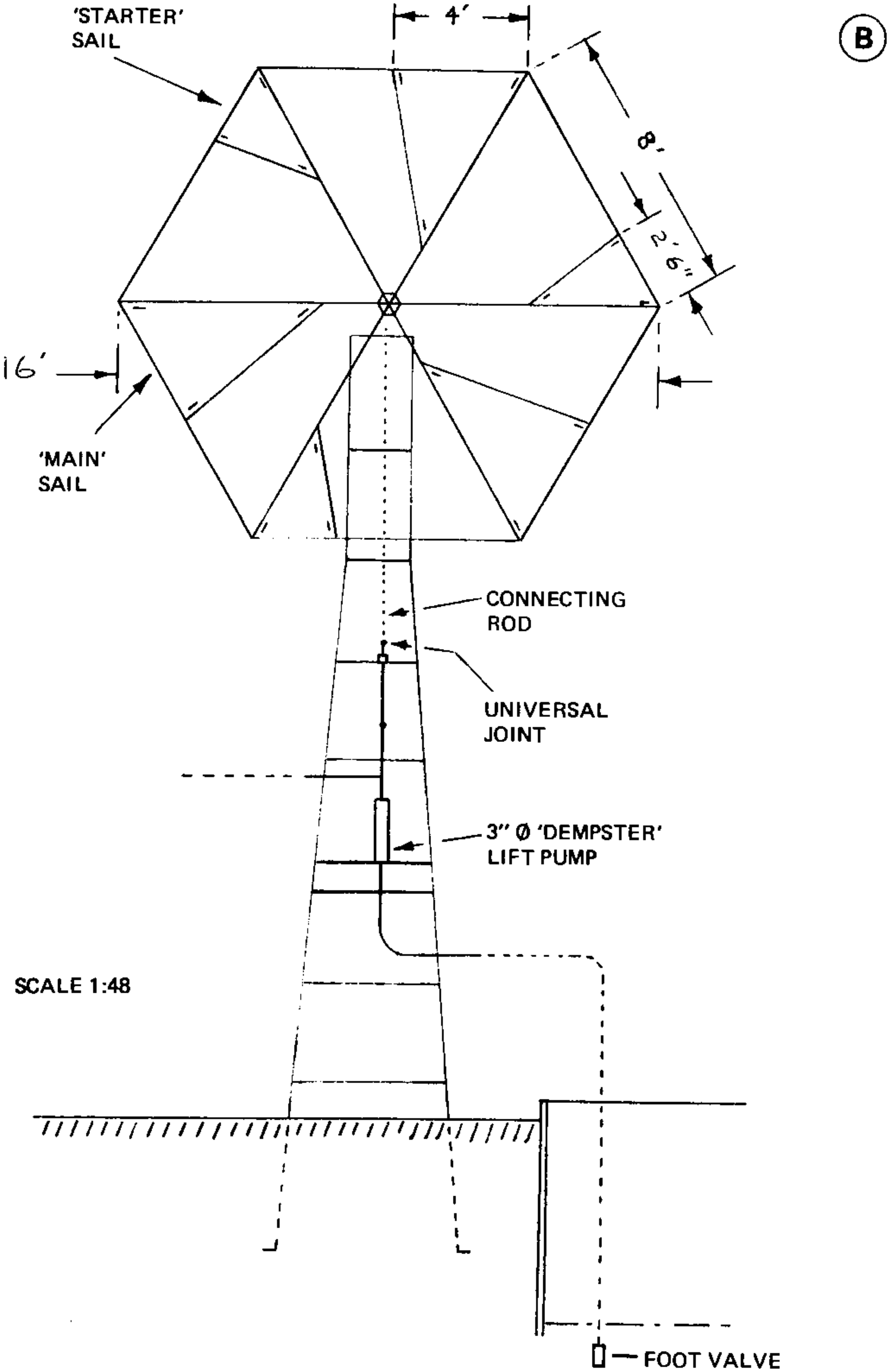
The sails in operation.



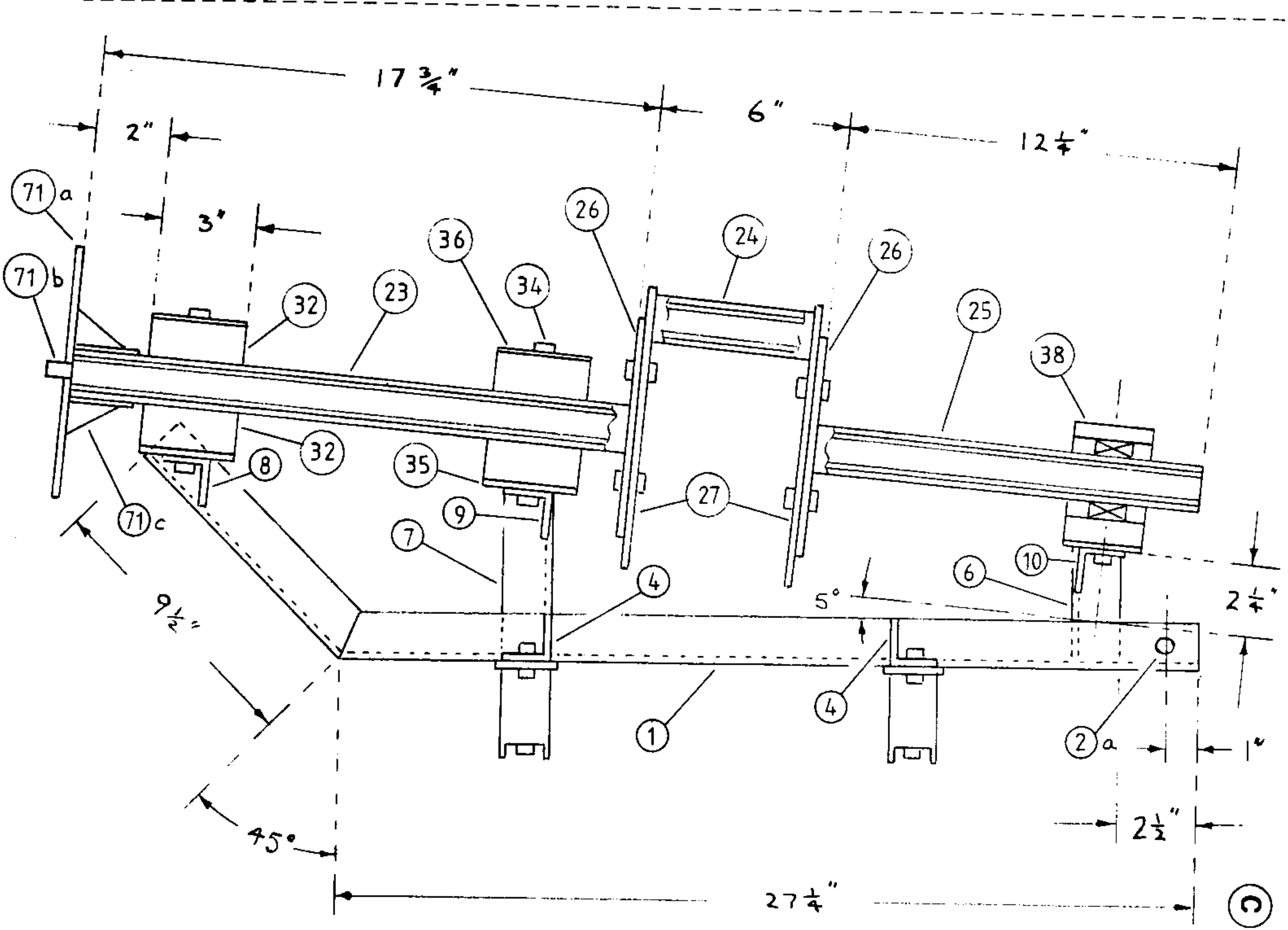
The erected wind-pump in action.

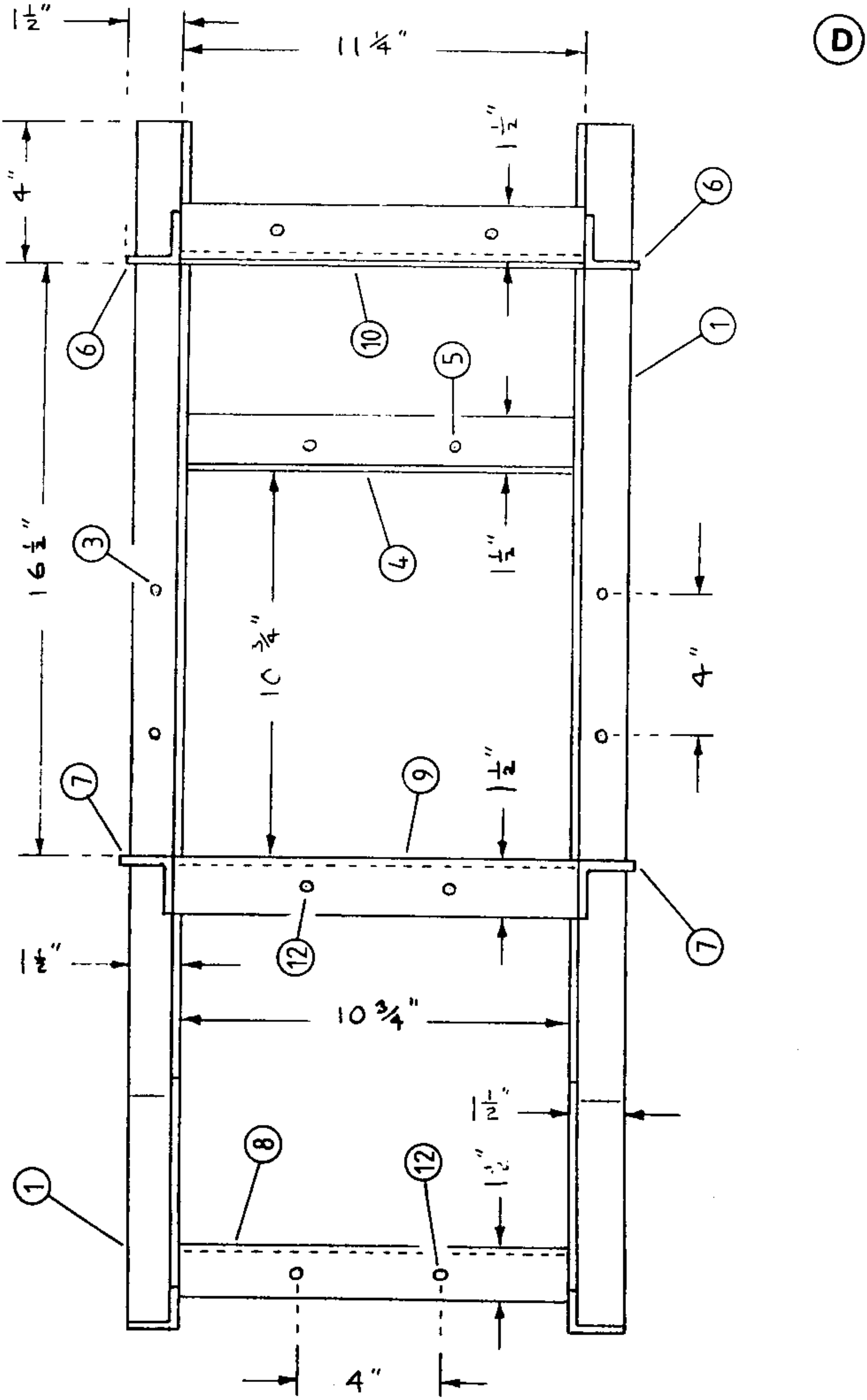


A
CONED-INCLINED WINDWHEEL
CRANK DRIVE
ARTICULATED TAIL BOOM
TAIL FIN
22"
66"
5°
8'
6'6½"
18"
8°
16'
SCALE 1:48
14' LIFE
4'



B
'STARTER'
SAIL
4'
8'
2'6"
16'
'MAIN'
SAIL
CONNECTING
ROD
UNIVERSAL
JOINT
3" Ø 'DEMPSTER'
LIFT PUMP
SCALE 1:48
FOOT VALVE


17 3/4"
6"
12 1/4"
2"
3"
71 a
71 b
71 c
32
23
36
34
26
24
25
38
35
8
9
7
4
27
10
6
5°
2 1/4"
1
2 a
1"
2 1/2"
9 1/2"
45°
27 1/4"
C


D
11 1/4"
1 1/2"
4"
16 1/2"
10 3/4"
1 1/2"
10 3/4"
4"
1 1/2"
4"
1
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7
8
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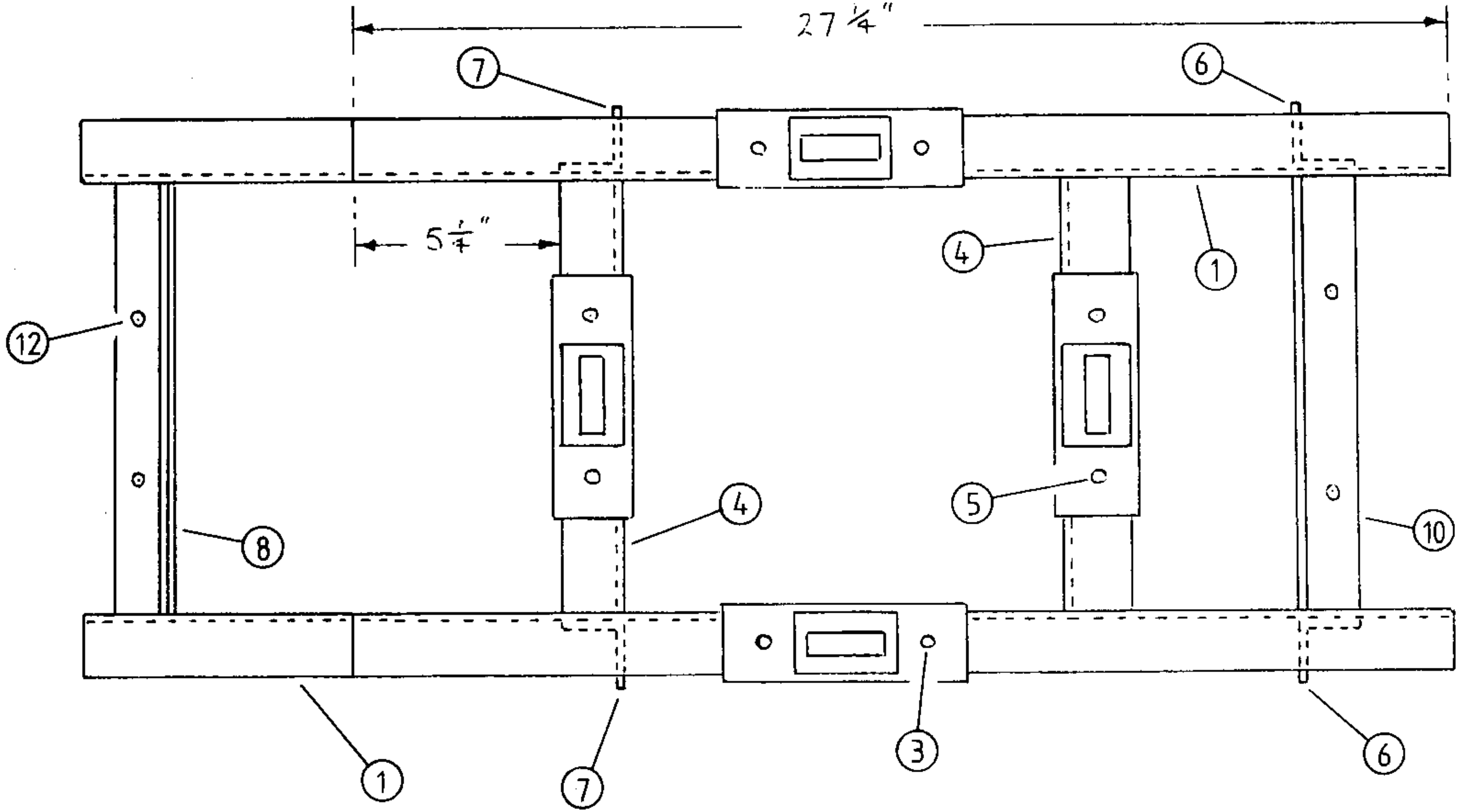
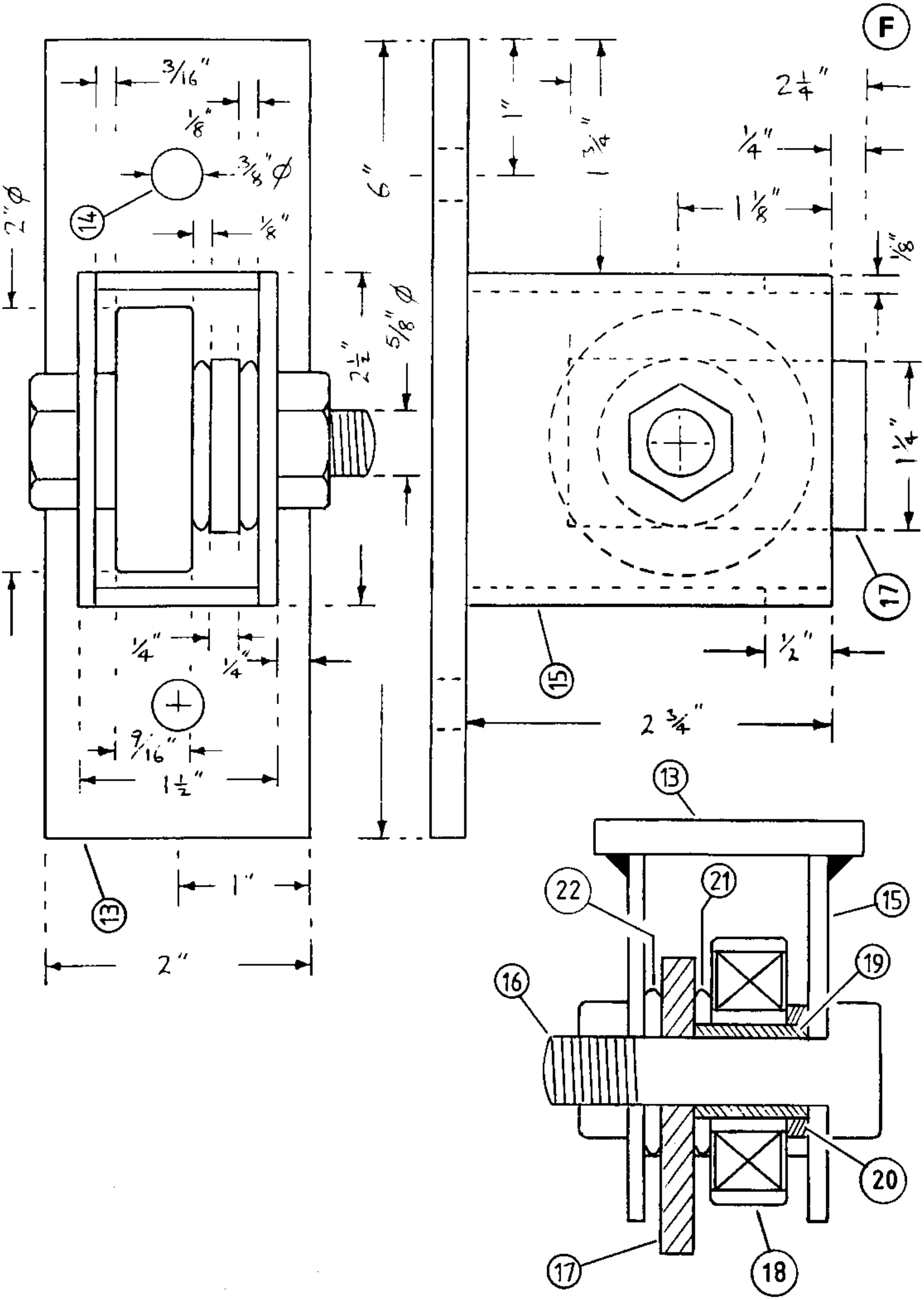
10
12


27 1/4"
5 1/4"
7
6
1
4
12
5
8
10
3


F
3/16"
1/8"
3/8" Ø
14
2" Ø
1/8"
5/8" Ø
2 1/2"
6"
1"
1 3/4"
2 1/4"
1/4"
1 1/8"
1/8"
1 1/4"
17
1/2"
15
2 3/4"
1/4"
1/4"
9/16"
1 1/2"
13
1"
2"
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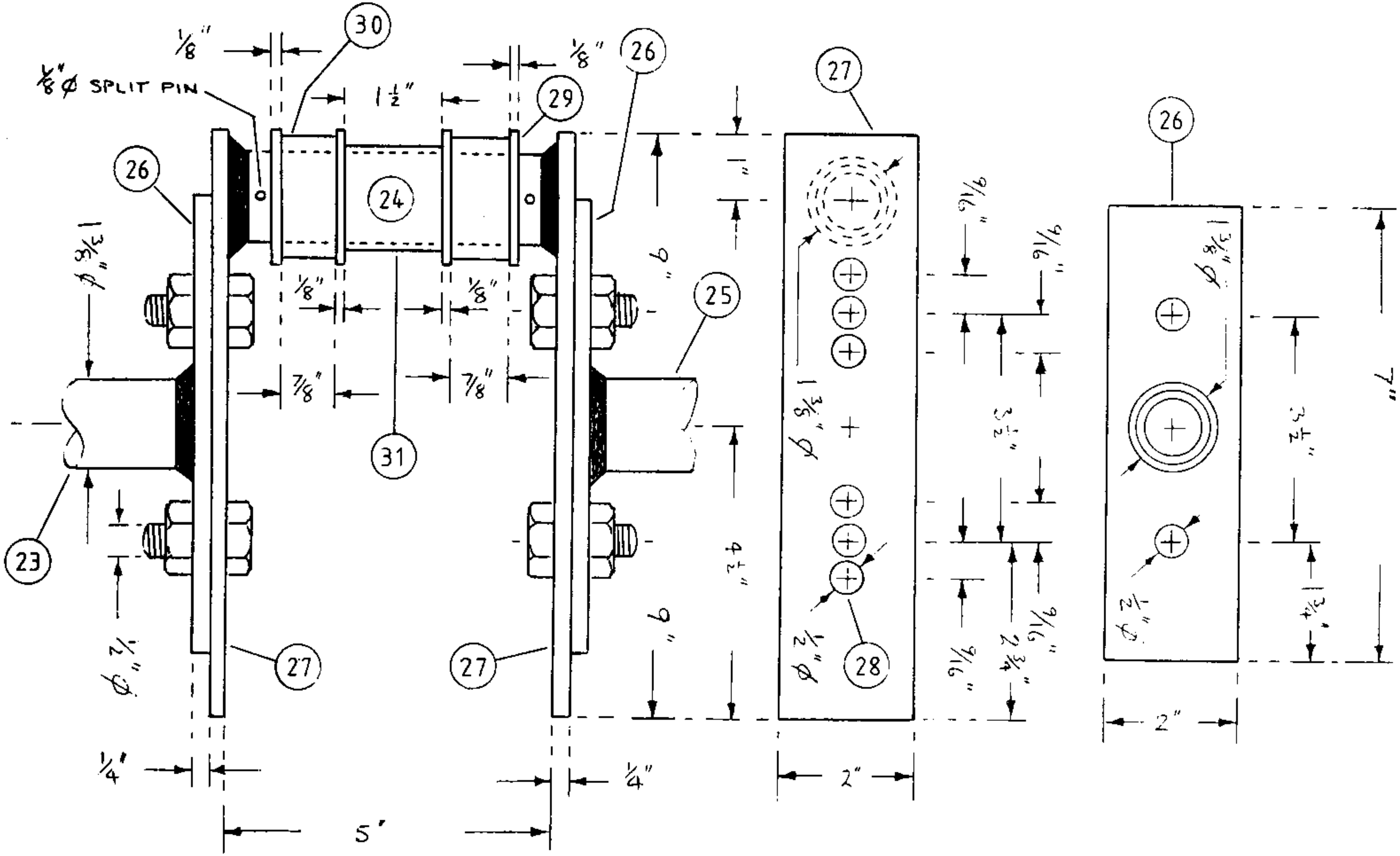
1/8" Ø SPLIT PIN
1/8"
1 1/2"
7/8"
1"
9"
4 1/2"
9/16"
3 1/2"
2 3/4"
1 3/4"
7"
2"
1/4"
5'
Ø 1 3/8"
Ø 1/2"
23
24
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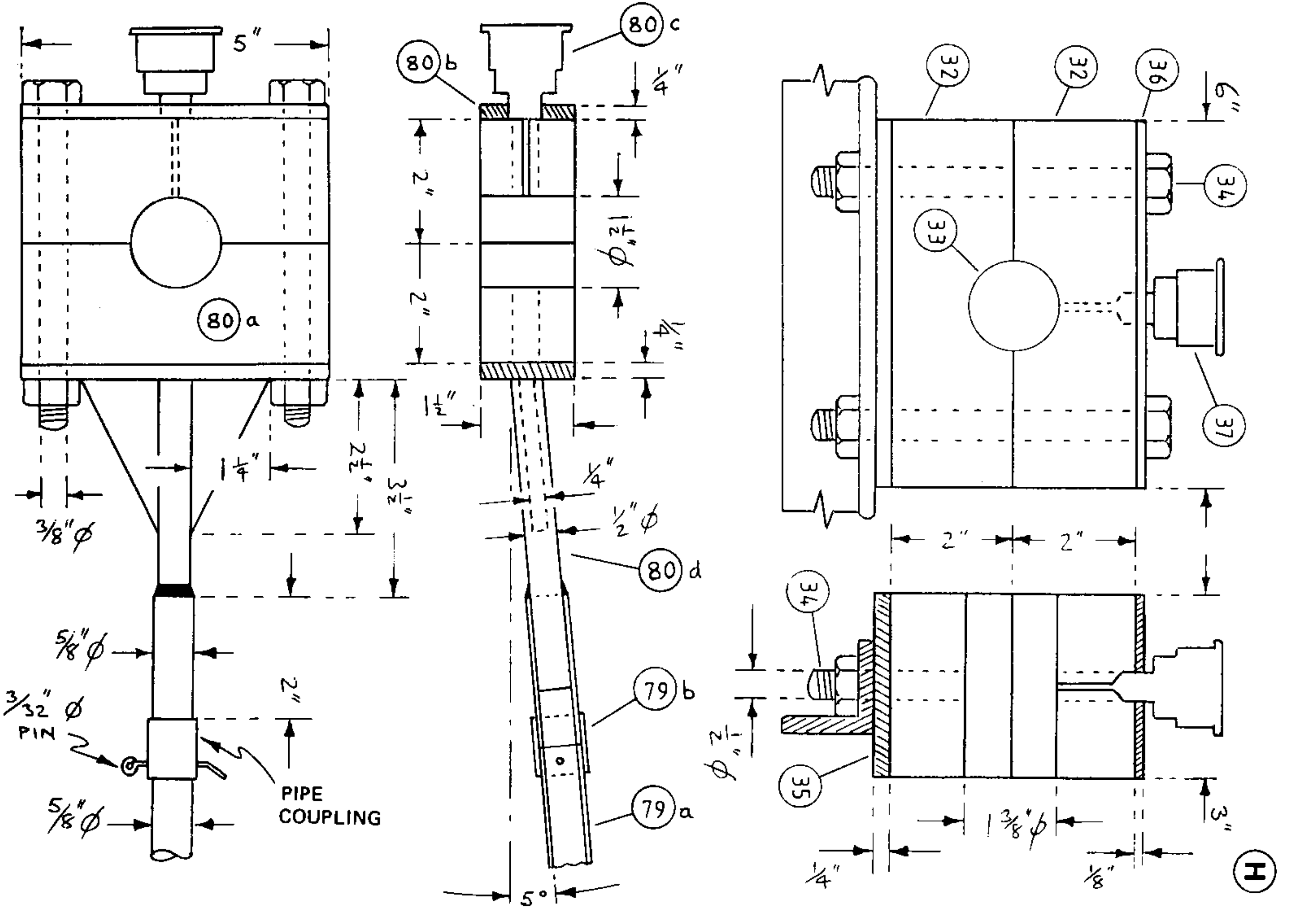
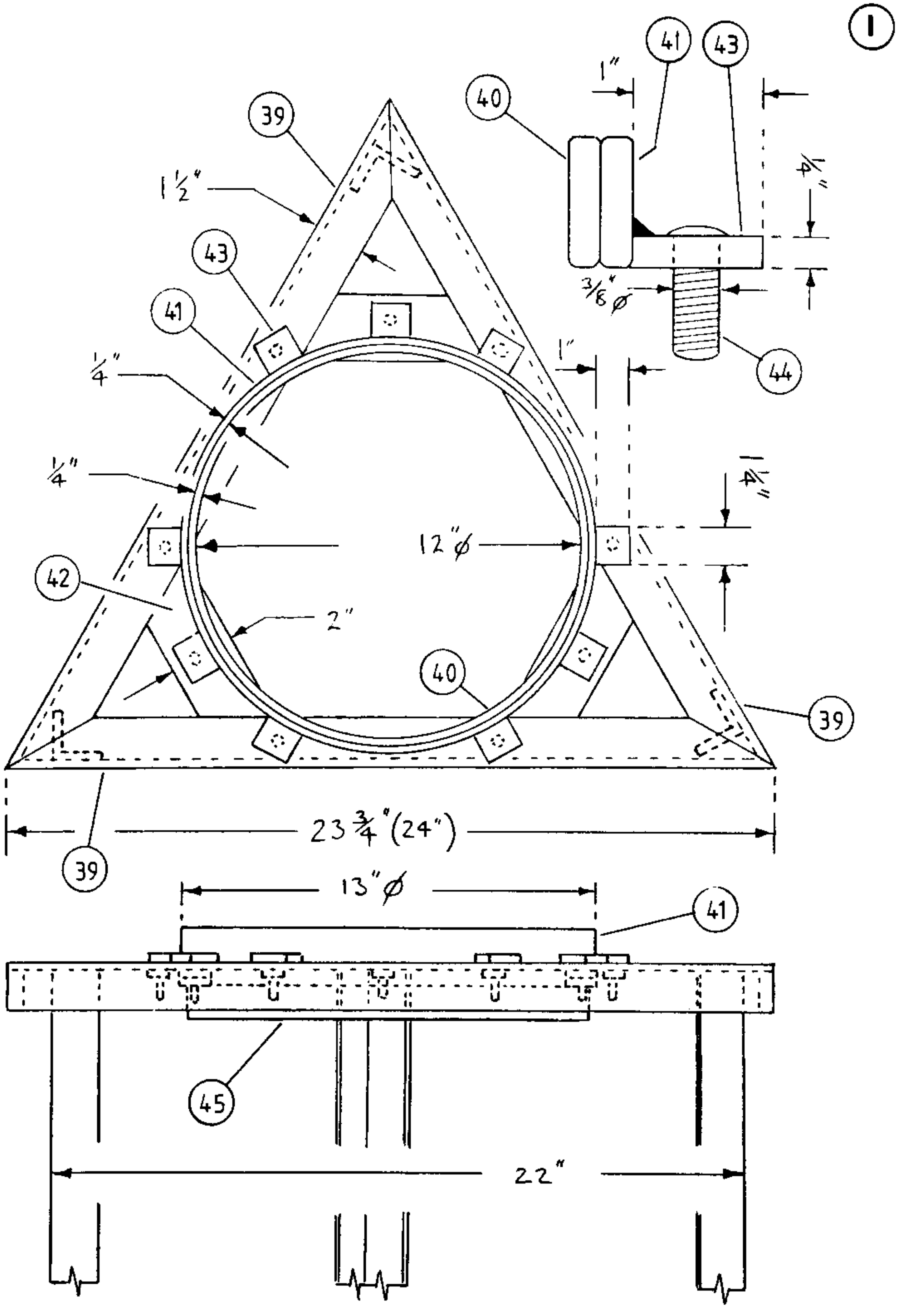
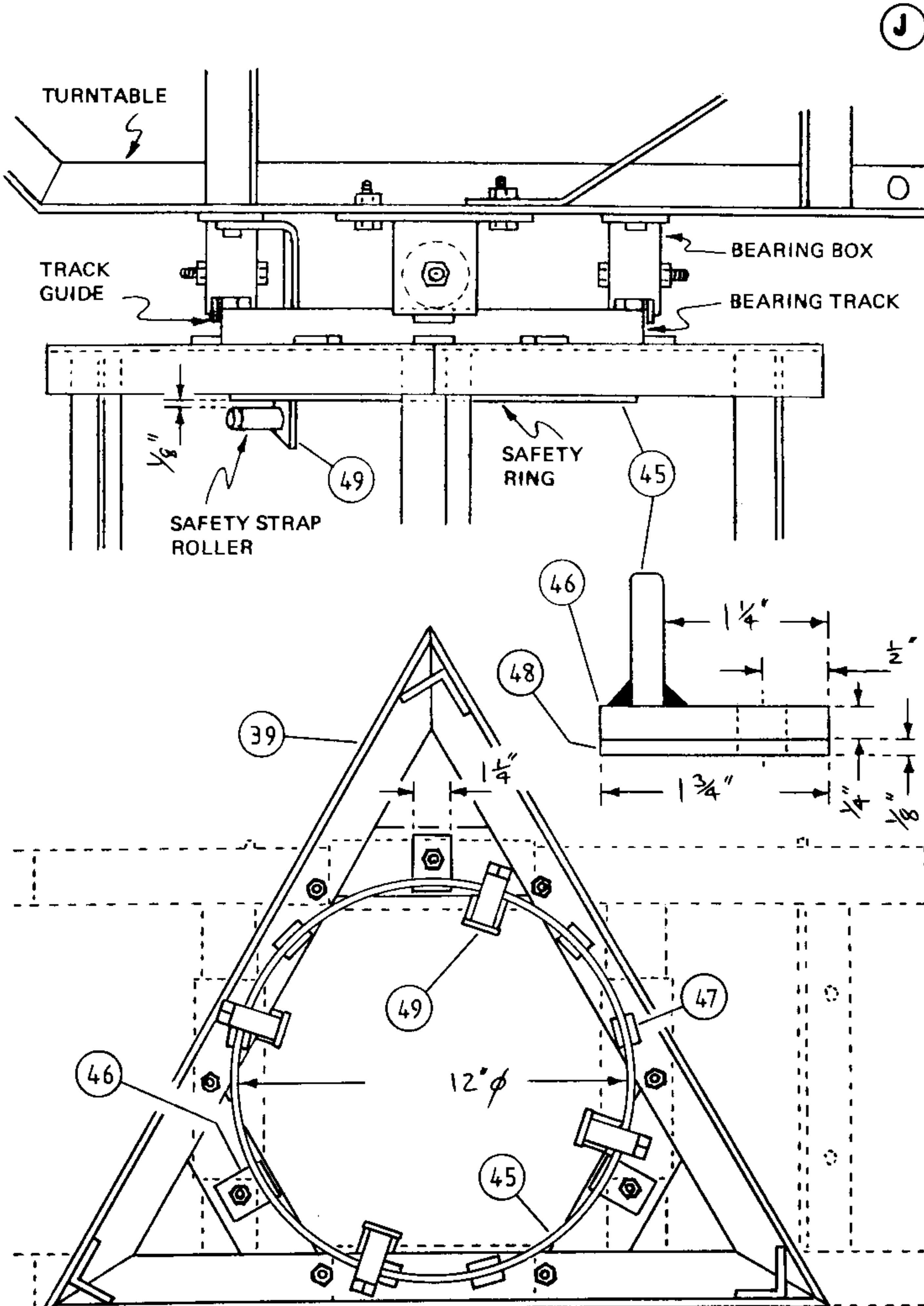
28
29
30
31

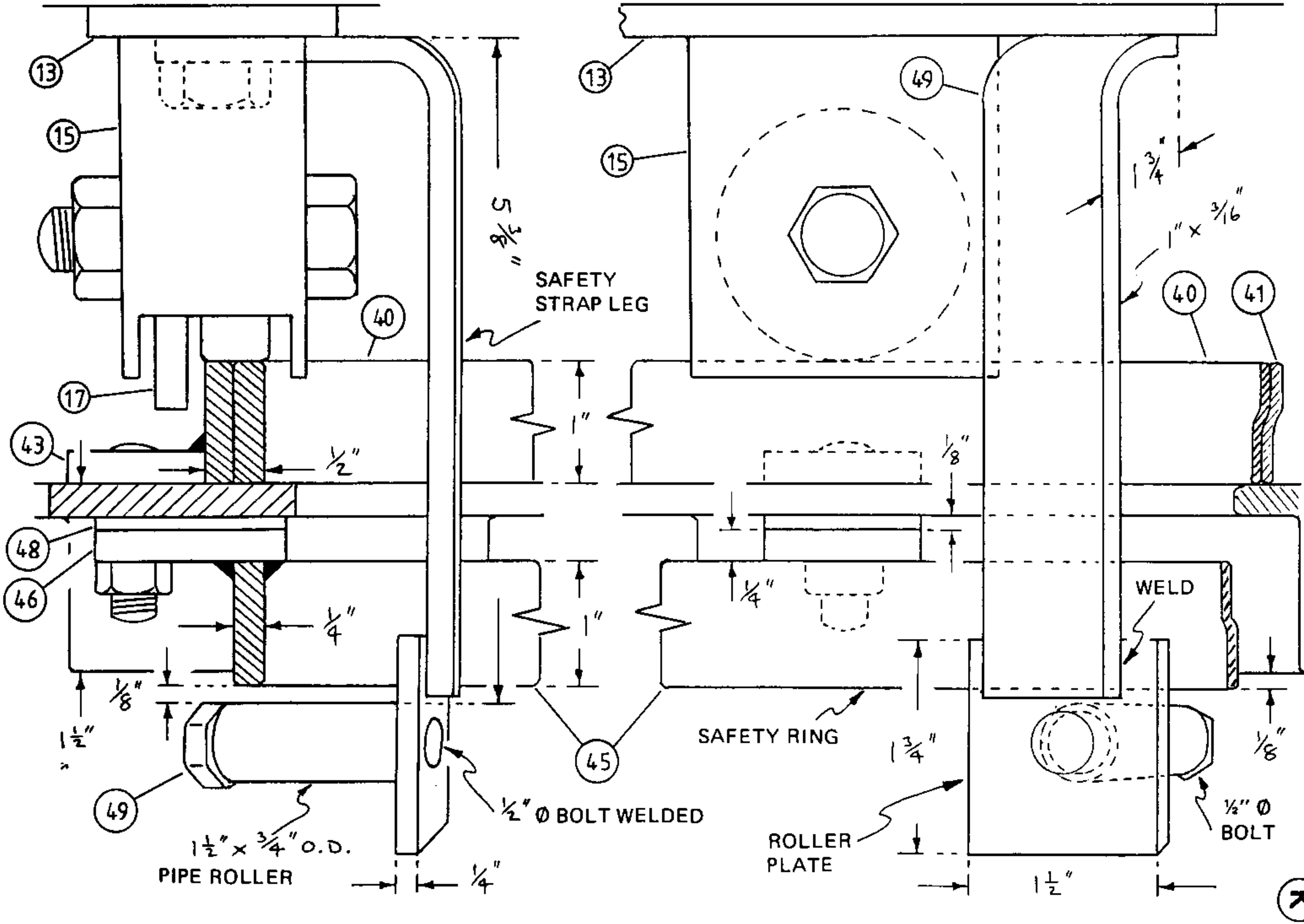
G

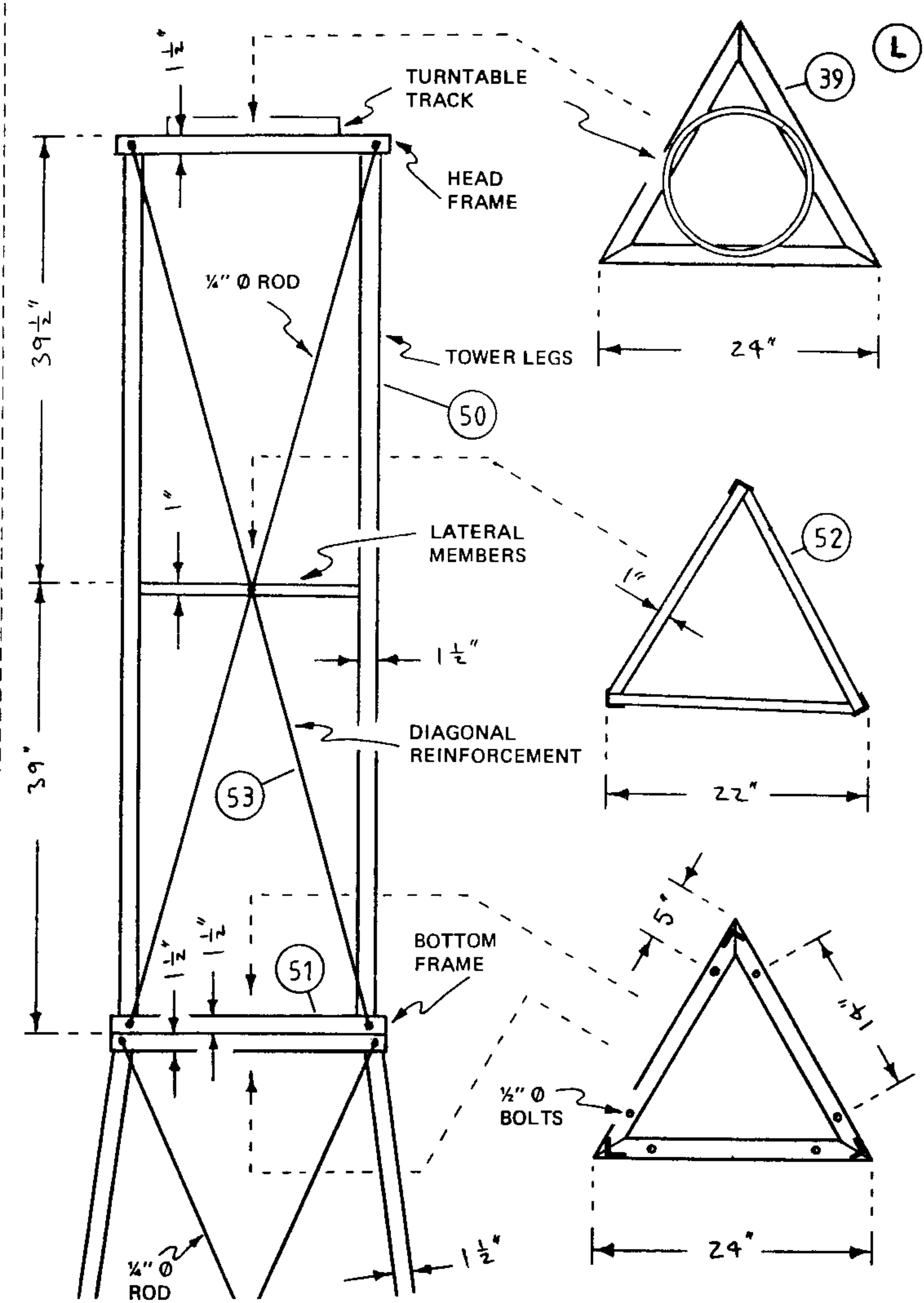

5"
80 c
80 b
1/4"
2"
1 1/2" Ø
2"
1/4"
80 a
1 1/2"
2 1/2"
3 1/2"
1 1/4"
1/4"
3/8" Ø
1/2" Ø
80 d
5/8" Ø
3/32" Ø
PIN
2"
79 b
PIPE
COUPLING
5/8" Ø
79 a
5°
32
32
36
6"
34
33
37
2"
2"
34
Ø 1/2"
35
1 3/8" Ø
3"
1/4"
1/8"
H



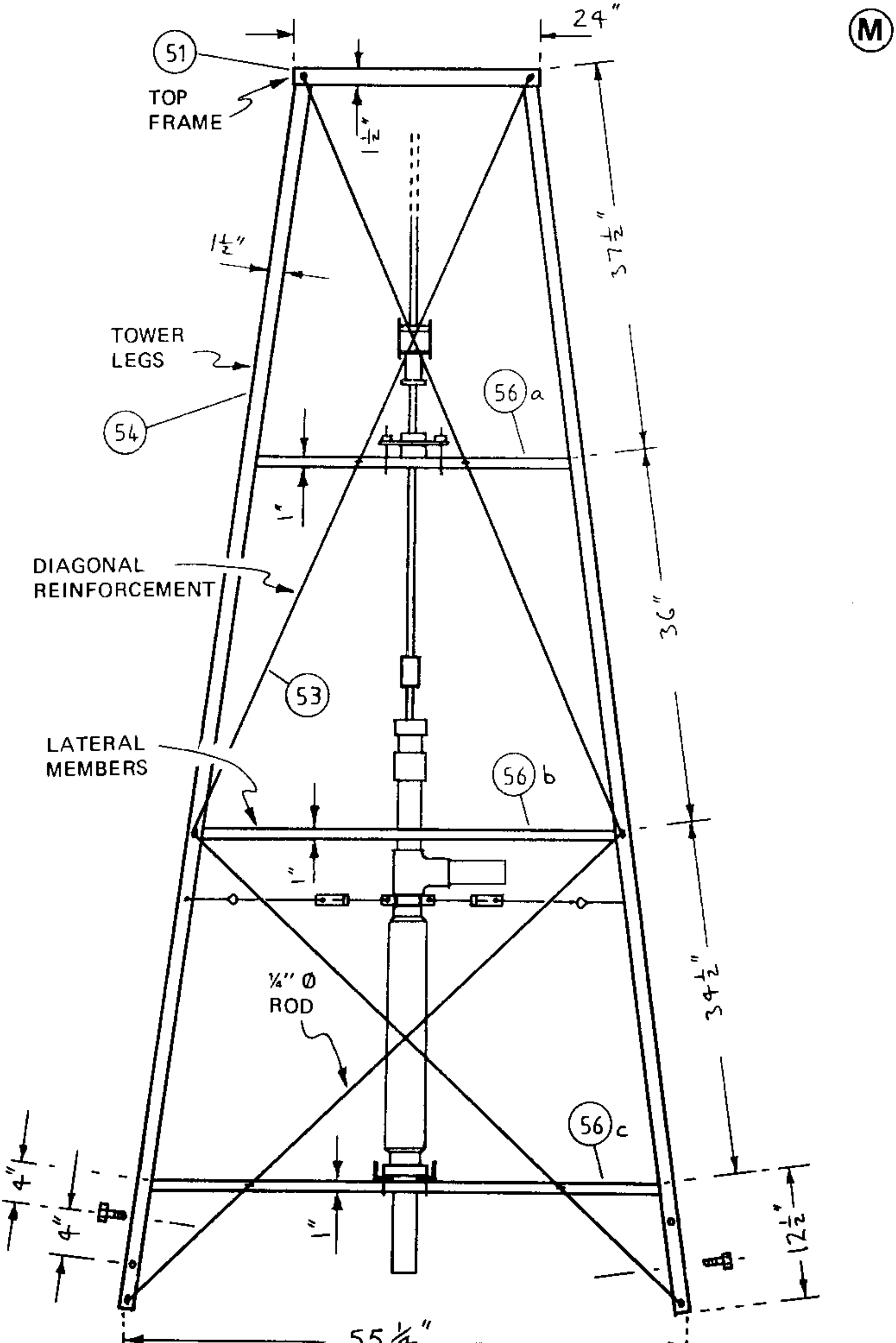
1
41
43
1"
40
39
1 1/2"
1/4"
3/8"Ø
43
41
1/4"
1"
44
1/4"
1/4"
12"Ø
42
2"
40
39
23 3/4"(24")
39
13"Ø
41
45
22"


J
TURNTABLE
TRACK GUIDE
BEARING BOX
BEARING TRACK
1/8"
SAFETY STRAP ROLLER
49
SAFETY RING
45
46
1 1/4"
1/2"
48
1 3/4"
1/4"
1/8"
39
1 1/4"
49
47
46
12" ⌀
45

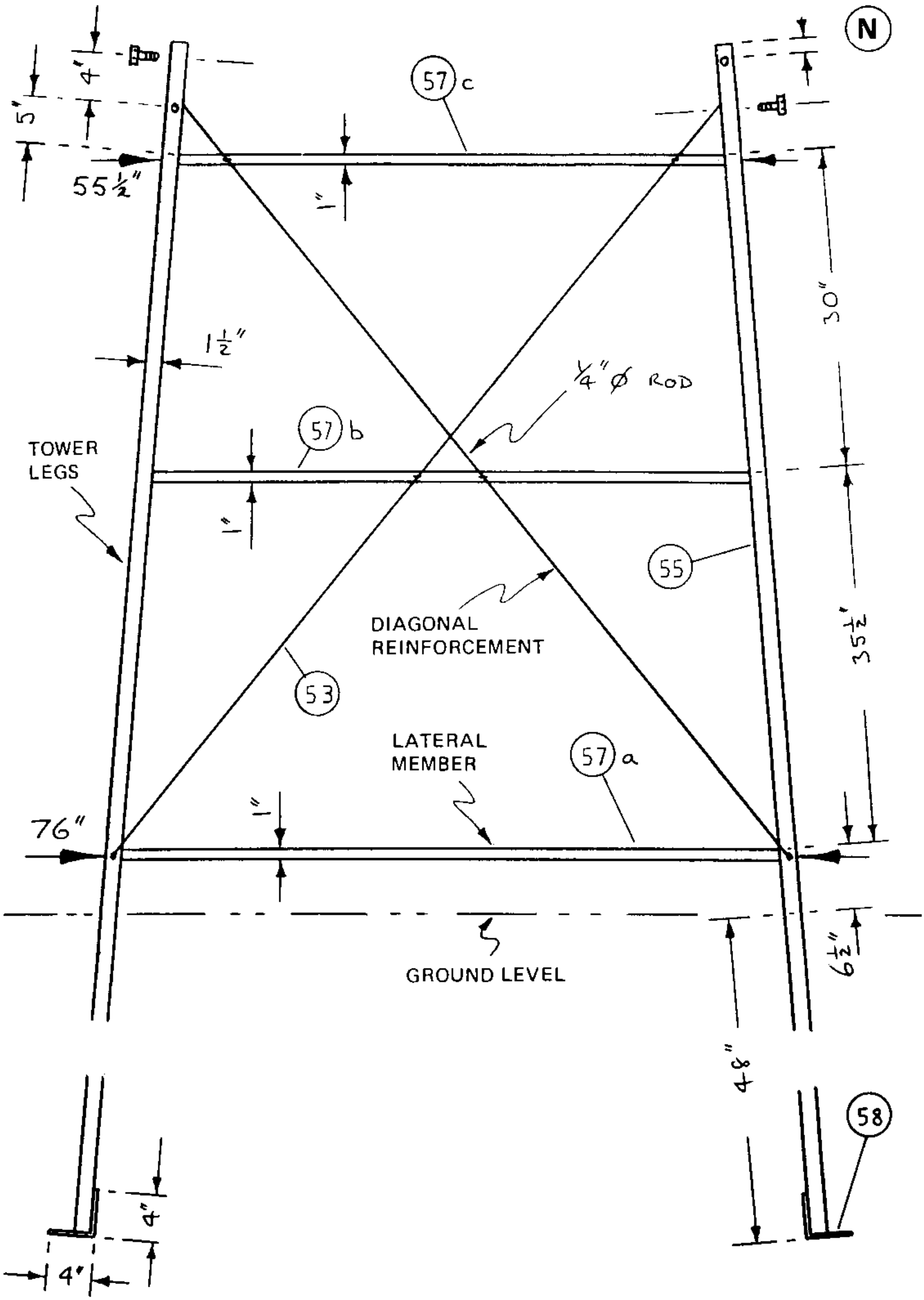

13
15
17
43
48
46
49
40
41
45
5 3/8"
SAFETY STRAP LEG
1"
1/2"
1/4"
1/8"
1 1/2"
1 1/2" x 3/4" O.D.
PIPE ROLLER
1/2" Ø BOLT WELDED
1 3/4"
1" x 3/16"
WELD
SAFETY RING
ROLLER PLATE
1/2" Ø
BOLT
K

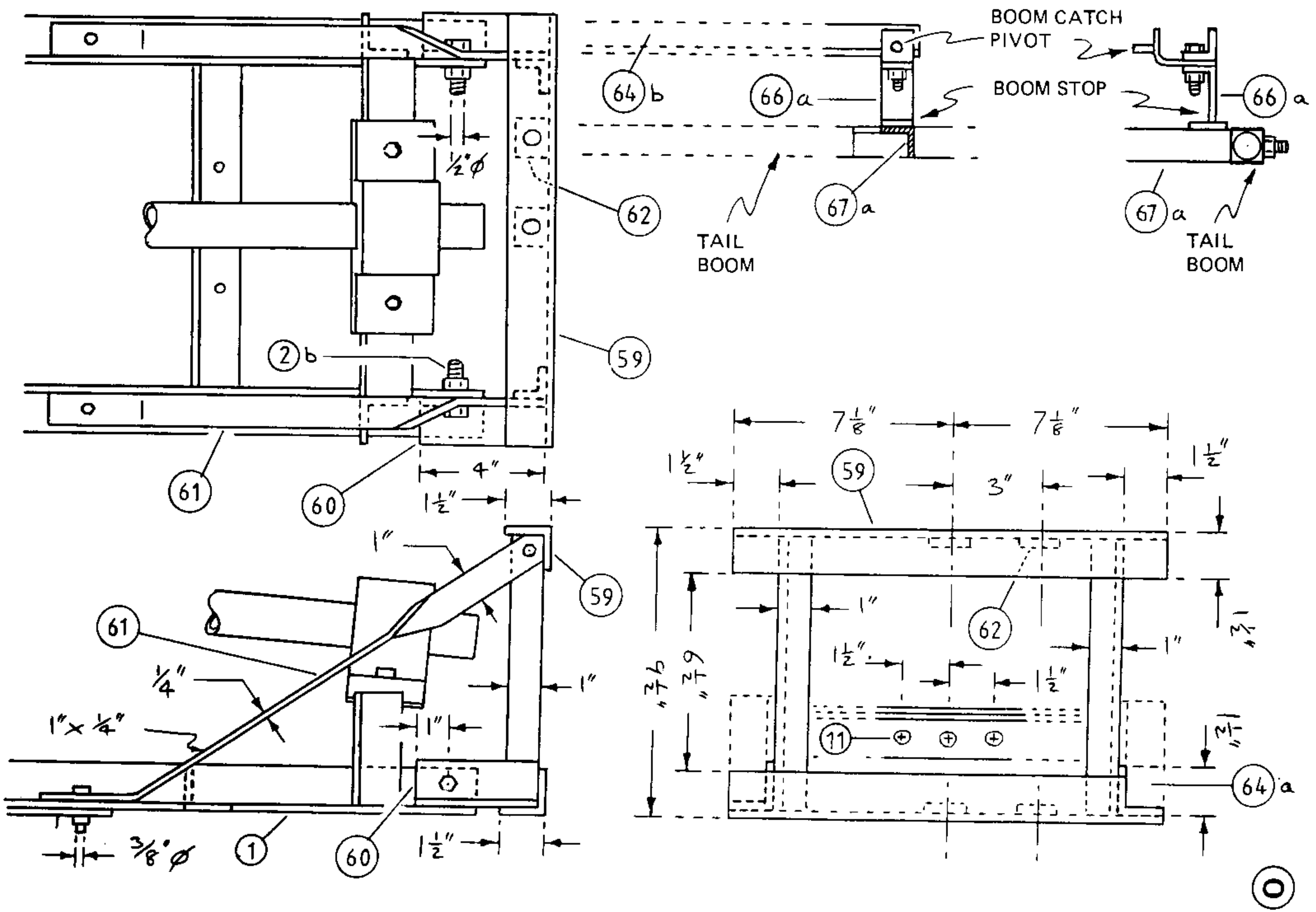


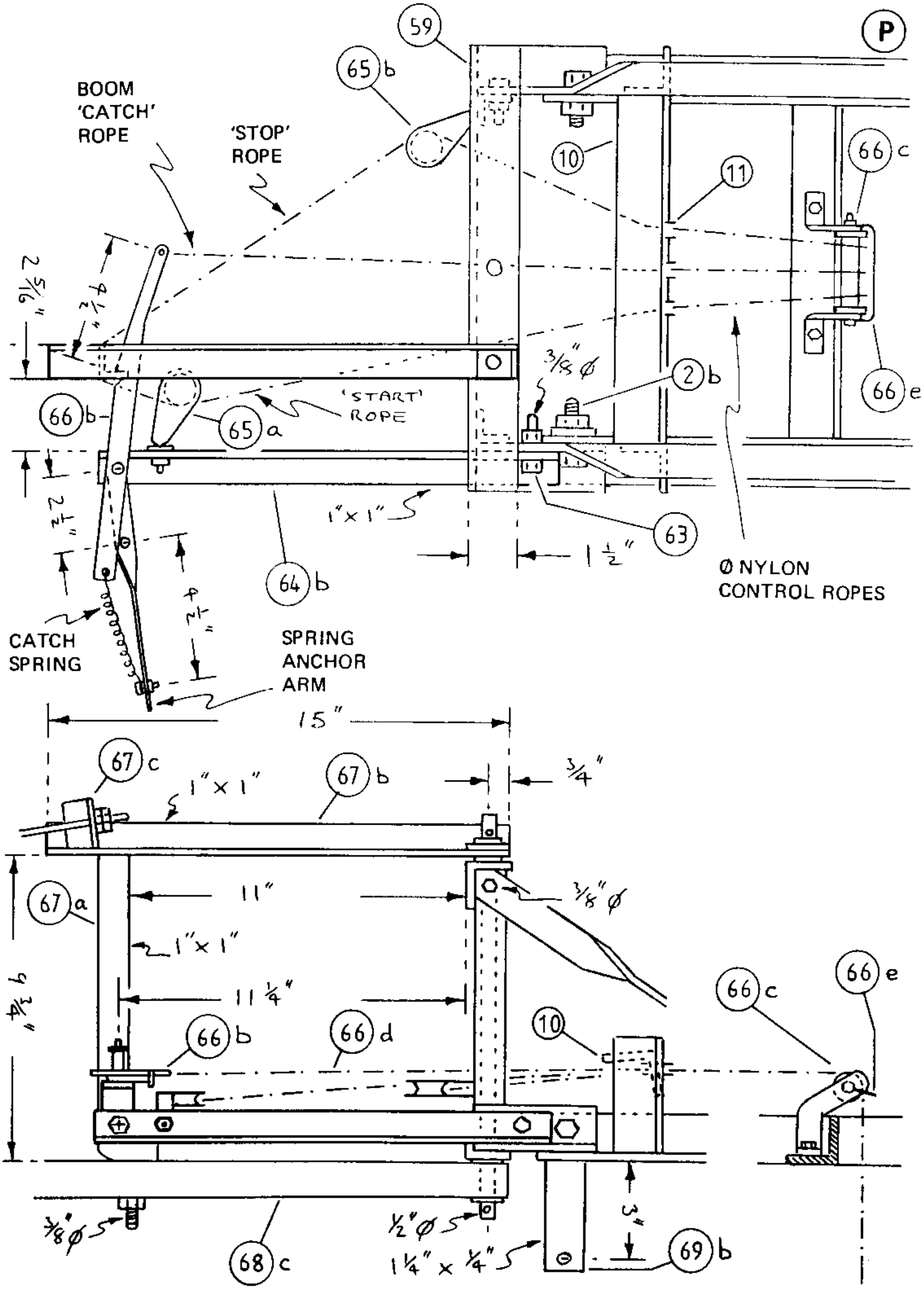
L
TURNTABLE
TRACK
HEAD
FRAME
39
¼" Ø ROD
TOWER LEGS
24"
50
LATERAL
MEMBERS
52
1"
1½"
DIAGONAL
REINFORCEMENT
53
22"
BOTTOM
FRAME
51
5"
½" Ø
BOLTS
24"
¼" Ø
ROD
1½"
39½"
39"
1½"

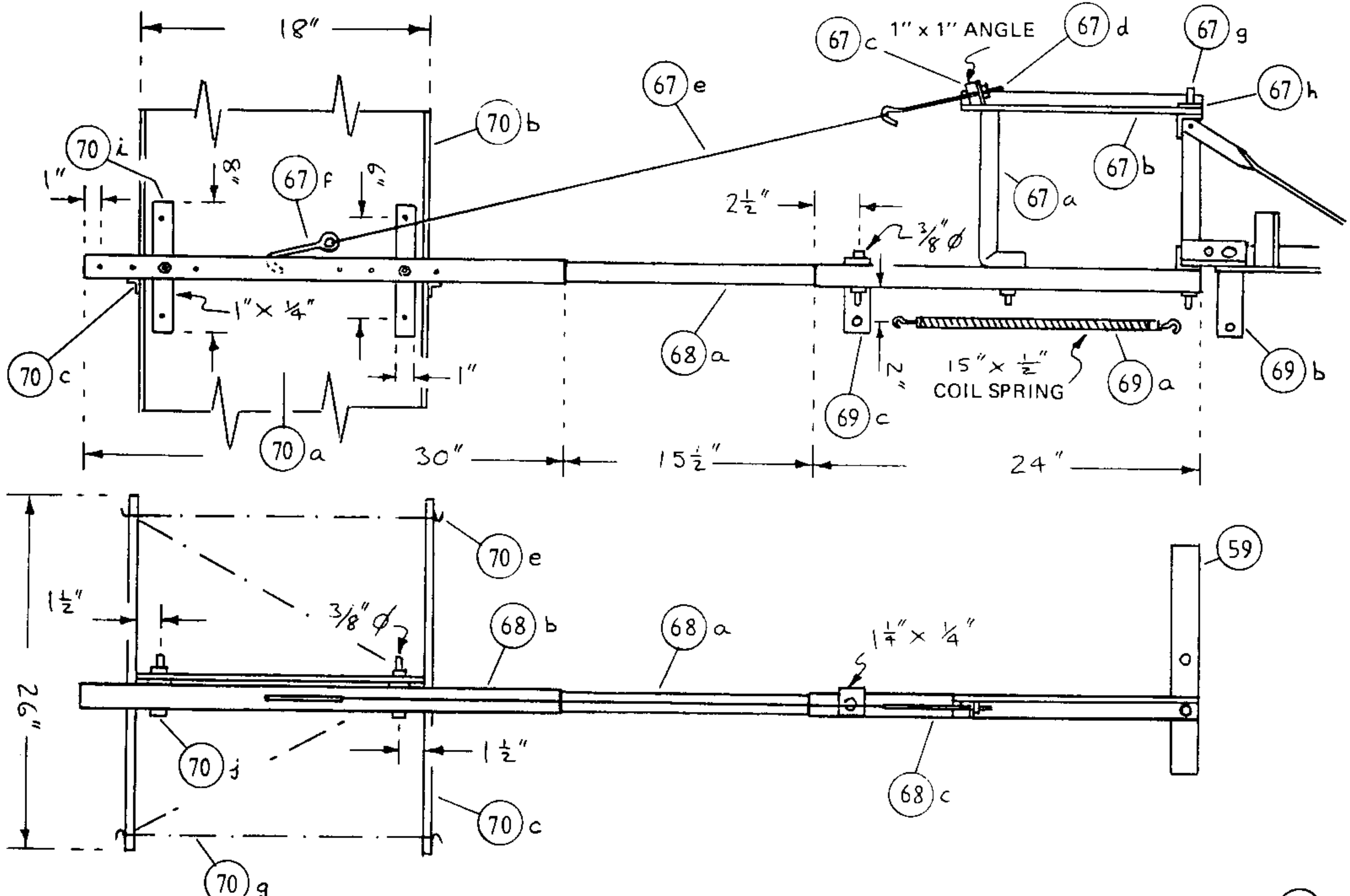


M
24"
51
TOP FRAME
1½"
37½"
TOWER LEGS
54
56 a
1"
36"
DIAGONAL REINFORCEMENT
53
LATERAL MEMBERS
56 b
1"
¼" Ø ROD
34½"
56 c
4"
4"
1"
12½"
55¼"

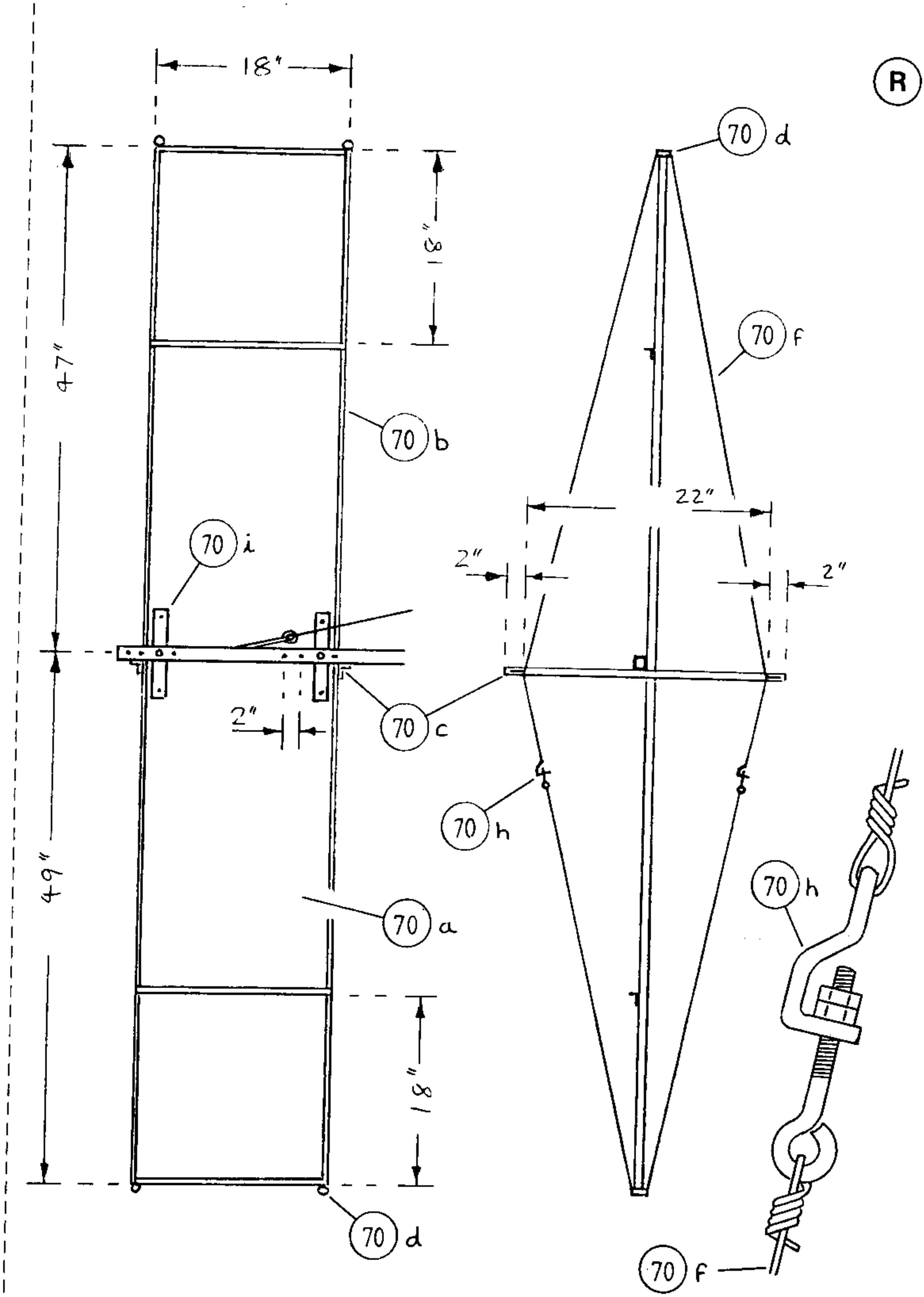

N
57 c
4'
5'
55½"
1"
30"
1½"
¼" Ø ROD
57 b
TOWER
LEGS
1"
55
35½"
DIAGONAL
REINFORCEMENT
53
LATERAL
MEMBER
57 a
76"
1"
GROUND LEVEL
6½"
48"
58
4"
4'

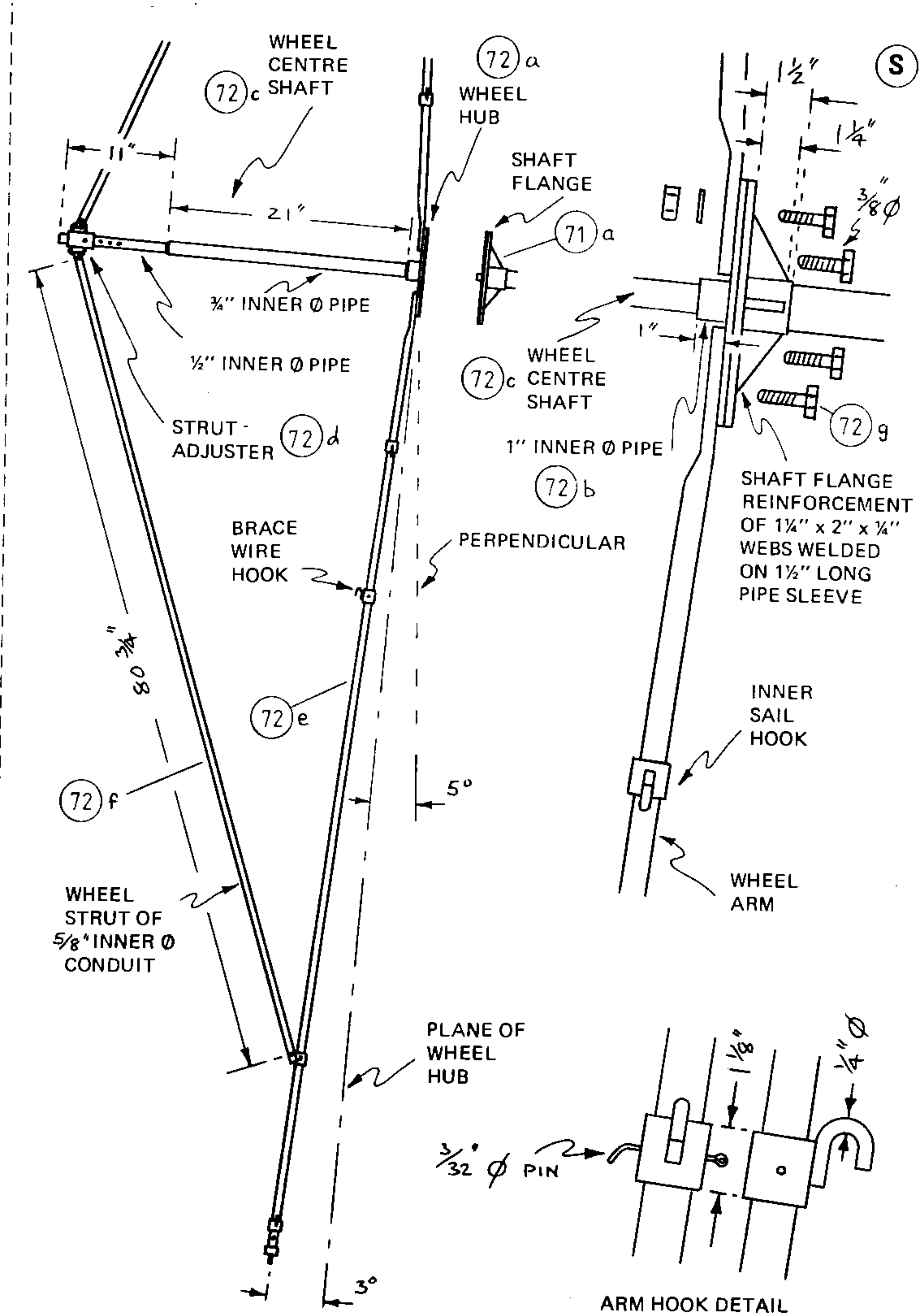

BOOM CATCH
PIVOT
BOOM STOP
TAIL
BOOM
TAIL
BOOM
64 b
66 a
67 a
62
59
60
61
2 b
1/2" ⌀
4"
1 1/2"
1"
1/4"
1" × 1/4"
3/8" ⌀
1
7 1/8"
3"
6 1/2"
9 1/2"
1 1/2"
64 a
11
O

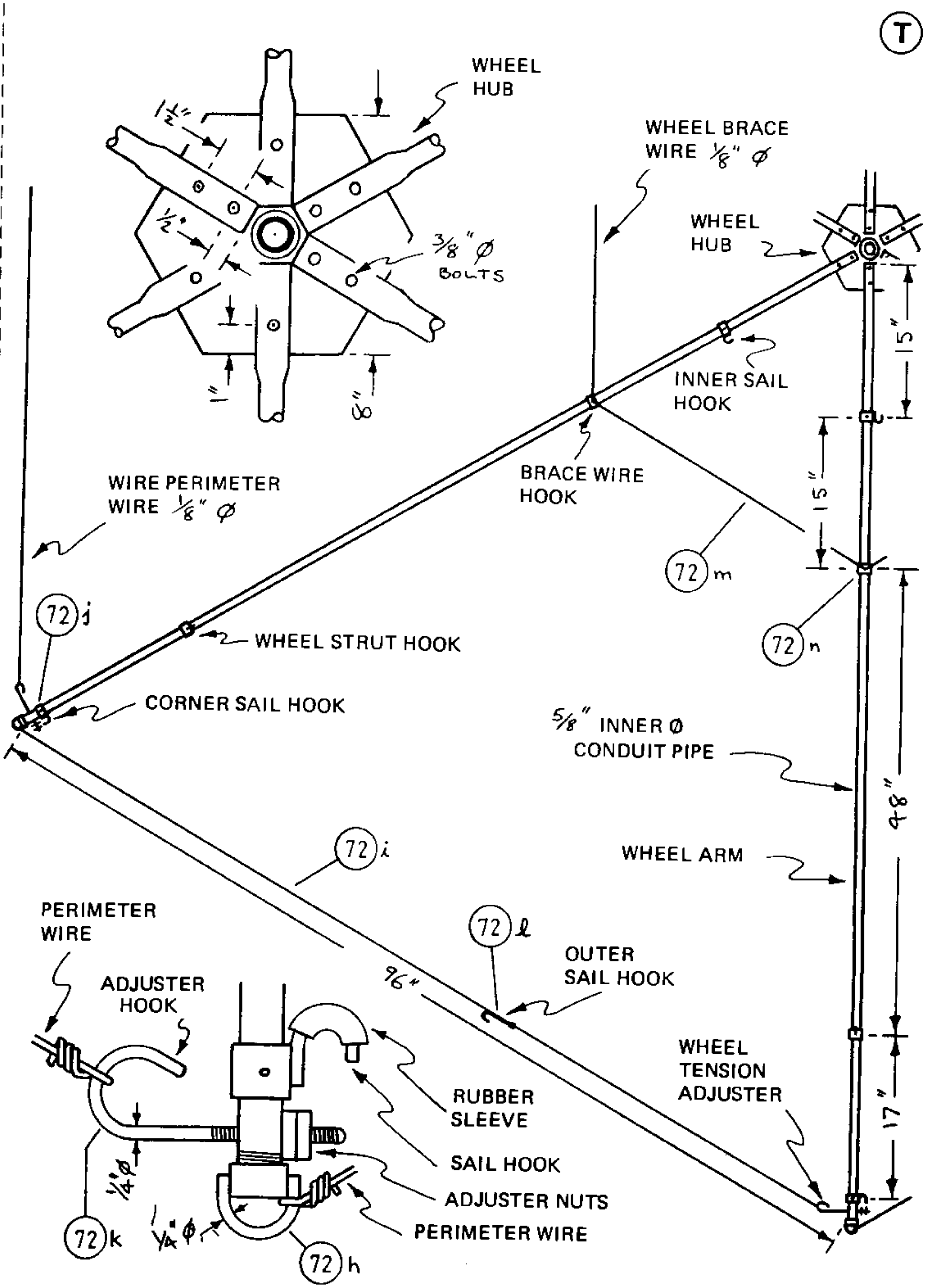

P
59
65 b
BOOM 'CATCH' ROPE
'STOP' ROPE
10
11
66 c
2 5/16"
4 1/2"
3/8" Ø
2 b
66 e
66 b
65 a
'START' ROPE
2 1/2"
1"×1"
63
1 1/2"
Ø NYLON CONTROL ROPES
64 b
4 1/2"
CATCH SPRING
SPRING ANCHOR ARM
15"
67 c
1"×1"
67 b
3/4"
11"
3/8" Ø
67 a
1"×1"
9 3/4"
11 1/4"
66 e
66 c
66 b
66 d
10
3"
3/8" Ø
1/2" Ø
1 1/4" × 1/4"
68 c
69 b

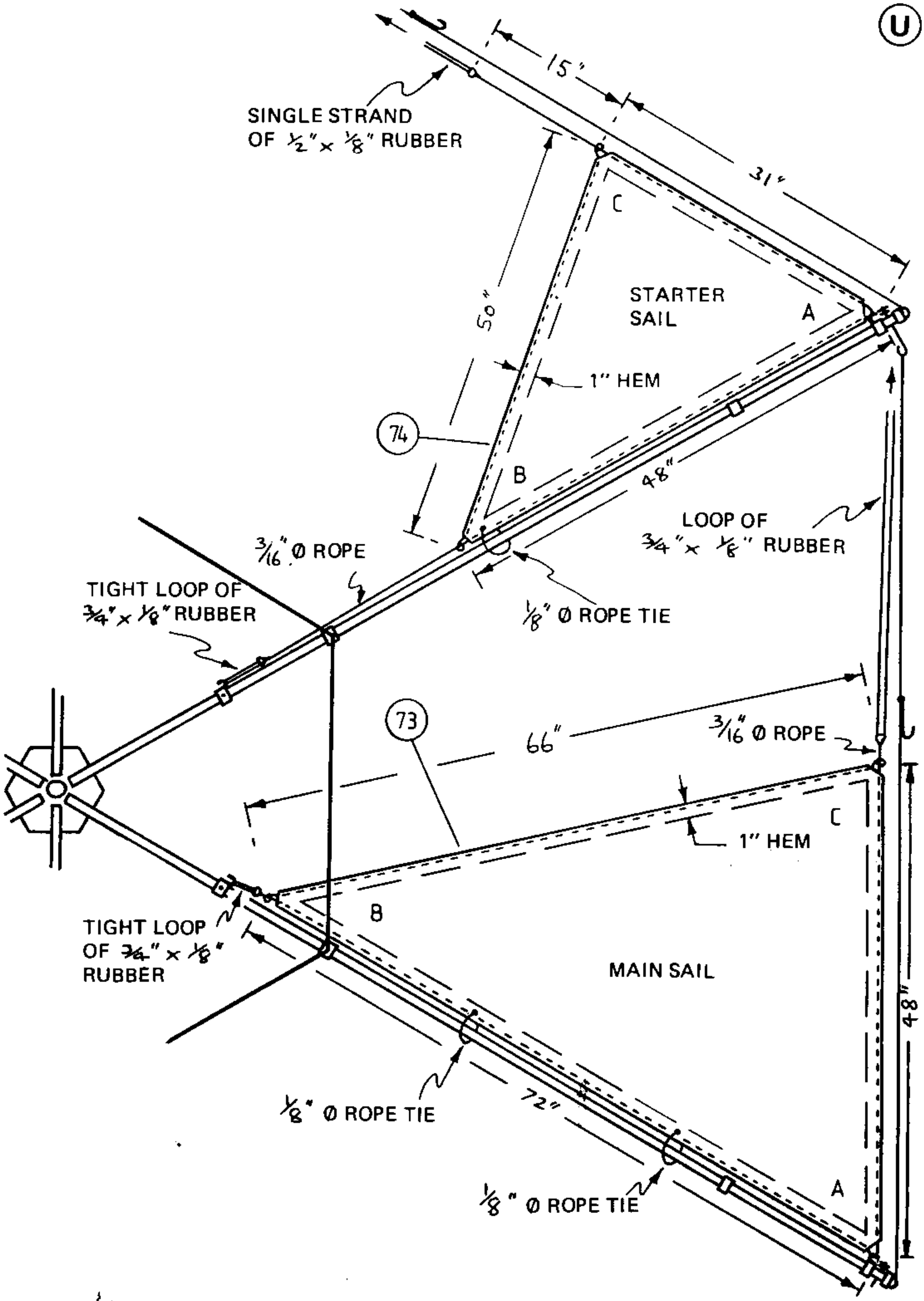

18"
1" x 1" ANGLE
67 c
67 d
67 g
67 e
67 h
70 b
70 i
67 f
67 b
67 a
1"
8"
9"
2 1/2"
3/8" Ø
1" x 1/4"
70 c
68 a
15" x 1/2"
COIL SPRING
69 a
69 b
2"
69 c
1"
70 a
30"
15 1/2"
24"
70 e
59
1 1/2"
3/8" Ø
68 b
68 a
1 1/4" x 1/4"
26"
70 j
1 1/2"
68 c
70 c
70 g

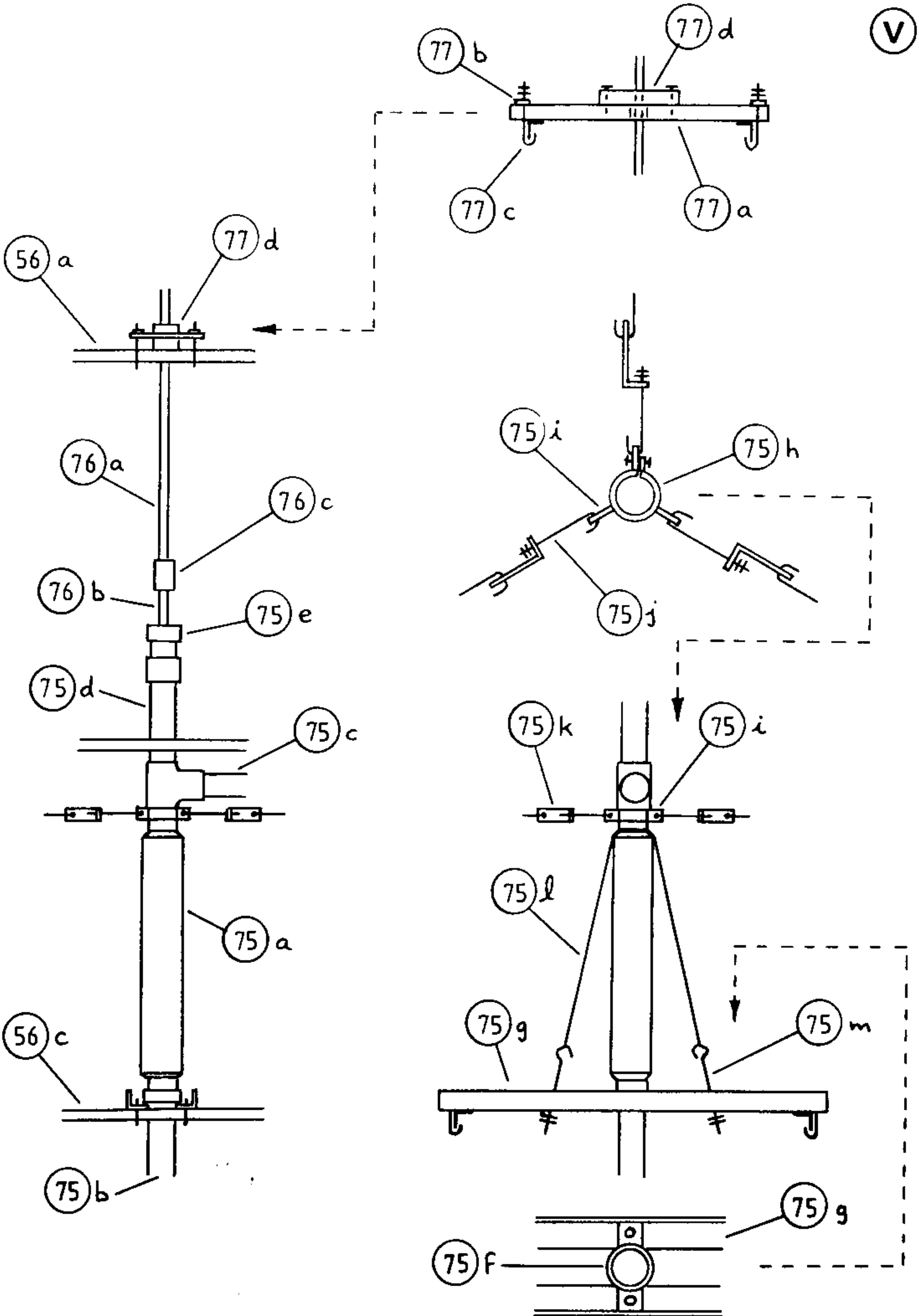
D

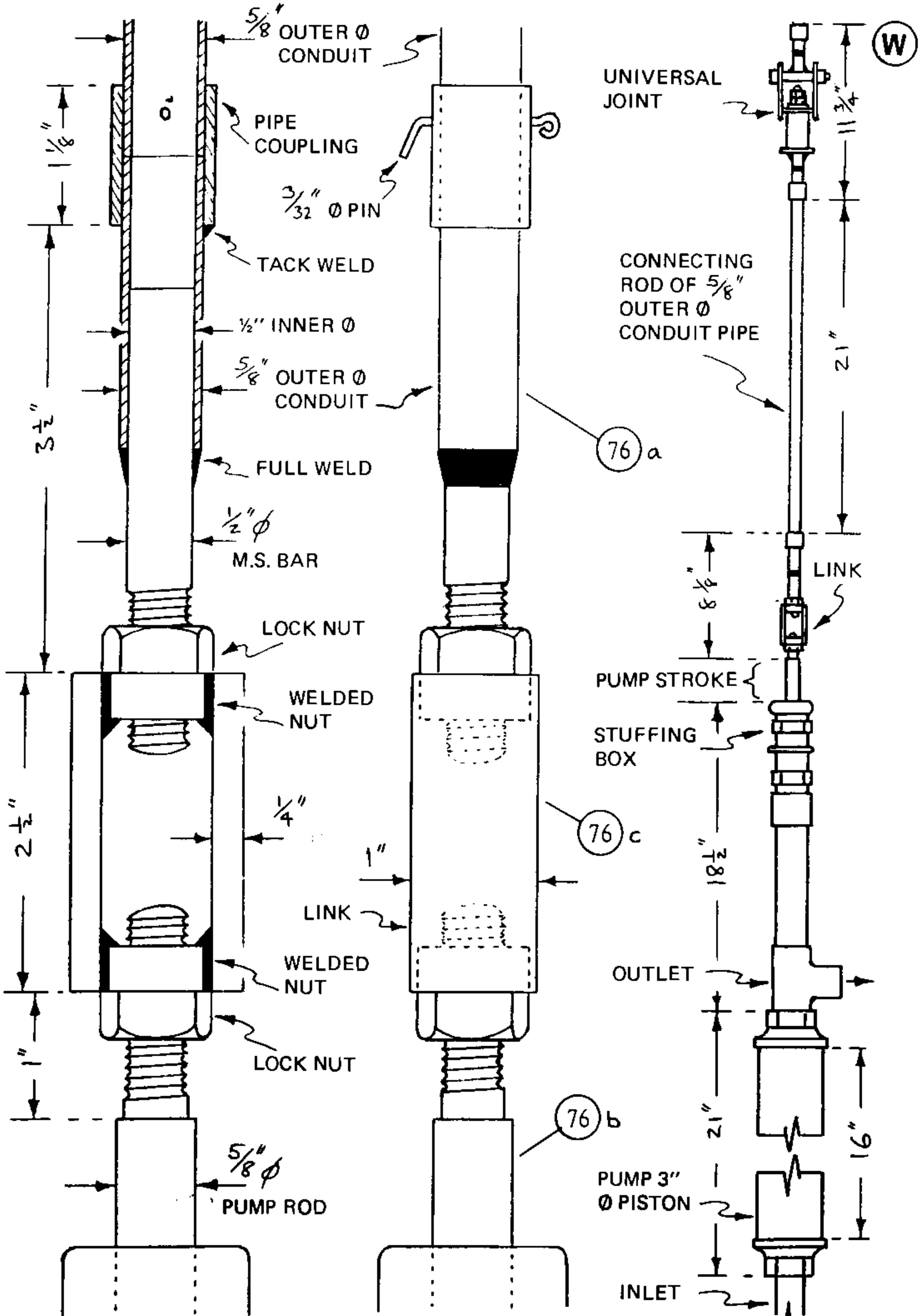

R
18"
18"
47"
49"
18"
22"
2"
2"
2"
70 a
70 b
70 c
70 d
70 d
70 f
70 f
70 h
70 h
70 i


WHEEL
CENTRE
SHAFT
72 c
72 a
WHEEL
HUB
S
1½"
1¼"
11"
21"
SHAFT
FLANGE
71 a
3/8" Ø
¾" INNER Ø PIPE
1"
½" INNER Ø PIPE
WHEEL
CENTRE
SHAFT
72 c
STRUT -
ADJUSTER
72 d
1" INNER Ø PIPE
72 b
72 g
SHAFT FLANGE
REINFORCEMENT
OF 1¼" x 2" x ¼"
WEBS WELDED
ON 1½" LONG
PIPE SLEEVE
BRACE
WIRE
HOOK
PERPENDICULAR
80 ¾"
72 e
INNER
SAIL
HOOK
72 f
5°
WHEEL
ARM
WHEEL
STRUT OF
5/8" INNER Ø
CONDUIT
PLANE OF
WHEEL
HUB
1 1/8"
¼" Ø
3/32" Ø PIN
3°
ARM HOOK DETAIL

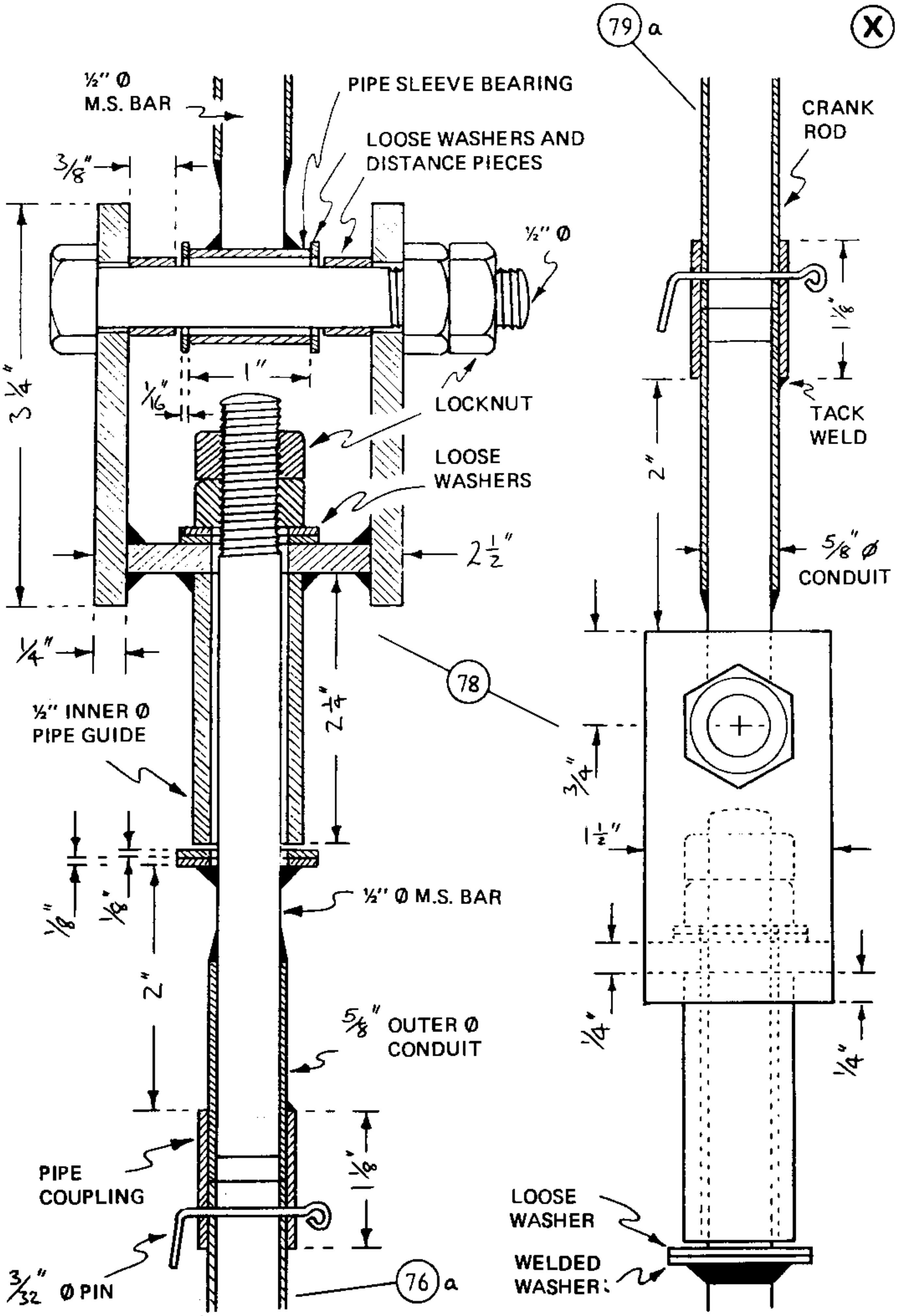

T
WHEEL
HUB
1½"
½"
3/8" Ø
BOLTS
1"
6"
WHEEL BRACE
WIRE 1/8" Ø
WHEEL
HUB
15"
INNER SAIL
HOOK
BRACE WIRE
HOOK
15"
WIRE PERIMETER
WIRE 1/8" Ø
72 m
72 j
72 n
WHEEL STRUT HOOK
CORNER SAIL HOOK
5/8" INNER Ø
CONDUIT PIPE
98"
WHEEL ARM
72 i
PERIMETER
WIRE
72 l
OUTER
SAIL HOOK
ADJUSTER
HOOK
96"
WHEEL
TENSION
ADJUSTER
RUBBER
SLEEVE
17"
1/4" Ø
SAIL HOOK
ADJUSTER NUTS
1/4" Ø
PERIMETER WIRE
72 k
72 h


U
15"
31"
SINGLE STRAND
OF 1/2" x 1/8" RUBBER
C
STARTER
SAIL
A
50"
1" HEM
74
B
48"
LOOP OF
3/4" x 1/8" RUBBER
3/16" Ø ROPE
TIGHT LOOP OF
3/4" x 1/8" RUBBER
1/8" Ø ROPE TIE
73
66"
3/16" Ø ROPE
C
1" HEM
B
TIGHT LOOP
OF 3/4" x 1/8"
RUBBER
MAIN SAIL
48"
1/8" Ø ROPE TIE
72"
A
1/8" Ø ROPE TIE


V
77 b
77 d
77 c
77 a
56 a
77 d
76 a
76 c
76 b
75 e
75 d
75 c
75 a
56 c
75 b
75 i
75 h
75 j
75 k
75 i
75 l
75 g
75 m
75 g
75 f



5/8" OUTER Ø CONDUIT
PIPE COUPLING
1 1/8"
3/32" Ø PIN
TACK WELD
½" INNER Ø
5/8" OUTER Ø CONDUIT
3 ½"
FULL WELD
½" Ø M.S. BAR
LOCK NUT
WELDED NUT
2 ½"
1/4"
1"
LINK
WELDED NUT
LOCK NUT
1"
5/8" Ø PUMP ROD
76 a
76 c
76 b
W
UNIVERSAL JOINT
11 3/4
CONNECTING ROD OF 5/8" OUTER Ø CONDUIT PIPE
21"
8 1/4"
LINK
PUMP STROKE
STUFFING BOX
18 ½"
OUTLET
21"
16"
PUMP 3" Ø PISTON
INLET


79 a
X
½" Ø
M.S. BAR
PIPE SLEEVE BEARING
LOOSE WASHERS AND
DISTANCE PIECES
3/8"
3 1/4"
½" Ø
1"
1/16"
LOCKNUT
LOOSE
WASHERS
2 1/2"
1/4"
78
2 1/4"
½" INNER Ø
PIPE GUIDE
1/8"
1/8"
½" Ø M.S. BAR
2"
5/8" OUTER Ø
CONDUIT
PIPE
COUPLING
1 1/8"
3/32" Ø PIN
76 a
CRANK
ROD
1 1/8"
TACK
WELD
2"
5/8" Ø
CONDUIT
3/4"
1 1/2"
1/4"
1/4"
LOOSE
WASHER
WELDED
WASHER

In 1974 Bob Mann, the author, was posted to the Gambia to work with the Christian Council on a small-scale village level agricultural programme. One of the projects in hand was the introduction of vegetable production and the prevailing method of irrigation was by bucket carried from nearby wells. While this was adequate during the nine month dry season, it was obviously a limiting factor for future development. The need for a simple mechanical water-lifting device was recognised and work began on its development.

The design was based on a series of low-lift windmills which had been developed for the Geleb tribesmen by the American Presbyterian Mission at their station near the Omo River in Ethiopia (*Food from Windmills* by Peter Fraenkel, Intermediate Publications, 1975). However, as the wind regime in the Gambia is much lighter, the design had to be adapted accordingly and was improved at the same time. The final result was a very successful windpump which, when scientifically tested, pumped nearly twice as much water as the original Omo design.

The text, photographs and drawings in *How to Build a 'Cretan Sail' Windpump* are extremely precise and accurate and any practical engineer should find no difficulty in building a windpump from the plans and details provided.

Bob Mann, a versatile and creative engineer, was formally an ITDG Agricultural Project officer and has had wide experience in designing and developing agricultural machinery for the Intermediate Technology Development Group. He has produced over 30 simple and practical tools for the small farmer. Before working with ITDG, he spent some years with the Ministry for Agriculture, Tanzania on various aspects of agricultural development. His other publications include *Rural Africa Development Project: An Example of Farm Land Survey Techniques Using Local Resources* and *How to Make a Metal-Bending Machine*.

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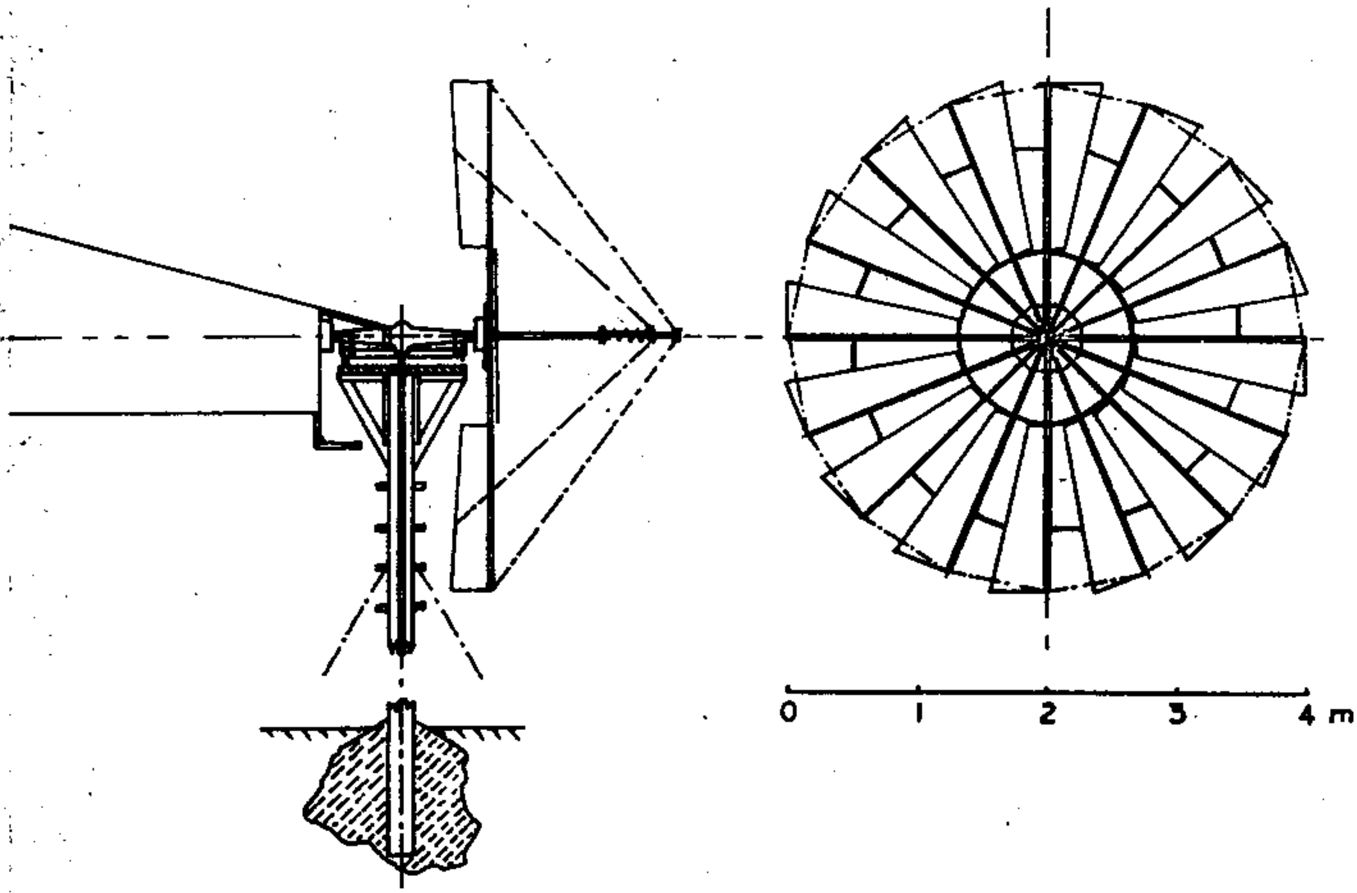
£ 6.95

ISBN 0-903031-66-3
9 780903 031660

The Intermediate Technology Development Group was founded by the late Dr E.F.Schumacher. Intermediate Technology enables poor people in the Third World to develop and use technologies and methods which give them more control over their lives and which contribute to the long-term development of their communities.

Intermediate Technology Publications is the publishing arm of the Intermediate Technology Development Group and is based at 103/105 Southampton Row, London WC1B 4HH, UK.



Low-cost Windmill for Developing Nations

multi-vane fan type

HARTMUT BOSSEL

a VITA publication

VITA, Inc.

First printing 1970

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AUG 1976
NOV 1976
FEB 1977
OCT 1977

INTRODUCTION

The VITA windmill (Fig. I1) is a complete aerodynamic and structural redesign of an earlier prototype designed, built and tested by W. Delameter and P. Miller under the supervision of H. Bossel of the Mechanical Engineering Department. The fullscale prototype proved the soundness of the rotor design, overloading control (blade feathering), and directional control (vane).

The VITA windmill consists of five major components: the transmission, the rotor with overloading control (feathering), the vane for directional control, the turntable (supporting rotor, transmission, and vane), and the platform and tower structure.

The rotor is constructed from steel rod, support wires, and sheet metal blades hinged to the spokes. A simple spring-loaded mechanism allows the blades to feather in high winds or when overloaded. The mechanism is explained in Fig. I2. The rotor center plate is bolted to the brake drum of the rear axle of a small car. The wheelbrake stops the rotor when it is not is use. The other wheel is permanently locked, resulting in a transmission ratio of about 1:4 from the horizontal to the vertical. The rear axle is free to swivel about the vertical on a turntable. A vane, which is set at a small angle to counteract the torque transmitted vertically, keeps the rotor pointing into the wind. The whole assembly is mounted on a small platform on a single-beam tower.

Detailed blueprints are not presented in this report, since the design will differ with the materials, parts, and skills the builder finds at his disposal. He should understand that most dimensions and details (except those stated explicitly) are not critical, and can be adapted to suit the needs. There are a few exceptions in particular. First, number, shape, and angles of the blades should remain unchanged to obtain the specified performance. Second, the control spring should come close to the stated specifications in order to adequately protect the rotor from possible destruction. Third, vane area, vane arm from the vertical axis, and vane angle should remain as given in the report for the same rotor and transmission ratio. More generally, the product (vane area) x (vane arm) x (vane angle) should remain constant, where the vane angle should always be less than about ten degrees. This product must remain proportional to the torque transmitted; i.e., it should be doubled if a transmission ratio of 1:2 instead of 1:4 is used for the same rotor.

A few possible modifications of the basic design might be of interest.

Automobile rear axles offer a rather wide choice of transmission ratios depending on how they are mounted, and whether one wheel drum or the slip gears are locked or removed. This range is from approximately 1:4 from rotor to vertical shaft if the rotor is mounted on the wheel drum, to 4:1 if the rotor is mounted on the drive shaft side. In the first case, a second rear axle and/or an automobile gear box could be used to further increase the rotational speed and drive a centrifugal pump, circular saw, electric generator, feed mill and the like. In the second case, the slow rotation would permit driving directly a reciprocating pump, or other machninery requiring slow rotation. In that case, the torque in the vertical shaft cannot be counteracted by the aerodynamic torque of a vane of reasonable size and the rotor must either be mounted rigidly in the direction of prevailing winds, or turned manually and locked, or turned by a nonreversible control mechanism (which would greatly increase the complexity). Manual turning should also be considered for the case of lower torque and higher shaft speed of rotation. It would eliminate the vane and simplify the central bearing problem, since less precision and some friction would be permitted. Specifications for a smaller 2 meter windmill, and suggestions for electric power generation are provided in the Appendix.

PERFORMANCE DATA

Performance at sea level

Windspeed				
m/sec	4	6	8	10
km/h	14.4	21.6	28.8	36.0
mph	9.0	13.4	17.9	22.4
Rotor speed				
revolutions per minute (rpm)	21.0	31.5	42.0	52.5
Rotor torque				
mkg_f	8.8	19.8	35.2	55.0
ft lb	63.6	143.2	255.0	398.0
Starting torque				
mkg_f	15.3	34.5	61.4	96.0
ft lb	111.0	250.0	445.0	695.0
Power				
mkg_f/sec	18.1	61.1	145.0	283.0
kw	0.177	0.60	1.42	2.77
hp	0.24	0.81	1.91	3.73

Altitude effects

Altitude					
m	0	1000	2000	3000	4000
ft	0	3280	6560	9840	13,100
percentage reduction of power and torque					
%	0	9	18	26	33

(rotor rpm unaffected)

Feathering Information

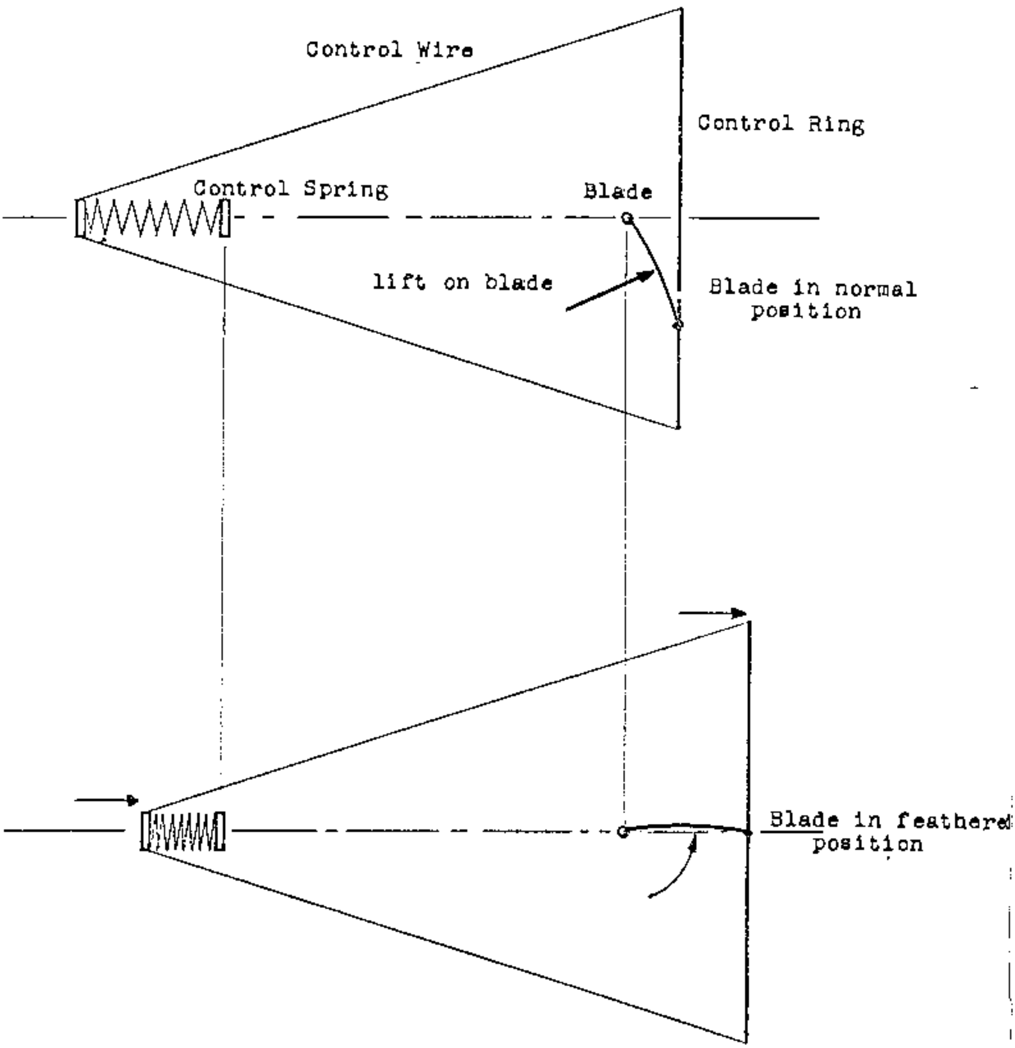
For control spring of spring constant 1.5kg_f/cm precompressed to 13.5 kg_f:

Rotor braked: Blades begin to feather at a wind speed V of 6 m/sec. Blades fully feathered at V = 10 m/sec.

Rotor running under load: Blades begin to feather at V = 8 m/sec. Blades fully feathered (and rotor stopped) at V = 12.5 m/sec.

Rotor running free: Little or no feathering. Rotor speed will increase with wind speed, and damage is likely. Always brake rotor when not running under load.

Sketch of Blade Feathering Mechanism



When lift on blades becomes excessive, control spring compresses and blades feather so that blade angle is steeper, thus slowing the rotor. When windmill is stopped, blades feather parallel to wind. Control ring forces all blades to feather evenly.

Fig. I2

TOOLS

Protractor (to measure angles)
Hack saw
Welder (gas or electric)
Sheet metal shears
Steel drills (approximately 3 to 30 mm)
Hammer
Pliers
Adjustable wrenches, or set of wrenches

General Notes:

All sheet metal, nuts, bolts, wires, nails should be galvanized, if available.

All nuts must be secured by using spring washers, lock washers, or a second nut tightened against the first.

CONVERSIONS

1 m = 100 cm = 1000 mm = 3.28 ft = 39.4 in
1 in = 25.4 mm
1 kg_f = 2.2 lb_f

1 m/sec = 3.6 km/h = 2.24 mph
1 kw = 1.34 hp

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United Nations, Proceedings of the United Nations Conference on New Sources of Energy, Volume 7, Wind Power, United Nations Publication Sales No: 63.I.41, New York, 1964.

W. Delameter, R. Sprankle, Park H. Miller III, Windmill and Waterpump for Developing Nations. Mechanical Engineering Dept., University of California, Santa Barbara, Calif., June 1969.

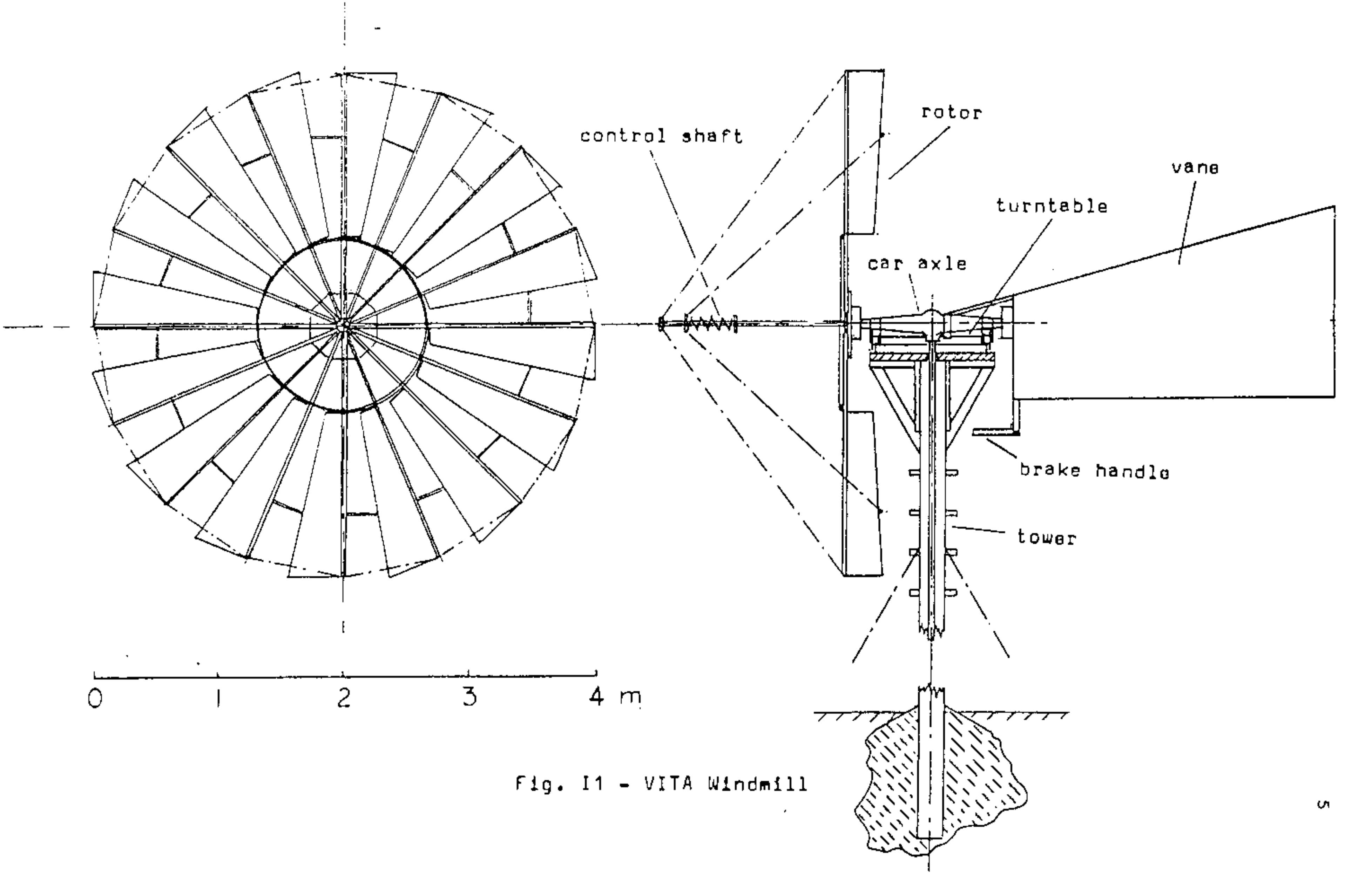


Fig. I1 - VITA Windmill

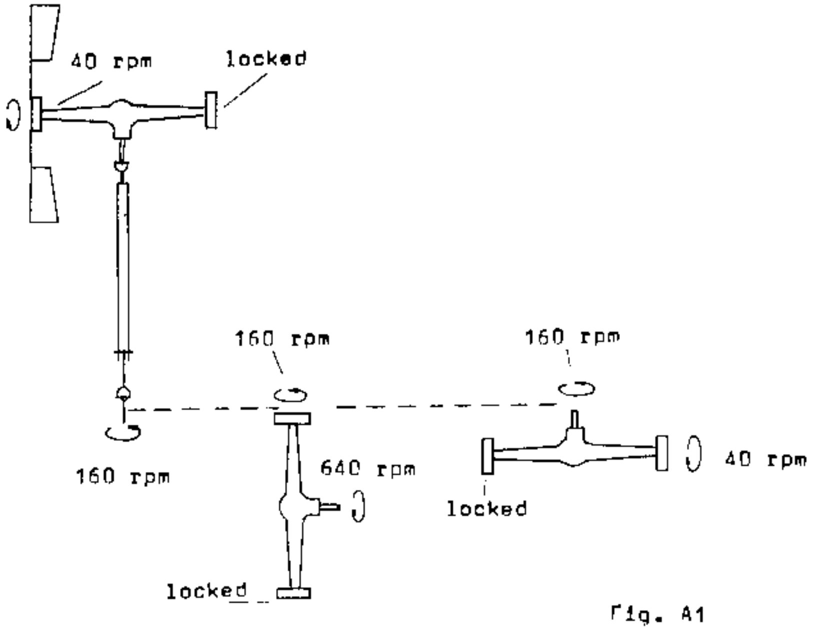


Fig. A1

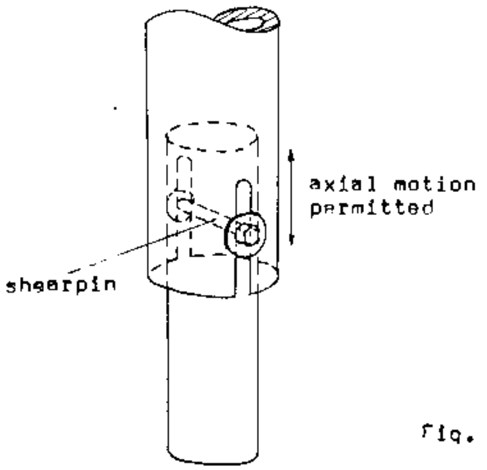


Fig. A2

TRANSMISSION

The present design uses a rigid rear axle and differential (from a small car) with mechanical brakes. Other car axles can be used with corresponding modifications. If the wheels have hydraulic brakes, use the master brake cylinder and other components from the car brake system to build a rotor brake system.

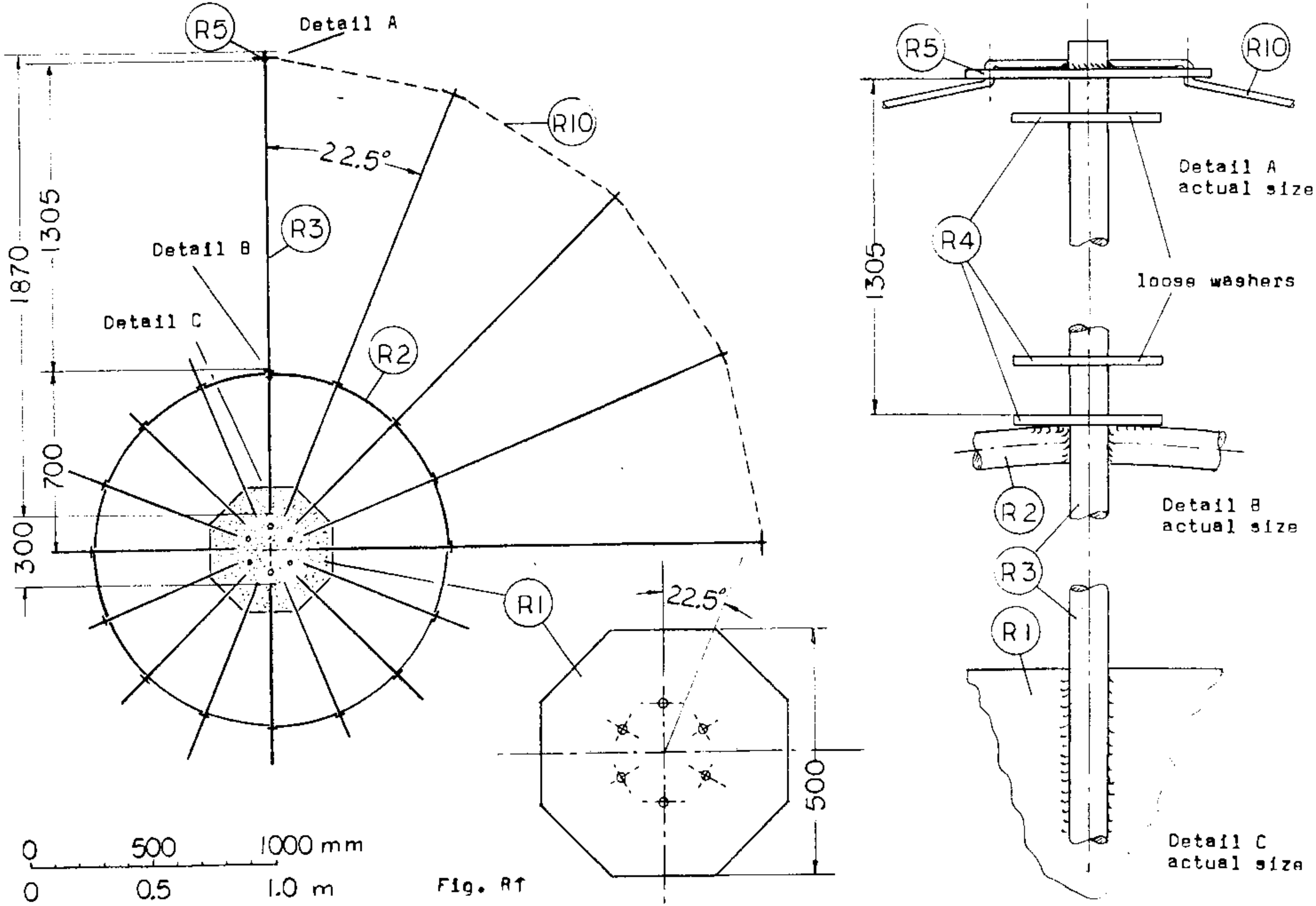
Lock permanently the wheel drum on which the vane is to be mounted, by either locking the brake completely and permanently, or by blocking the slip gear. In most cars the rotational speed of the drive shaft will then be approximately four times higher than that of the rotor mounted on the wheel drum.

The drive shaft and the two universal joints are used to transmit the rotor power to the driven machinery (see Fig. A1). The drive shaft can be lengthened by using pipe of approximately 20 to 40 mm outer diameter. Note: Permit some axial motion of the drive shaft to allow for thermal expansion and use shear pin to prevent damage (see Fig. A2).

Various possibilities of transmissions using a second automobile rear axle and/or automobile transmission are shown in Fig. A1.

ROTOR

Part number	Quantity	Remarks (see Figs. R1 - R7)
R1	1	Steel plate 0.5m x 0.5m, approximately 5 mm thick. For mounting on axle, drill same drill pattern as required for rear wheels (Fig. R1).
R2	1	Steel rod (same as for spokes), 4.35m long, approximately 6 to 8 mm diameter. Bend into circle of 1.39m outer diameter, weld ends together (Fig. R2)
R3	16	Round steel rods for spokes 1.87m long, approximately 6 to 8 mm diameter (Fig. R1).
R4	48	Washers to fit loosely on spokes, approximately 2mm thick, 30mm outer diameter. Note: washers can be square and home-made from sheet metal.
R5	16	Sheet metal strips approximately 50mm x 70mm 2-3mm thick. Drill one centerhole to fit on spokes (R3) and three holes for wire (R10) and rigging wire (R13) (Fig. R1, Fig. R4).
R6	16	Galvanized sheet metal blades, made from 8 pieces 1.3m x 0.75m, approximately 0.5mm thick (Fig. R2).
R7	48	Sheet metal strips, approximately 50mm x 70mm; 1.5 - 2mm thick. Bend to shape shown (Fig. R2).
R8	16	Sheet metal strips, approximately 50mm x 50mm; same material as vanes (Fig. R2).
R9	16	Rubber strips, approximately 50mm x 100mm, made from side walls of used car tire (Fig. R2).
R10	1	Steel wire or cable, 26m long, 2 - 3 mm diameter.
R11	1	Steel wire or cable, 6 m long, 2 - 3 mm diameter.
R12	8	Steel wire or cable, 2.5m long, 2 - 3 mm diameter.
R13	16	Steel wire or cable, 3 m long, 2 - 3 mm diameter.
		Rivets or small nuts and bolts to fasten hinges and rubber strips on vane.



R5
Detail A
R10
22.5°
R3
Detail B
Detail C
R2
R1
1870
1305
700
300
22.5°
500
0
500
1000 mm
0
0.5
1.0 m
R4
Detail A
actual size
loose washers
Detail B
actual size
Detail C
actual size

Fig. R1

CONSTRUCTION OF ROTOR

Prepare parts (R1) - (R10).

Make the blade bending rig (Fig. R3). Bend blades (R6) into correct shape (see Fig. R3). Hint: Use rollers, or bend by hand over piece of pipe. Take care that hinge line remains straight.

Rivet or bolt hinges (R7) to vanes (Fig. R2). Very important: make sure hinges line up exactly.

Rivet or bolt rubber strips (R9) between blade (R6) and washer plate (R8) (Fig. R2, Fig. R6).

Weld spokes (R3) to centerplate (R1) (Fig. R1).

Weld ring (R2) to spokes at correct (22.5°) intervals (Fig. R1).

Weld 16 washers (R4) to intersections of ring (R2) and spokes (R3) (Fig. R1, Fig. R5).

Slide one washer (R4) on each spoke.

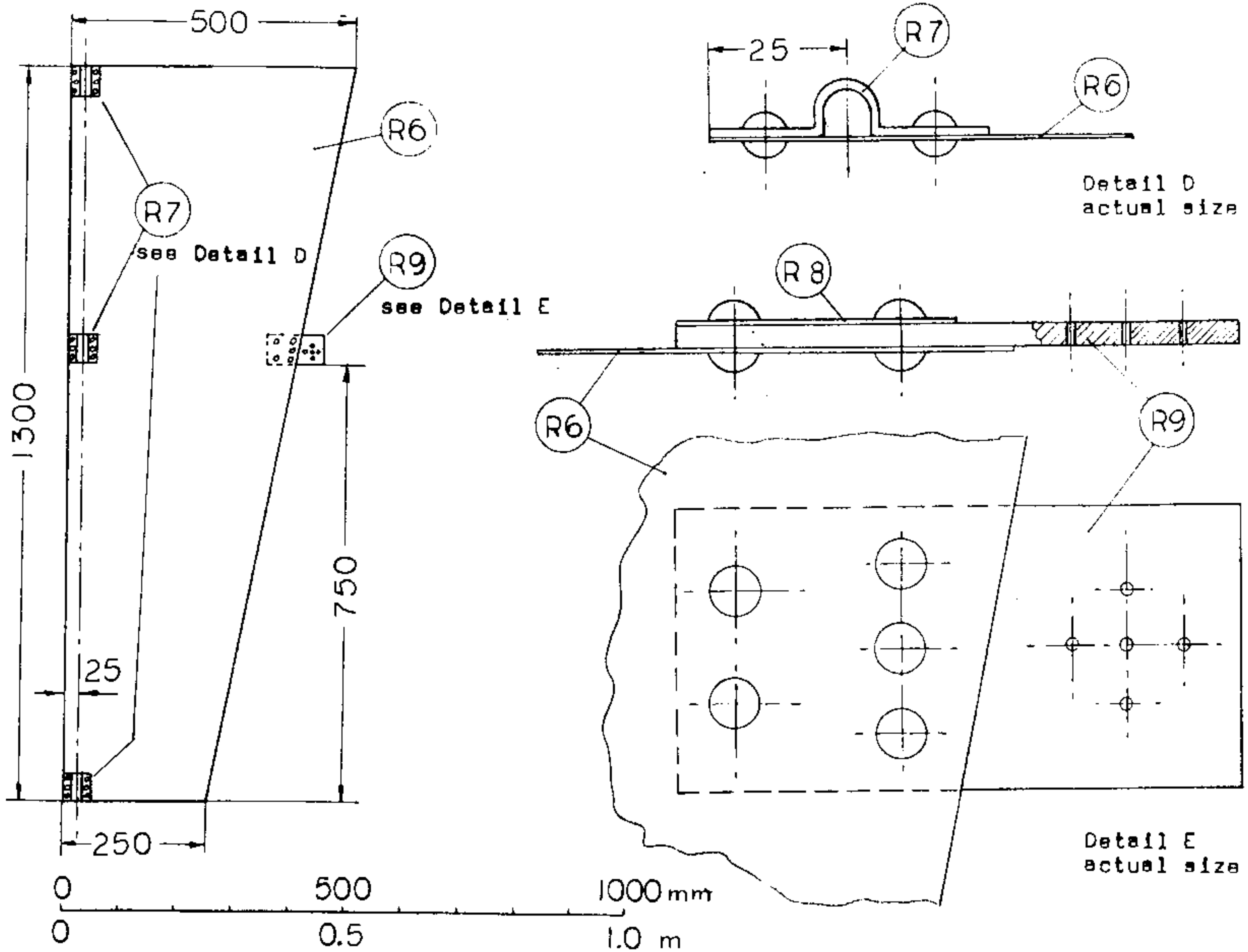
Grease spokes at hinge locations.

Slide blades on spokes with the wider blade tip facing outward. Very important: All blades must rotate freely. If this is not the case, adjust blade shape, spokes, or hinge locations.

Slide one washer (R4) on each spoke.

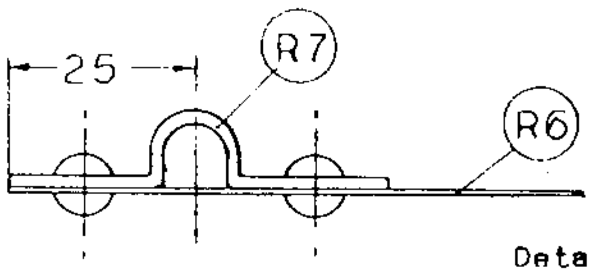
Weld parts (R5) onto tips of spokes, giving about 1 mm play (blade movement in the direction of the spoke) (Fig. R1, Fig. R4).

Thread wire or cable (R10) through holes of parts (R5) and align spokes at 22.5° intervals (Fig. R4). After completing circle, stretch taut and connect both ends.

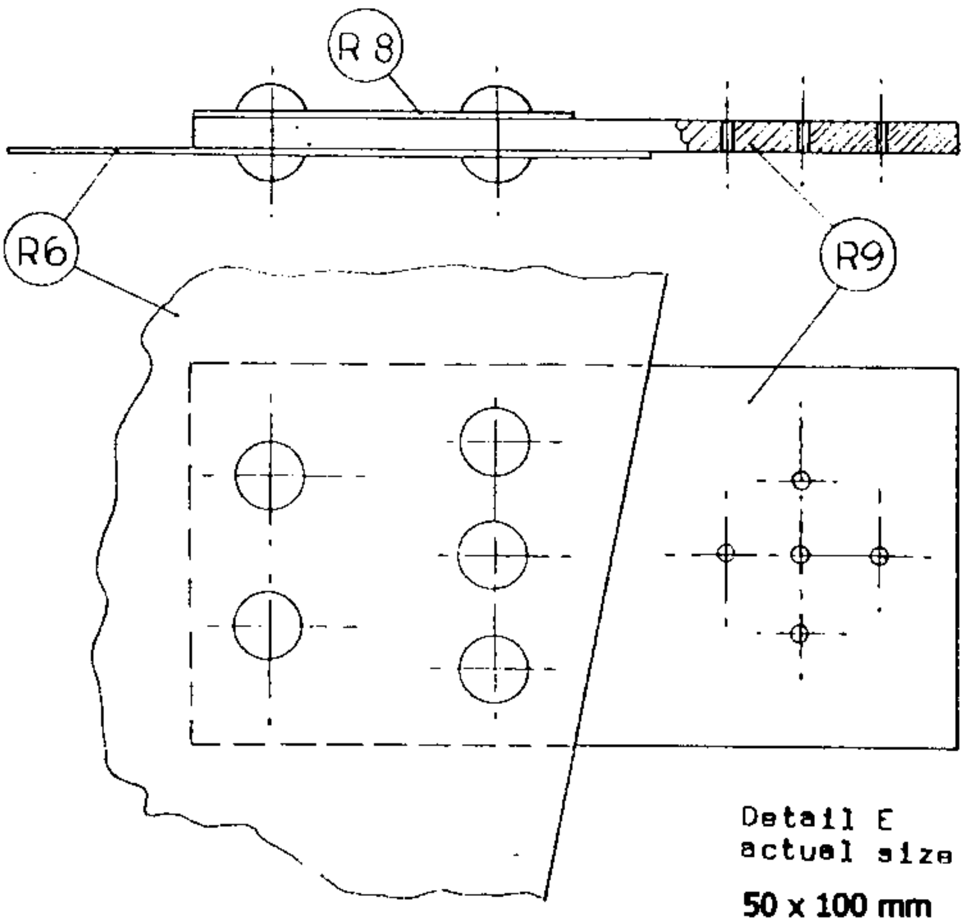


500
1300
R6
R7
see Detail D
R9
see Detail E
750
25
250
0
500
1000 mm
0
0.5
1.0 m
25
R7
R6
Detail D
actual size
R 8
R6
R9
Detail E
actual size

Fig. R2



Detail D
actual size



Detail E
actual size

50 x 100 mm

Fig. R2

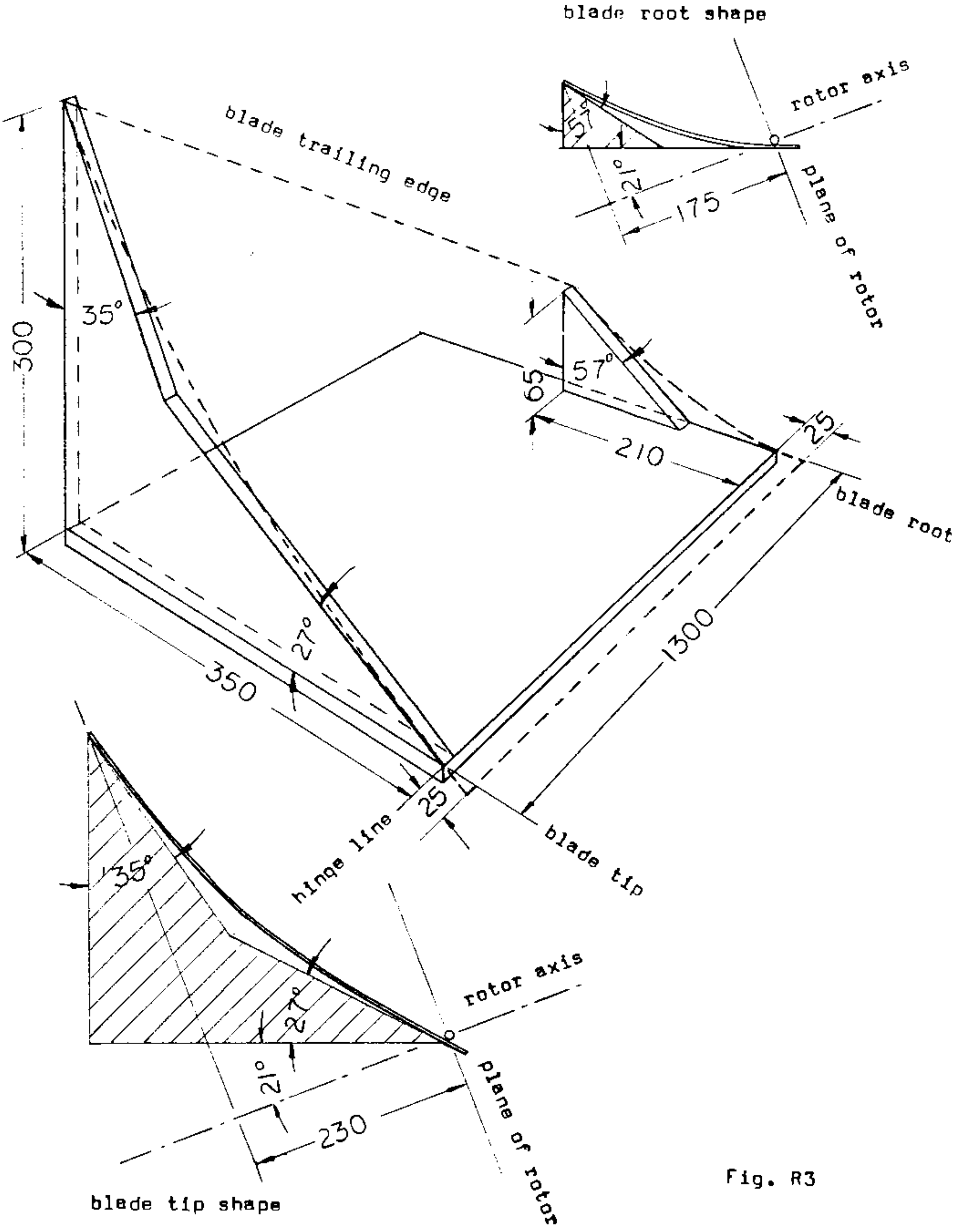

blade root shape
rotor axis
57°
21°
175
plane of rotor
blade trailing edge
35°
300
57°
65
210
25
blade root
1300
27°
350
25
hinge line
blade tip
35°
27°
rotor axis
21°
230
plane of rotor
blade tip shape

Fig. R3

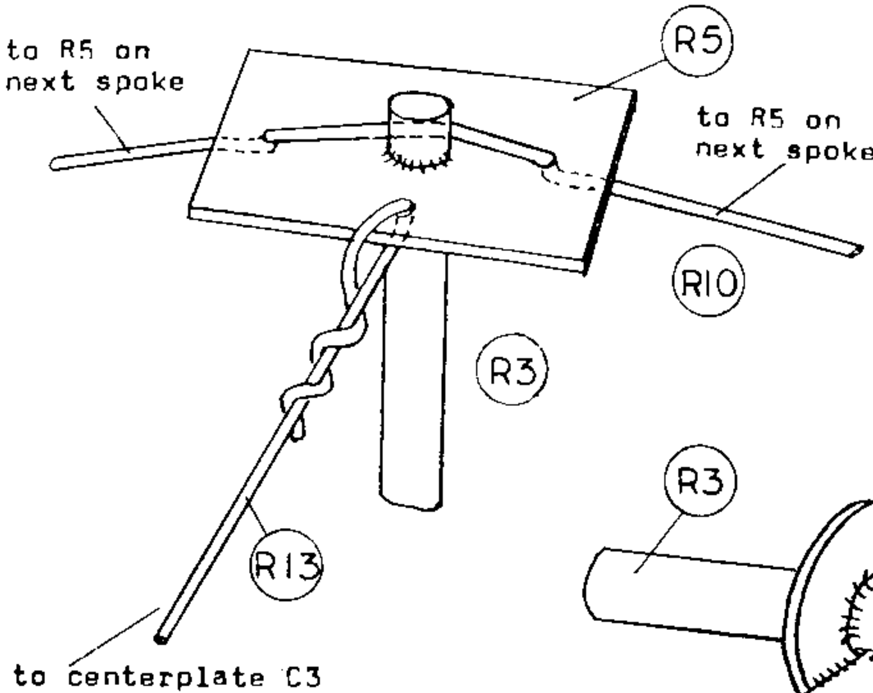


Fig. R4

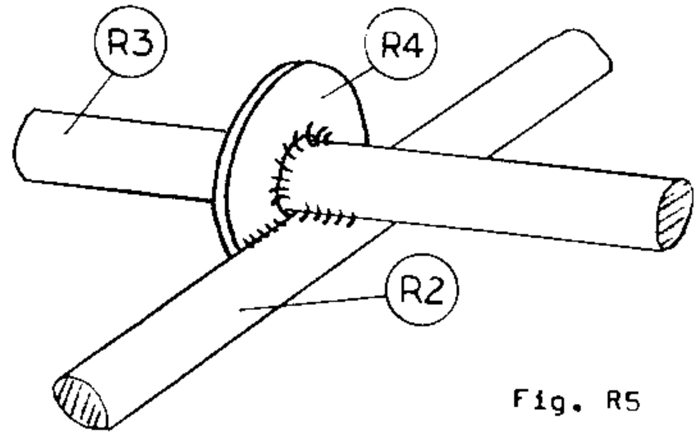


Fig. R5

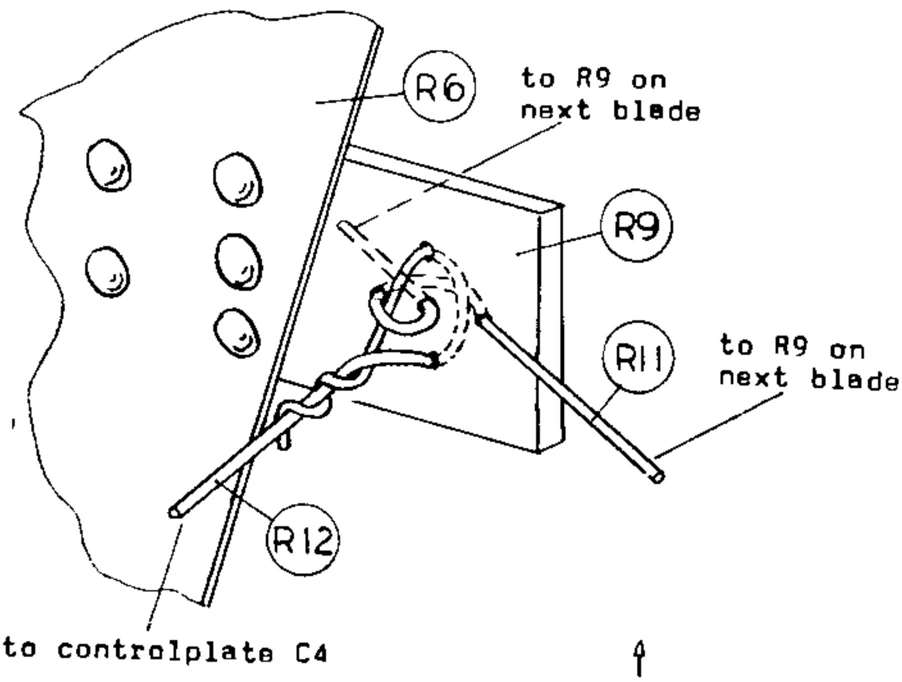
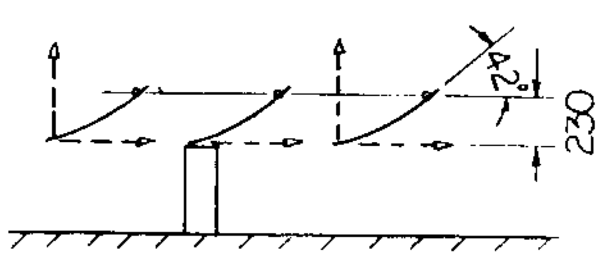


Fig. R6



blade tip alignment

Fig. R7

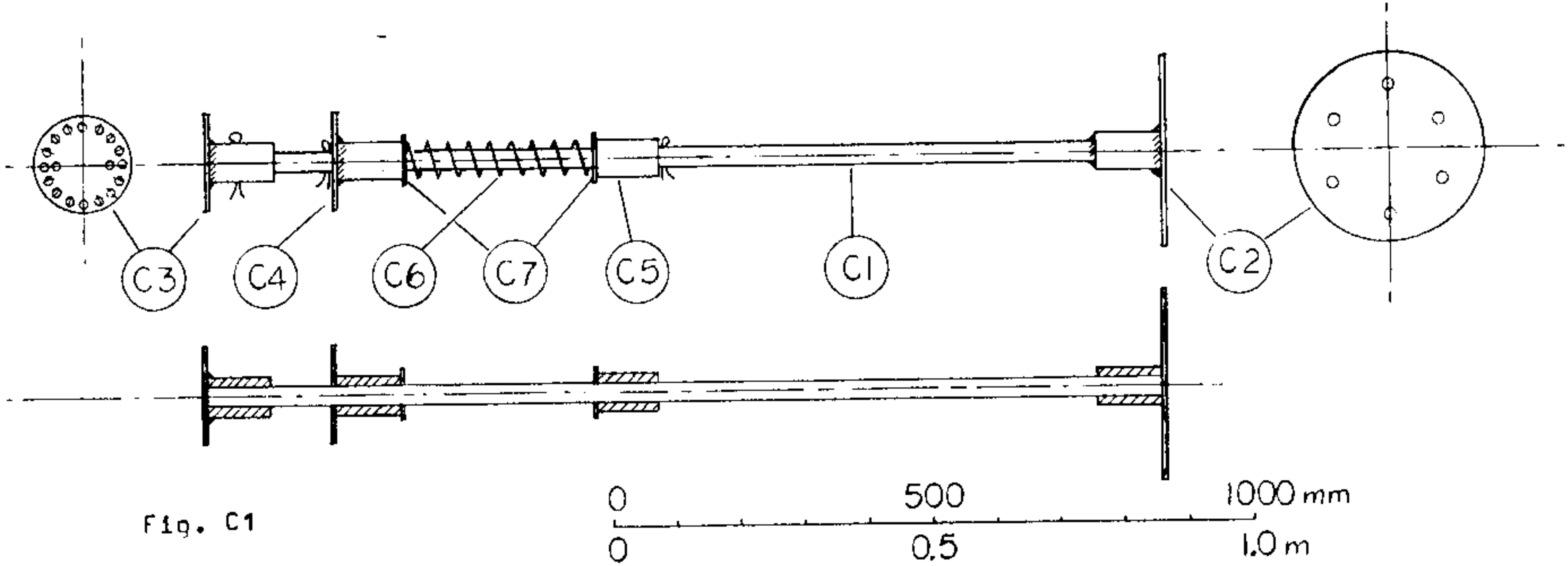


Fig. C1

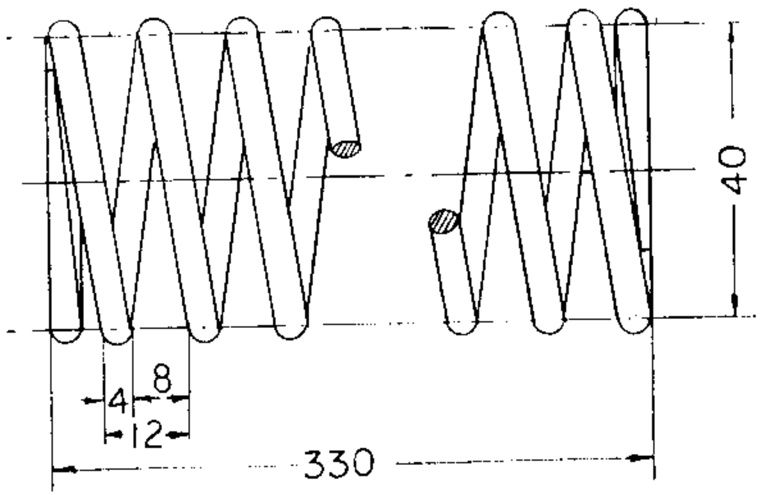


Fig. C2 - Control spring

CONTROL SHAFT

Part number	Quantity	Remarks **(See Figs. C1 - C3)**
C1	1	Steel pipe, 25 to 30 mm outer diameter, 1.5m long.
C2	1	Inner diameter same as outer diameter of part (C1). Use piece of pipe (also for C3, C4, C5). Drill end plate for wheel bolts (same drill pattern as part (R1)).
C3	1	Inner diameter same as part (C2). Plate has 16 evenly spaced holes for 16 support wires, and 2 holes for restraining rods (C8).
C4	1	Similar to part (C3), except plate has central hole and part slides freely on part (C1). 8 evenly spaced holes for 8 control wires, and 2 holes for restraining rods (C8).
C5	1	Part must slide on part (C1).
C6	1	Compression spring, approximately 330 mm long. Spring **constant** must be approximately 1.5 kg_f/cm (i.e. a compression of 1 cm for a weight of 1.5 kg). Note: Make spring from 4 mm steel wire according to Fig. C2, if suitable spring cannot be found. A softer spring can be used, but it must also be precompressed to 13.5 kg_f. Springs harder than 2 kg_f/cm should not be used.
C7	2	Washers (if spring diameter is larger than the outer diameter of parts (C4) and (C5)). Size depends on spring diameter. Make out of sheet metal approximately 2 mm thick.
C8	2	Wire, approximately 3 to 4 mm diamter, 400 mm long. Bend during installation (Fig. C3).
	4	Cotter pins, bolts, or wire to secure parts (C3), (C4), (C5) on shaft (C1).
	4	small washers

CONSTRUCTION OF CONTROL SHAFT

Make parts (C1) - (C7).

Lubricate shaft with heavy grease at the location of parts (C4) - **(C7).**

Mount all parts on shaft (C1) as shown.

Secure parts (C3) and (C4) by cotter pins, bolts, or wire.

Compress spring to a force of 13.5 kg_f and secure part (C5) by cotter pin, bolt, or wire at this location.

Install wires (C8) with washers as shown (Fig. C3). Bend each end to a loop. Wires **must** stick out 130 mm when pulled. (These **wires** prevent blades from going over dead center.)

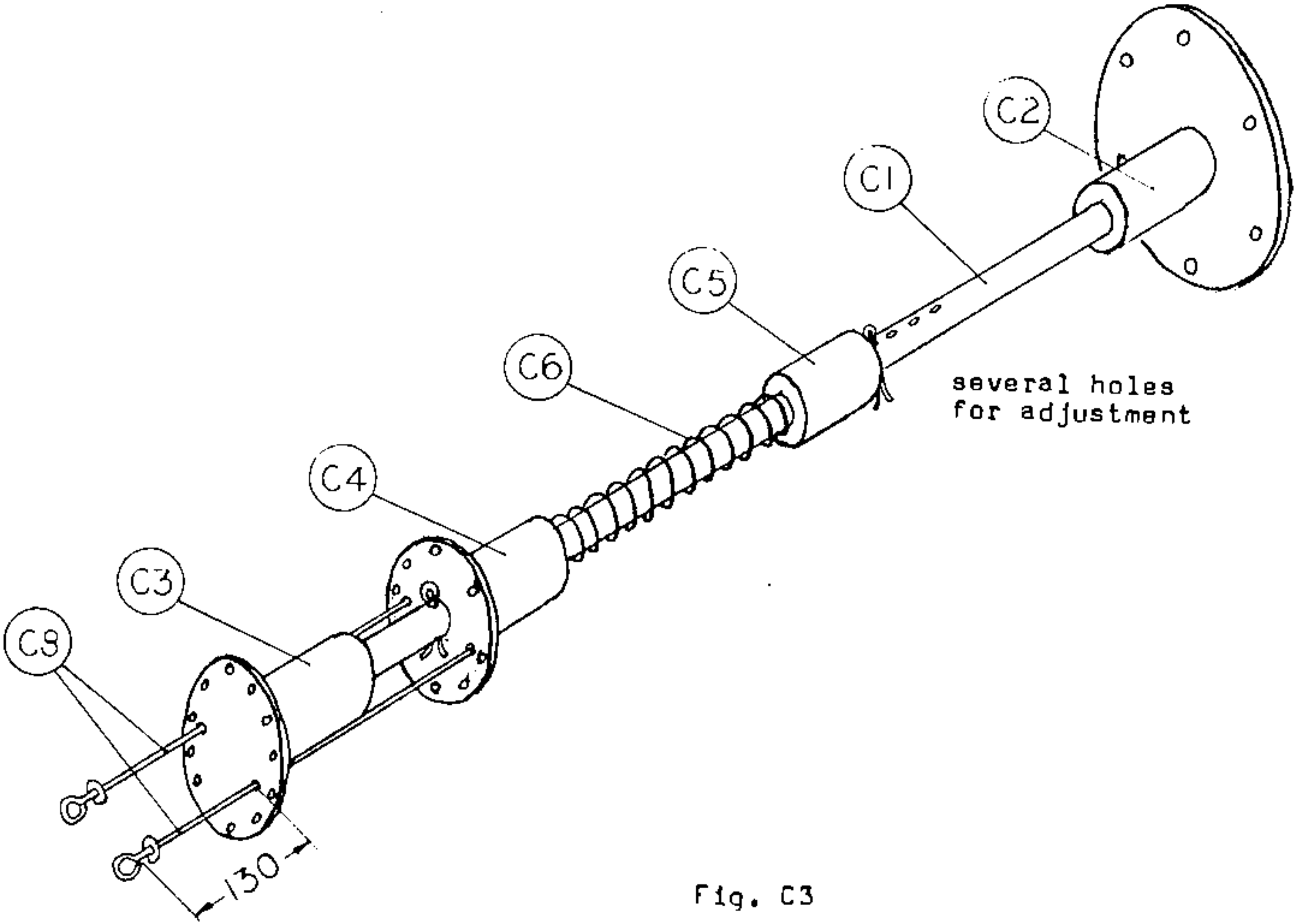


Fig. C3

ROTOR ASSEMBLY

Lay center plate (R1) of rotor on blocks to raise it approximately 0.5 m from the ground. (Side to which the spokes are welded "up"). Temporarily bolt the control shaft in place by two bolts through plates (C2) and (R1). Make sure control shaft is exactly vertical.

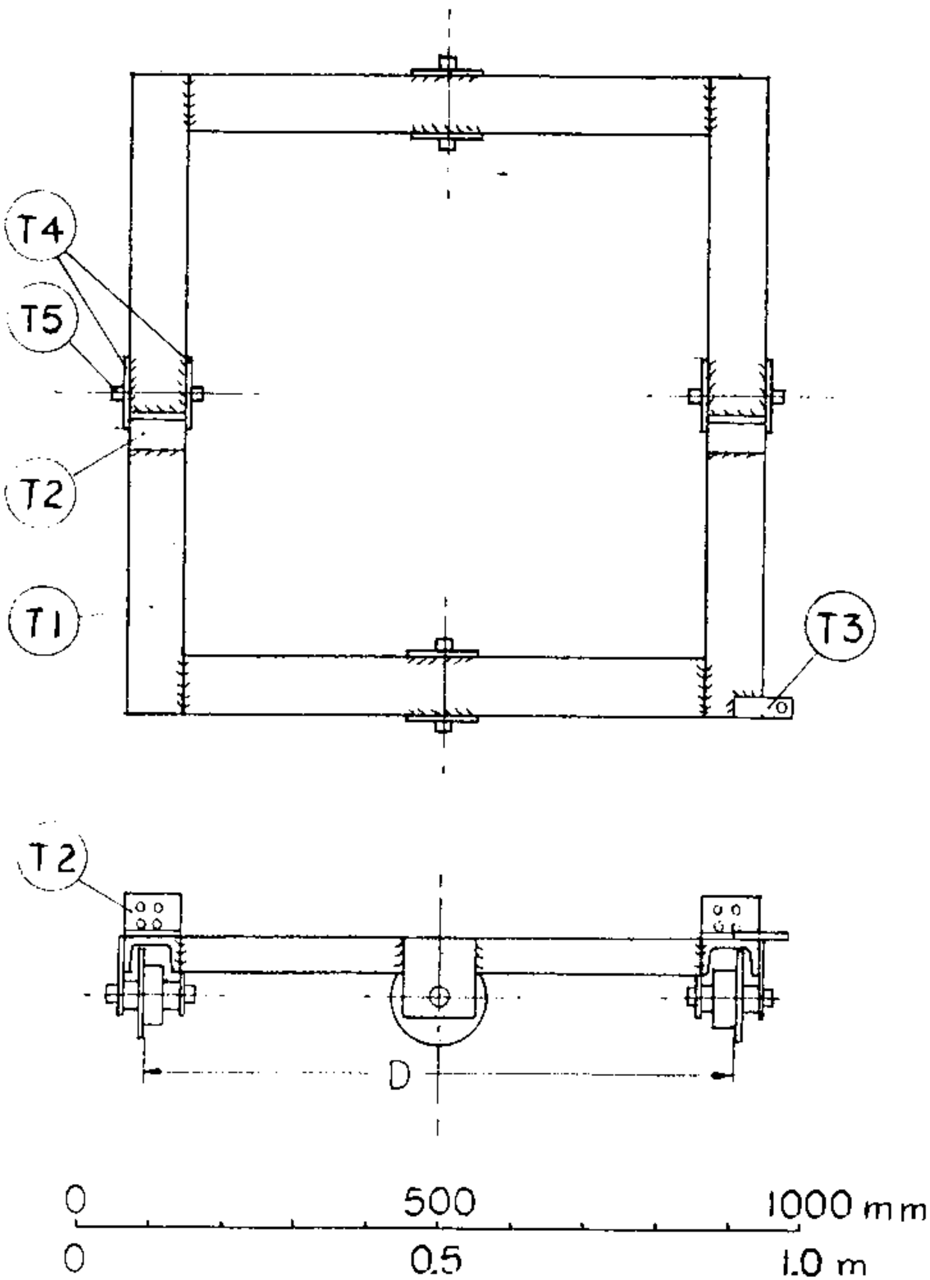
Connect the 16 wires or cables (R13) to the 16 holes of centerplate (C3).

Connect the 8 wires or cables (R12) to the 8 holes of control plate (C4).

Connect the 16 wires from (C3) to the holes in (R5) at the tips of the spokes (Fig. R4). Tighten the wires (or cables) at each spoke until the spoke is horizontal, then fasten wire securely. Note: do this simultaneously at opposing sides of the rotor to avoid bending of the control shaft. Do not proceed to next step unless all spokes are horizontal while control shaft is exactly vertical.

With wire or rope tied to (C3) pull (C4) up against the cotter pin. Connect the 8 wires from (C4) to the rubber strips on every second blade (Fig. R6). Adjust the wire length until the blade has the required angle (Figs. R3, R7), with the trailing edge of the blade tip 230 mm below the plane of the spokes (leading edge angle with that plane 42° at the tip). Fasten wire securely.

Using wire or cable (R11), connect all rubber strips (R9) with each other (Figs. R6, R7). Work in the direction shown, holding up every second blade in the correct position when connecting it. When the circle is completed, all blades must be at the same angle.


T4
T5
T2
T1
T3
T2
D
0
500
1000 mm
0
0.5
1.0 m

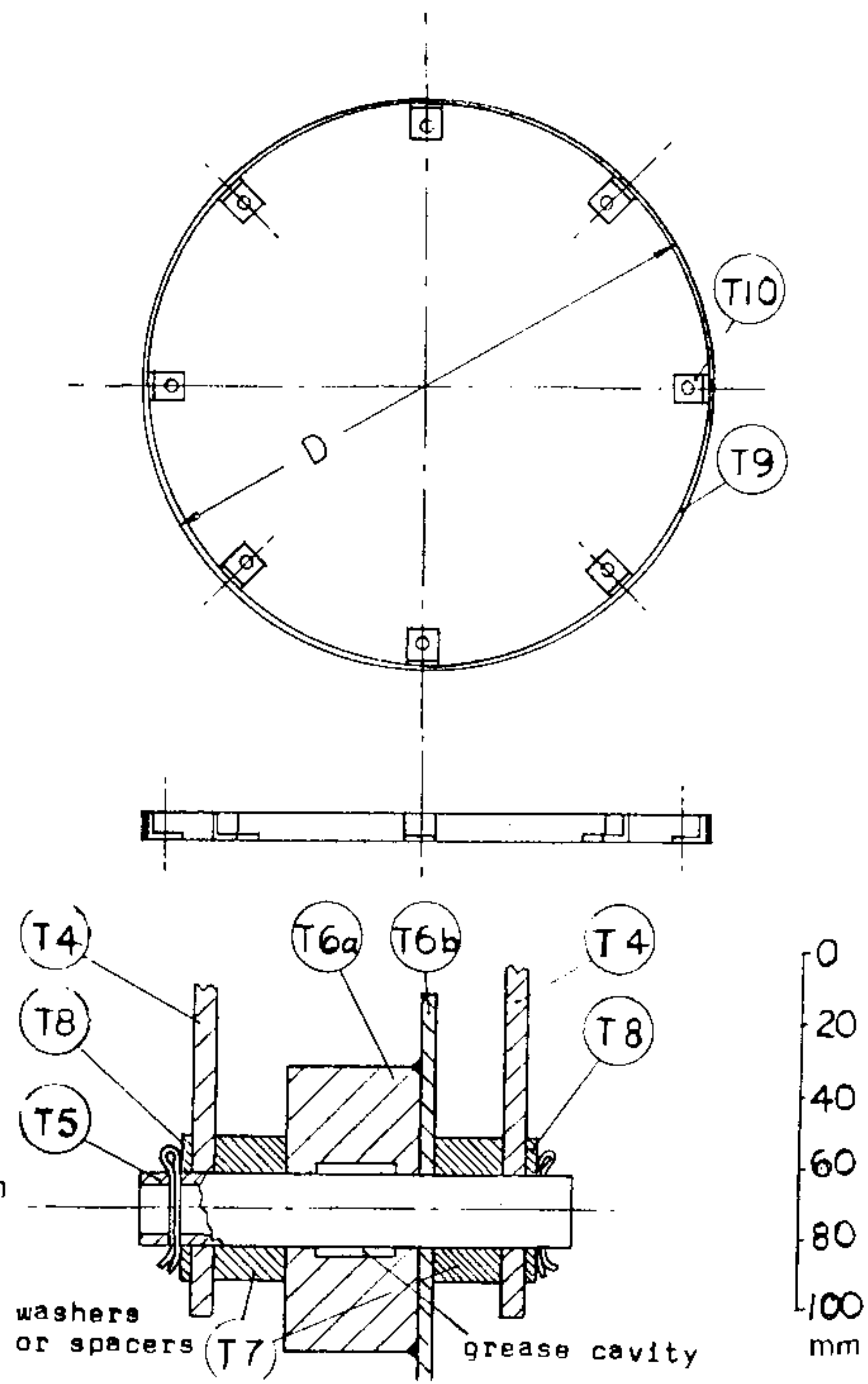

T10
T9
D
T4
T6a
T6b
T4
T8
T8
T5
washers
or spacers
T7
grease cavity
0
20
40
60
80
100
mm

Fig. T1

TURNTABLE

Part number	Quantity	Remarks (See Figs. T1, T2)
T1	1	Frame welded together from steel channel, approximately 50 to 80 mm wide. Frame is exactly square. Note: Dimension "D" (distance of brackets (T2), wheel distance, and outer diameter of circular track) depends on location of leaf spring mounts on car axle.
T2	2	Brackets made from angle iron (about 5 to 8 mm wall thickness). Drill pattern corresponds to that of leaf spring mounts on car axle.
T3	8	Steel plate approximately 4 to 10 mm thick.
T4	1	Steel plates approximately 5 to 10 mm thick.
T5	4	Steel axles 20 to 30 mm diameter. Thickwalled pipe can be used.
T6	4	Use whatever can be found. Diameter of wheel body (T6a) should not be less than 50 mm. Rim diameter (T6b) should be approximately 40 mm greater than that of (T6a). Prefer ball bearing, or bronze bearing, but simple steel cylinder (T6a) acceptable. Grease cavity recommended in this case. Weld or bolt rim (T6b) to (T6a).
T7	8	Spacers. Pieces of pipe, or several washers.
T8	20	Washers (can be made from sheet metal 1 - 2 mm thick).
T9	1	Circular track. Ribbon steel, approximately 30 mm wide, 5 to 10 mm thick. Bend and weld together to form ring of outer diameter "D". Ring must be exactly circular to avoid derailing of turntable.
T10	8	Brackets made from angle iron, or bent (heat!) ribbon steel approximately 5 to 8 mm thick.
	8	Cotter pins, or wire or nails.

Construction of Turntable and Track

Prepare wheel assembly (parts (T4) - (Tb)). Make sure wheels rotate with little friction.

Weld frame (T1) together.

Weld brackets (T2) onto frame such that car axle is exactly centered on the frame when mounted to the brackets (T2).

Weld part (T3) onto frame.

Bend and weld circular track (T9) and weld 8 brackets (T10) to its inside. Lay track on flat surface and make sure it has no waves and is perfectly horizontal.

Clamp wheel assemblies lightly to frame, with wheel rims facing outward. Set frame up on blocks on the circular track on a flat floor, with all wheels resting on the track. Weld parts (T4) to the frame, checking repeatedly that all wheels rest on track.

Wheels should have axial play of approximately 1 mm. Adjust by adding or removing washers.

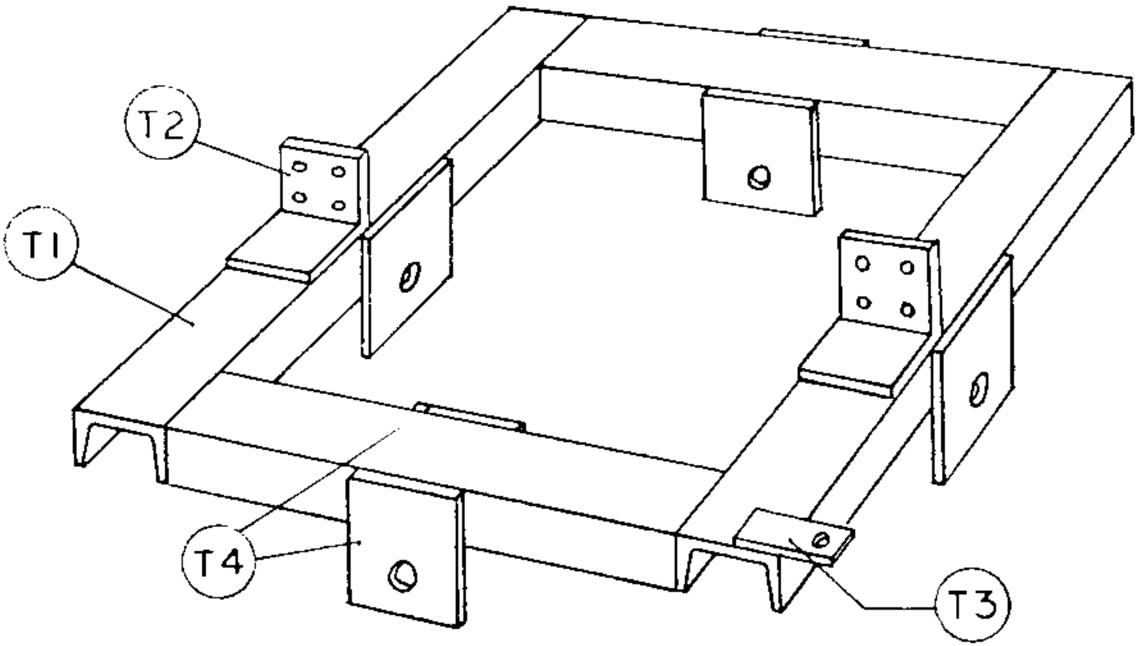


Fig. T2

Part number	Quantity	Remarks (See Figs. V1 - V4)
V1	1	Steel channel, approximately 50 to 80 mm wide, 3 to 5 mm wall thickness, 1.10 m long. Drill two holes to fit two wheel bolts on the wheel drum, and two holes for bolt supporting brake handle (V8).
V2	1	Angle iron, approximately 20 x 20 mm "L" shape, 2 to 3 mm wall, 3.30 m long.
V3	1	Angle iron, approximately 20 x 20 mm "L" shape, 2 to 3 mm wall, 2.50 m long.
V4	1	Angle iron, approximately 20 x 20 mm "L" shape, 2 to 3 mm wall, 2.60mlong.
V5	1	Ribbon steel, approximately 20 to 30 mm wide, 2 to 3 mm thick, 1.30 m long.
V6	1	Galvanized sheet metal, approximately 0.5 mm thick, 2.60 m x 1.50 m.
V7	1	Clamp made from ribbon steel approximately 30 to 40 mm wide, 2 to 4 mm thick. To fit over car axle. Weld to part (V2). Provide holes for clamping bolt.
V8	1	Brake handle. Ribbon steel, or angle iron, approximately 20 to 40 mm wide, 2 to 4 mm thick, 400 mm long. Hole for supporting bolt is to be approximately 2 mm wider than bolt diameter.
V9	1	Brake handle stop. Flat piece about 3 to 6 mm thick. Weld to (V1).
V10	2	Support wires or cable, approximately 2 to 3 mm diameter, each 3 m long.
		Rivets or small nuts and bolts to fasten sheet metal to vane frame (wire could also be used).

Vane Construction

Prepare parts (V1) - (V10). Bend (V2) 10 degrees, to one side.

Weld (or bolt) together parts (V1) - (V5), (V7) and (V9).

Fasten sheet metal (V6) to vane frame using rivets, small nuts and bolts, or wire no more than 300 mm apart.

Connect brake handle (V8) to channel (V1) (Fig. V3). Note: Hole in (V8) must be large enough to permit handle to be lifted over the stop (V9).

Connect wires (V10) to points "A" and "B".

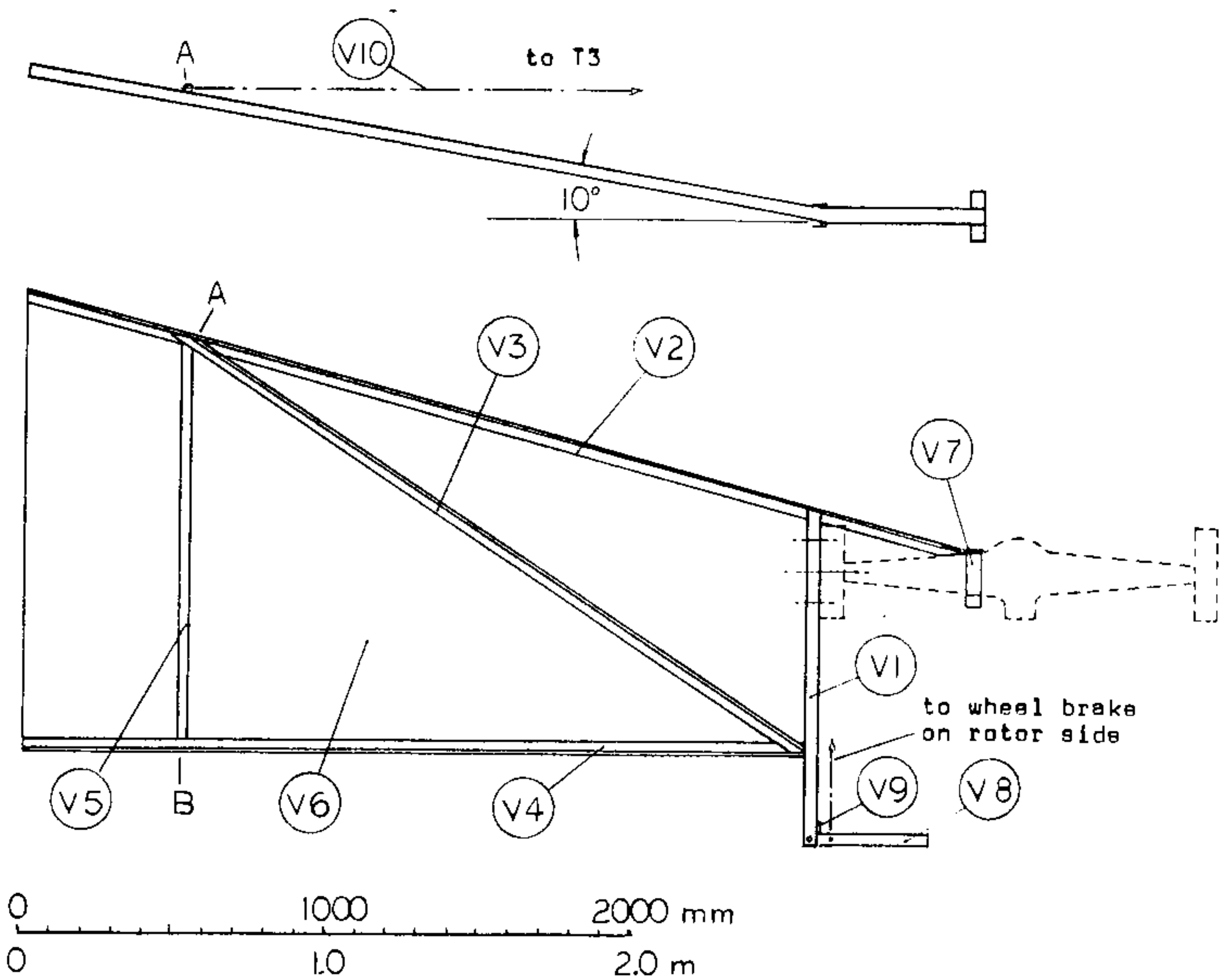

A
V10
to T3
10°
A
V3
V2
V7
V1
to wheel brake
on rotor side
V5
B
V6
V4
V9
V8
0
1000
2000 mm
0
1.0
2.0 m

Fig. V1

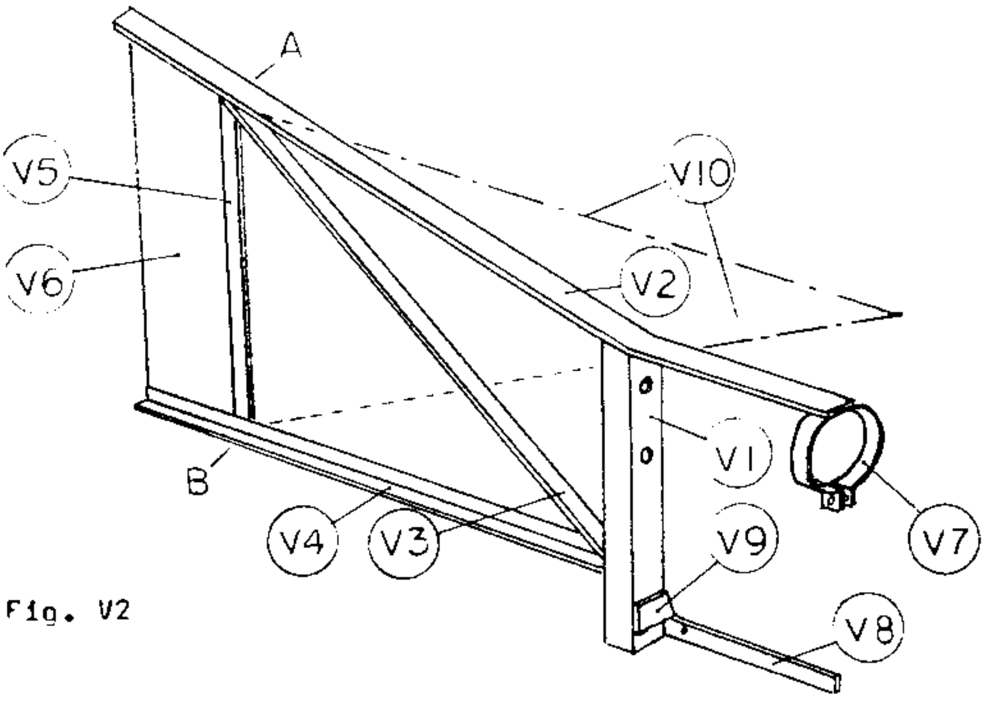


Fig. V2

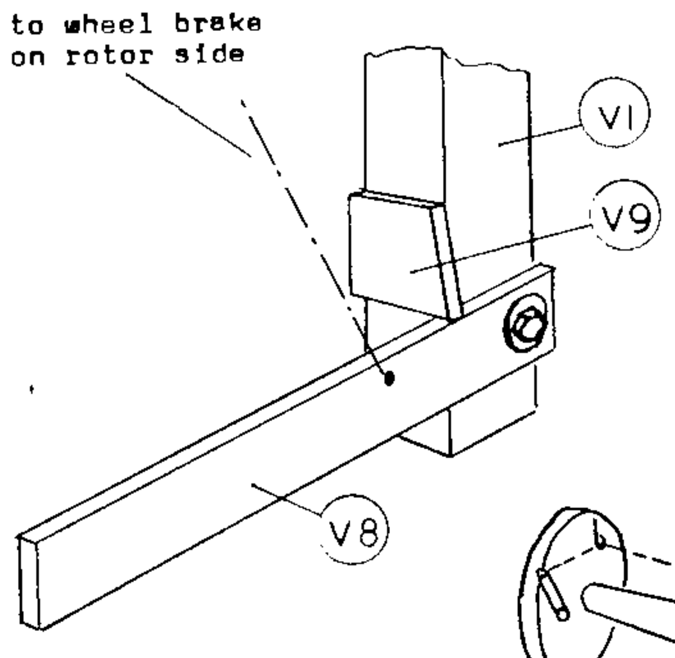


Fig. V3

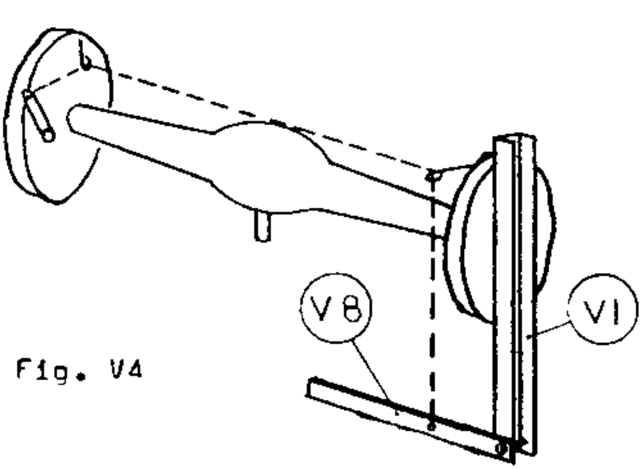


Fig. V4

PLATFORM AND TOWER

Part number	Quantity	Remarks (See Figs. P1, P2)
P1	1	Beam or pole, 6 to 12 m long, approximately 10 cm x 15 cm, or 15 - 20 cm diameter. Shape upper end to 10 cm x 15 cm.
P2	1	Platform: Thick plywood, or thick boards. Cut out 15 cm x 15 cm central hole. Note: diameter of platform depends on diameter of track (dimension "D").
P3	1	Galvanized sheet metal cover, somewhat larger than platform.
P4	1	Beam, approximately 4 cm x 8 cm.
P5	2	Beam, approximately 4 cm x 8 cm.
P6	2	Beam, approximately 4 cm x 8 cm.
P7	1	Piece, approximately 4 cm x 8 cm.
P8	2	Beam, approximately 4 cm x 8 cm.
P9	2	Beam, approximately 4 cm x 8 cm.
P10	10 - 20	Steps, approximately 4 cm x 8 cm x 35 cm.
		Nails approximately 10 cm long (galvanized, if available).
		Nails approximately 4 cm long (galvanized, if available).

Construction of Platform and Tower

Build platform from parts (P2),(P4) - (P7), with a 15 cm x 15 cm centerhole.

Shape upper end of tower beam so it fits into the space between (P4), (P5), and centerhole.

Nail platform to tower using parts (P8) and (P9).

(Reinforce joints by nailing strips of sheet metal over them with 4 cm nails).

Cover top of platform with sheetmetal and nail it down on the platform and over the sides.

Mount circular track (use nuts and bolts) so that its center coincides with the center of the square hole. Check roundness of the circle.

Nail steps to tower beam approximately 30 cm apart.

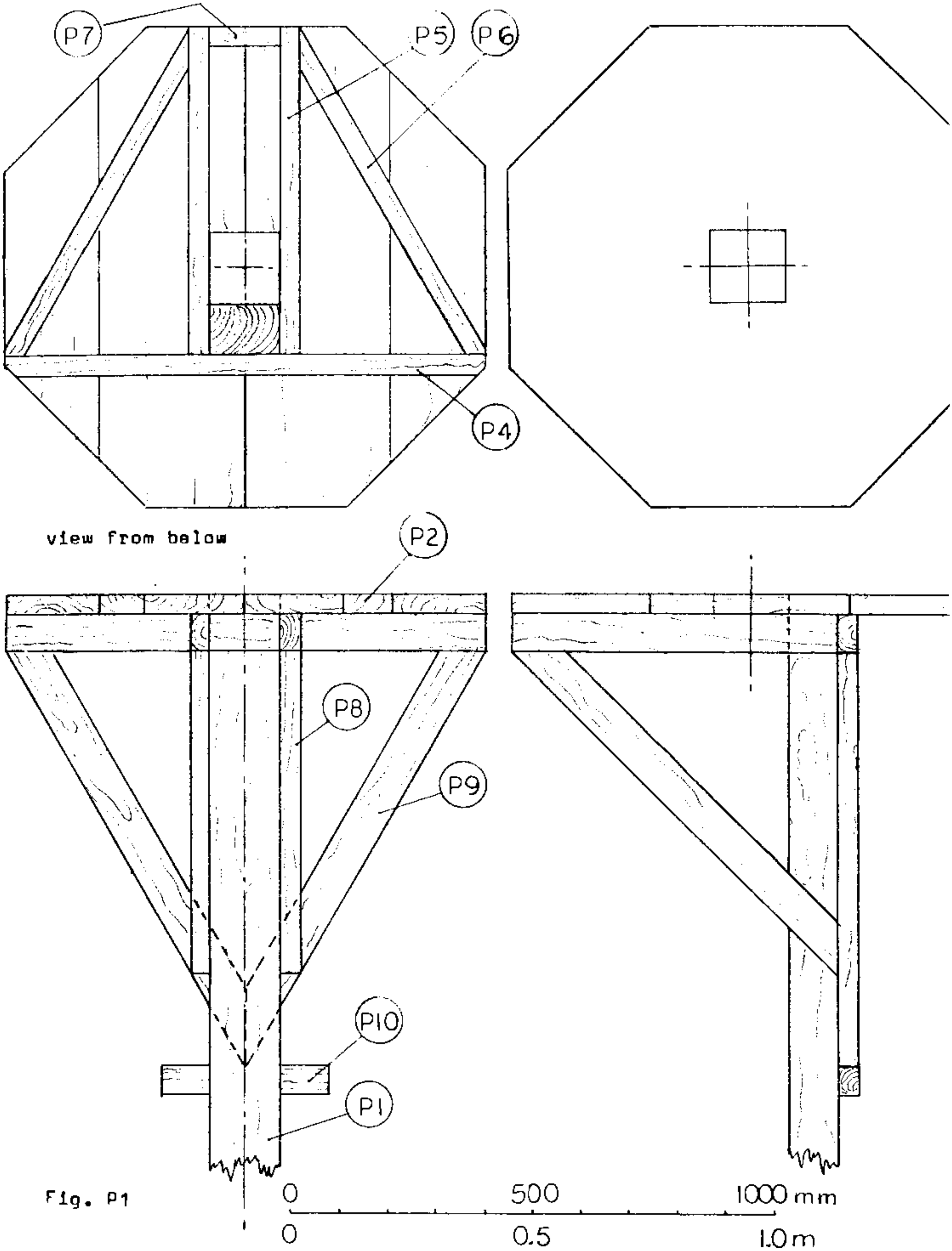


Fig. P1

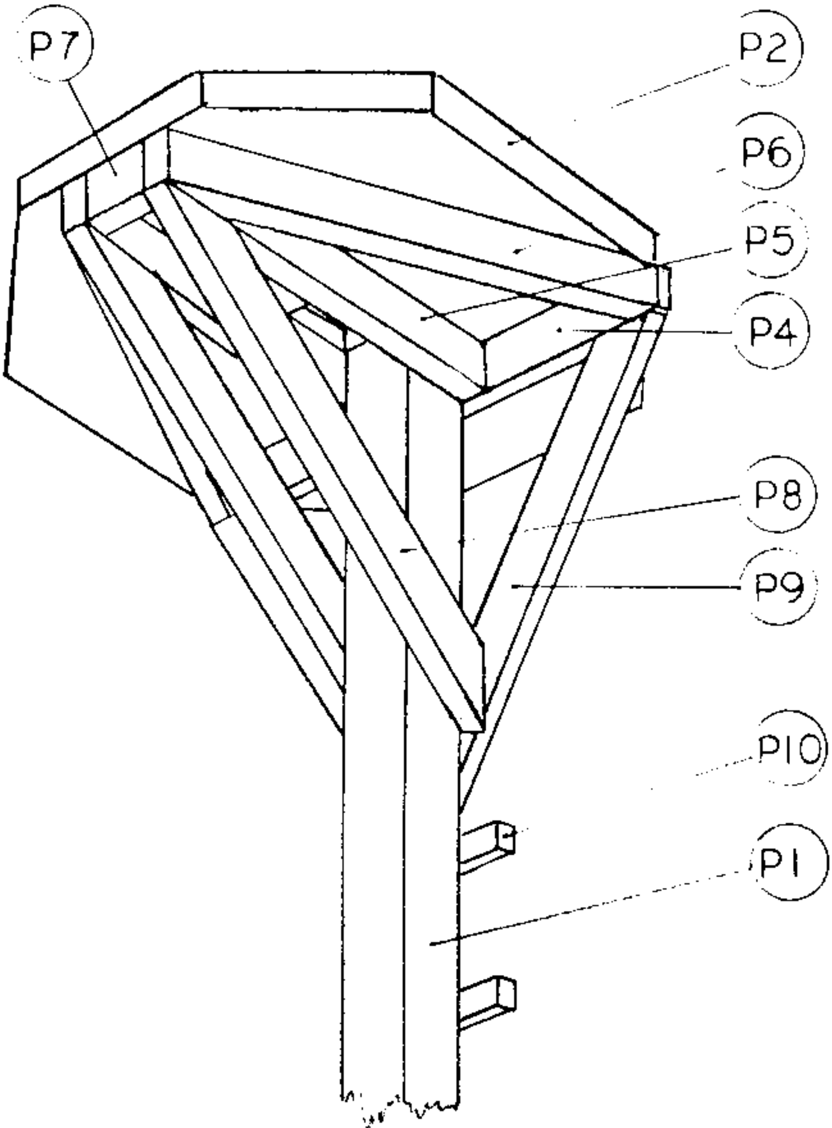


Fig. P2

WINDMILL ASSEMBLY

The best way to assemble the windmill will depend on local conditions, and on labor, cranes, ladders, scaffolds available. The steps in the assembly should be well thought through beforehand, and all assistants should be fully familiar with the planned procedure. The windmill should be erected on a calm day. The following is one possible assembly procedure.

Soak tower structure in creosote for a day, in particular the lower part which goes into the ground. If creosote is not available, burn the outside of the lower part to a depth of approximately 1/2 cm.

Dig a hole approximately 20% of tower height deep (less in rocky soil, more in sandy soil). Place tower vertically in hole, and fill hole with rocks and/or concrete, compacting thoroughly and repeatedly in the process. It is recommended that the tower be anchored also by at least 3 cables (mount at a low enough position on the tower so that they do not interfere with the rotor).

Mount the turntable on the circular track, and secure turntable to tower by wire or rope (temporarily but very rigidly).

Grease all sliding or rotating parts, and fill differential 1/3 full with heavy oil or light grease. Rustproof all metal parts (except aluminum or galvanized) by protective paint.

Mount car axle (drive shaft removed) on turntable.

Mount vane on one side of axle and connect the two wires or cables (V10) firmly from the vane (points "A" and "B") to part (T3) on the turntable.

Connect a cable from the wheel brake lever on the rotor side to the brake handle (V8) on the vane. Use wire or cable loops fixed to the drum or other means to achieve the necessary 90 degree change in cable direction (Fig. V4). Adjust the cable length so that rotor wheel is completely braked when handle (V8) has been pulled down to rest against stop (V9). Pull the brake handle, braking the rotor wheel.

Remove the temporary wires holding parts (C3) and (C4) of the control shaft together. Raise the rotor assembly. Remove the two temporary bolts holding parts (C2) and (R1) together (but keep control shaft in position). Bolt control shaft (C2) and rotor (R1) to the axle, tightening wheel bolts well.

Remove restraining wires cautiously from the turntable, watching for imbalance. If rotor appears much heavier than vane assembly, secure heavy rocks or pieces of scrap metal on the vane side of the turntable.

Release brake, and rotate rotor slowly, watching spoke and blade alignment. Make corrections where required. Pull brake.

Connect drive shaft and load.

Run windmill cautiously at first, checking for vibration, loose parts, misalignment etc., and making immediate adjustments.

MAINTENANCE AND OPERATION

Grease or oil all sliding or rotating parts monthly. Add oil to differential. Check for loose components. Always repair immediately, if breakages or misaligments occur.

Rustproof all metal parts (except galvanized or aluminum parts) once a year. Remove rust and chipped paint by wire brush, and scraper, then paint with protective paint. In some climates, new rigging wires may be required yearly.

Always brake rotor fully when windmill is unloaded or not in use.

If rotor blades feather at wind speeds considered too low, increase the precompression in the control spring.

If rotor blades feather at wind speeds considered too high, decrease the precompression in the control spring.

SPECIFICATIONS FOR A 2-METER WINDMILL

Construction essentially identical to that of 4 m VITA windmill, except that dimensions are to be adjusted accordingly. Listed below are the major changes; other secondary changes will be obvious to the builder.

PERFORMANCE DATA

Compared to the data for the 4 meter windmill:

rotor speed becomes twice that for the 4 meter windmill

rotor torque becomes one eighth (1/8) that for the 4 meter windmill

starting torque becomes one eighth (1/8) that for the 4 meter windmill

power becomes one fourth (1/4) that for the 4 meter windmill

altitude effects remain the same

Feathering Information

Remains the same for control spring of spring constant 0.75 kg_f/cm precompressed to 3.5 kg_f.

Fig. I1 - Rotor diameter becomes 2 m. Control shaft becomes half as long, vane becomes half as long and half as high.

Fig. A1 - All speeds of revolution become twice that shown.

VANE

Reduce height of vane to one half (approximately 0.75 m at tail).

Reduce length of vane to one half (approximately 1.3 m).

No change in vane angle (10^o).

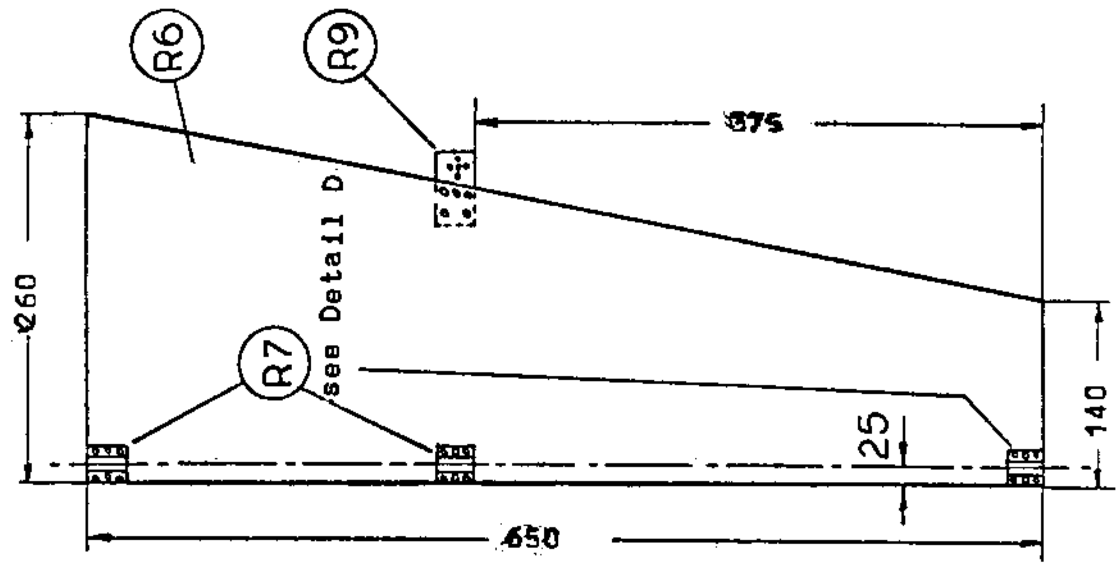
ROTOR

Outer diameter of ring (R2) becomes 0.69 m (length of rod 2.18m).

Length of spokes (R3) becomes 0.87 m.

Blades (R6) made from 8 pieces 0.65 m x 0.4 m.

New dimensions:



Blade bending rig for 2 m rotor (see new Fig. R3/2) has same angles as before, but all major linear dimensions are reduced to one half.

CONTROL SHAFT

Length of control shaft (C1) reduced to one half (0.75 m).

Compression spring (C6) changed to 165 mm long. Spring constant 0.75 kg_f/cm (i.e. a compression of 1 cm for a weight of 0.75 kg).

If suitable spring cannot be found, make spring of same dimensions as for 4 m rotor, except use 3 mm steel wire.

Control spring precompression changed to 3.5 kg_f.

Change indicated length of wires (C8) from 130 mm to 65 mm.(Fig. C3)

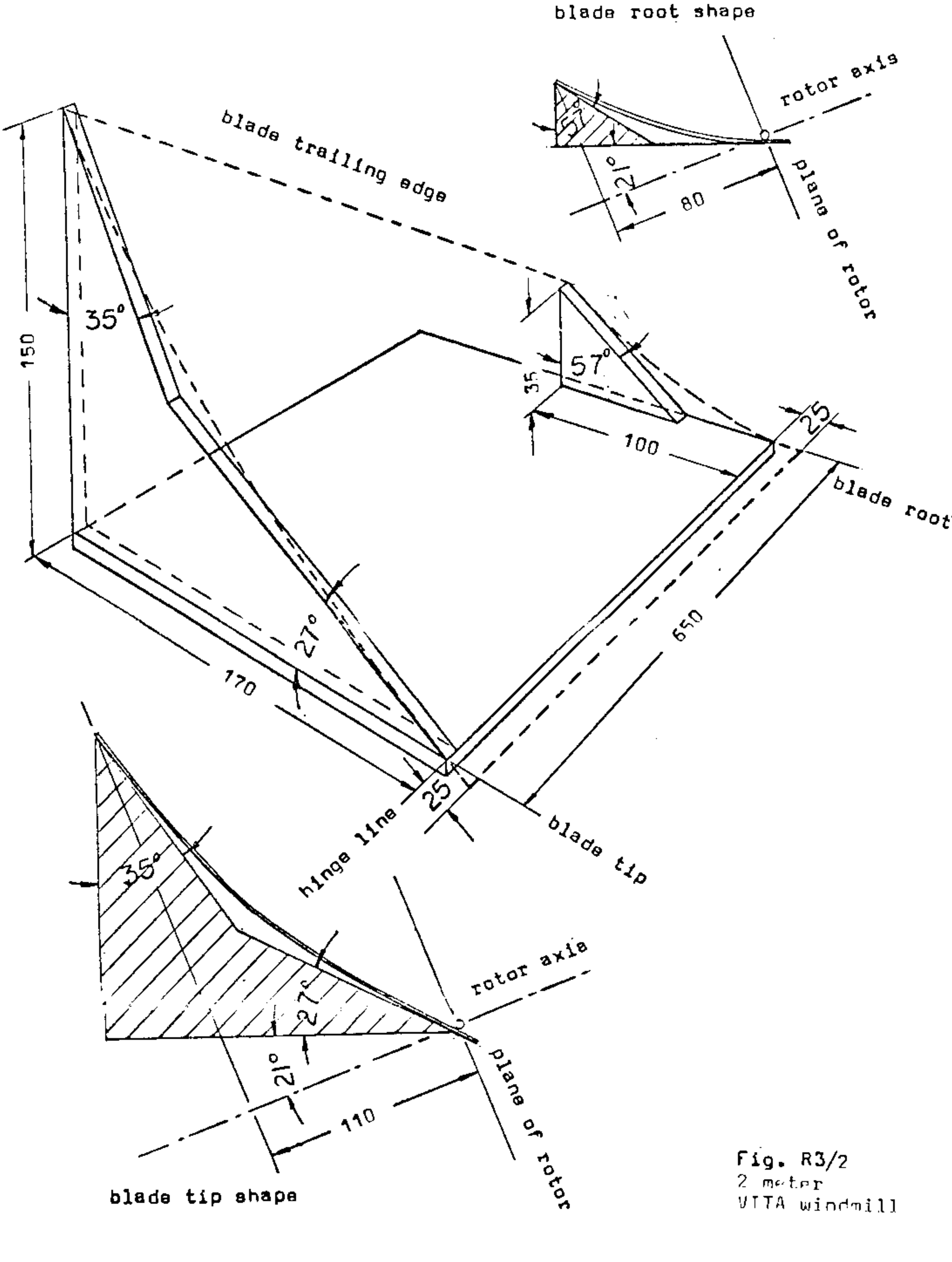


Fig. R3/2
2 meter
VITA windmill

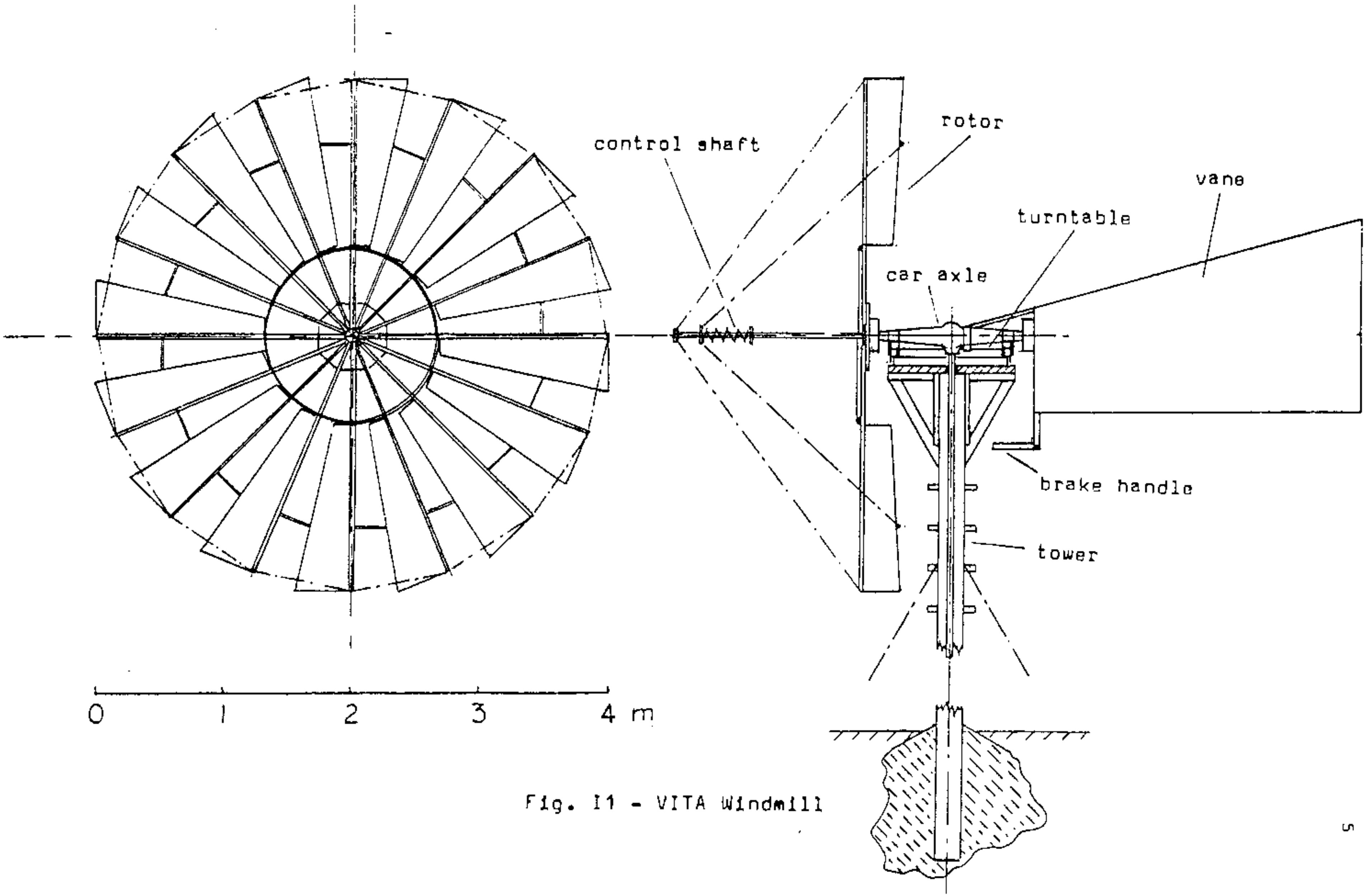
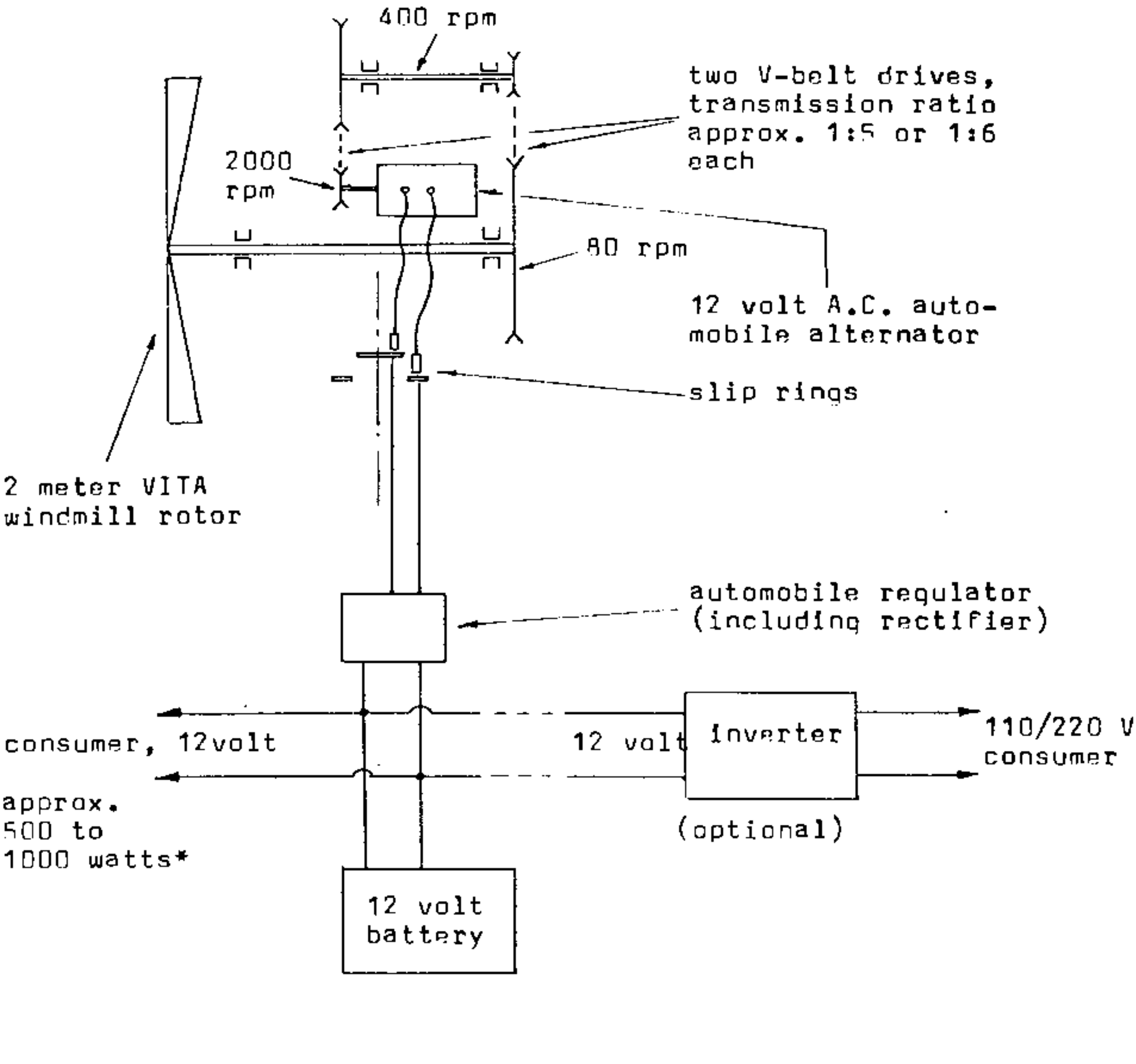


Fig. I1 - VITA Windmill

Suggestion for

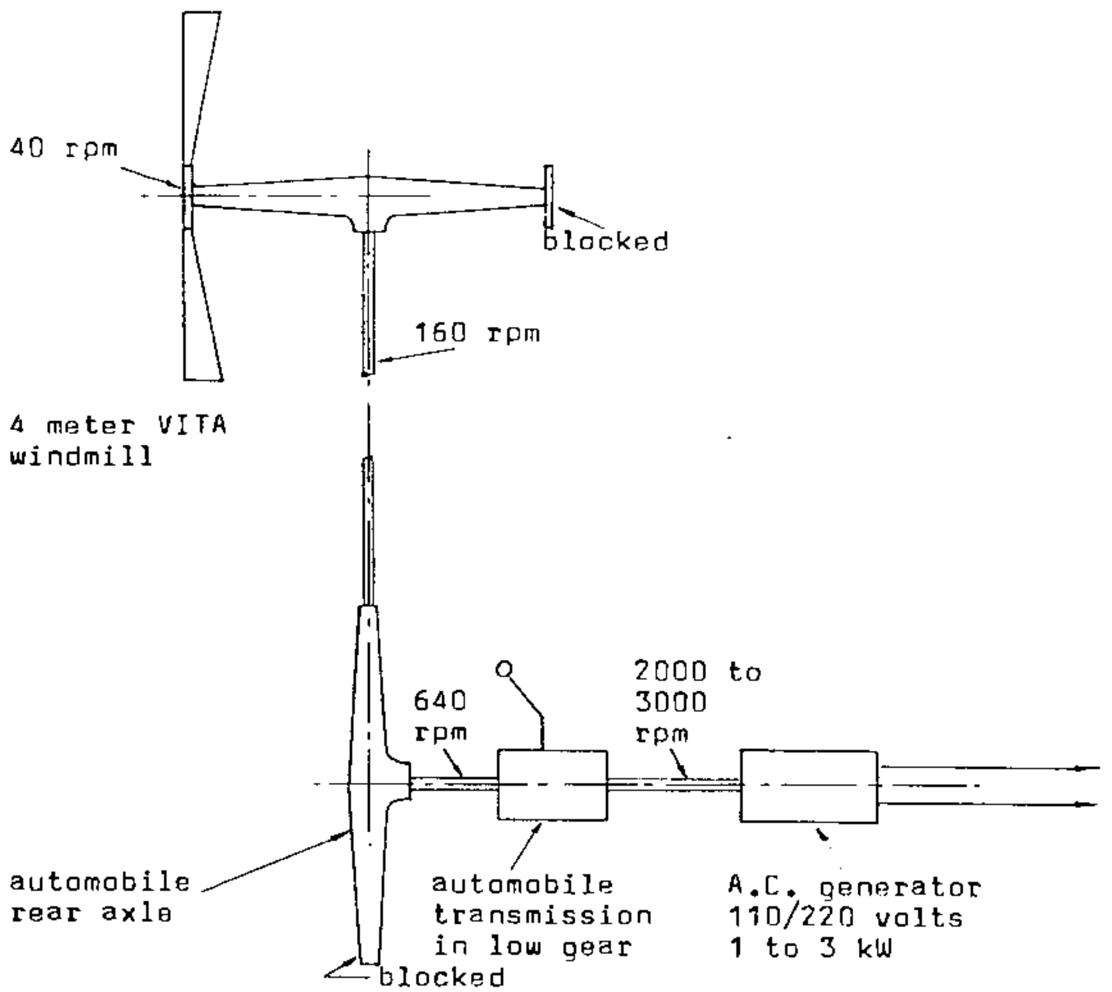
Electric Power Generation Using VITA 2 meter Windmill

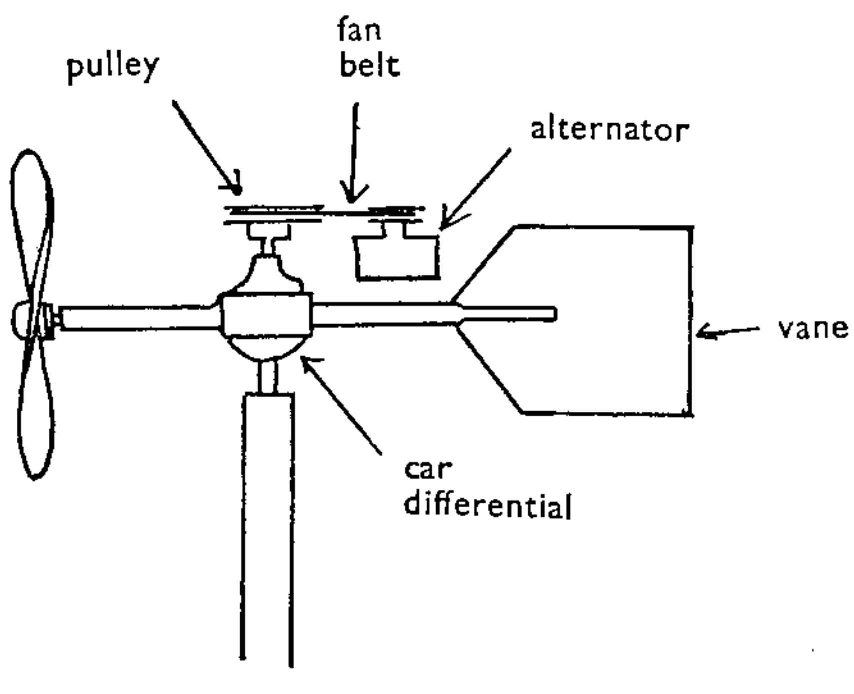


*depends on alternator used

Suggestion for

Electric Power Generation Using VITA 4 meter Windmill





DIFFERENTIAL MOUNTING

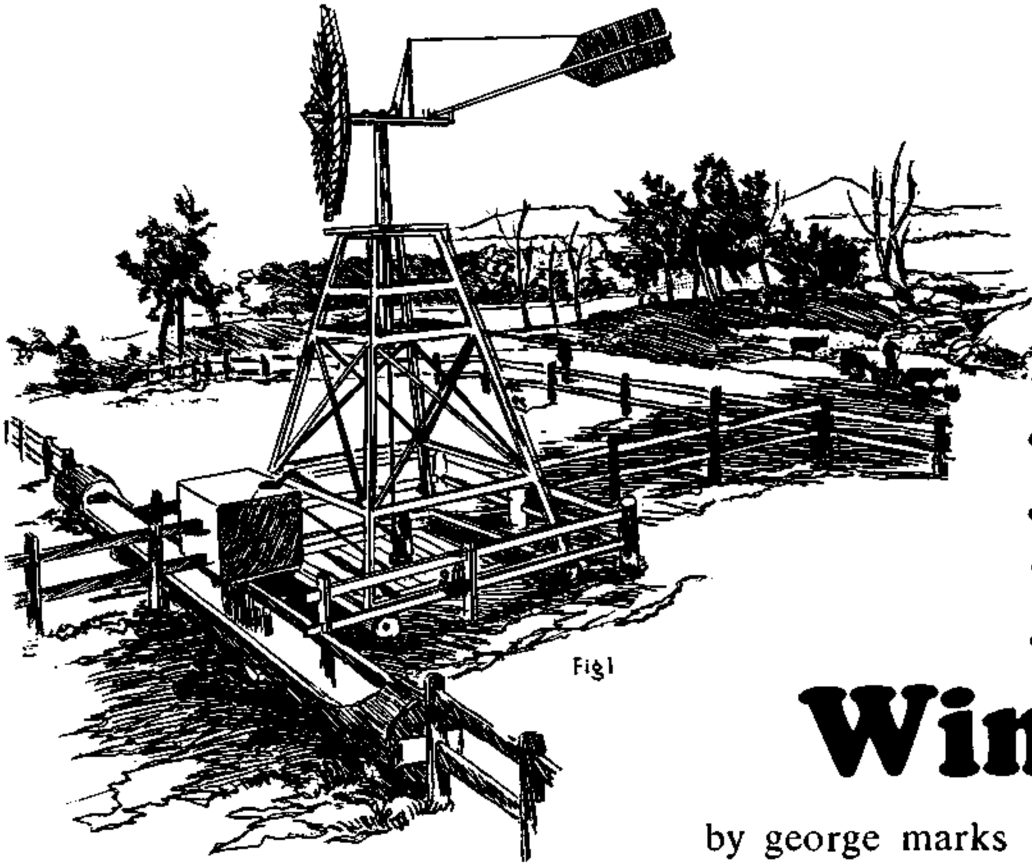


Fig 1

A Home Made Windmill

by george marks

The origin of the windmill is unknown. Early writers record its use in Europe as far back as the twelfth century. The windmill as then used consisted of arms carrying the sails and mounted upon a revolving post, and in order to keep the sails to the wind a lever was attached to this post and worked by hand. It was found necessary on this account to watch it continually, especially during periods of changing windy weather. To obviate this inconvenience, a 'tail' was fastened behind the fans in such a way that the force of the wind kept the sails in the desired direction.

At the commencement of the nineteenth century the windmill was almost exclusively used for pumping purposes, grinding grain, sawing, etc., and, although it has been superseded largely of late years by steam and other engines, still it is found to be used extensively in most of the European countries and in America as a means of supplying cheap power on the farm, particularly in those districts where fuel is scarce and work may be done intermittently. Economy in working forms a special feature in the utilization of wind power, and in suitable positions, with favourable conditions, a windmill may be expected to average about 8 hours work in the 24.

Any person of ordinary intelligence, having limited capital, but handy with tools, should be able to construct a useful and serviceable windmill, and apply its power on the farm, and thus effect a great saving in time and labour.

First of all a site has to be selected. This will depend to a large extent upon the use to which the windmill is to be put. For pumping purposes it would require to be near the spot it was intended to have the pump. In order to obtain the greatest amount of power from every prevailing wind, the highest and most exposed spot should be chosen. If it is intended to drive machinery in a barn the framework should be built sufficiently high to carry the fans clear of the buildings. In this case the frame would require to be made larger in proportion to the height.

Almost every farm has abundance of timber and no better foundation can be obtained than by securing two sound hardwood logs and letting them in the ground to half or their full thickness. If it be on a slope, the top side should be well let in so as to keep them level. For a frame 12 feet high the logs may be placed 9 feet apart. It is better to have them fairly long, as it would make the foundation more substantial and would also serve as a support for water-troughs, etc. This is very important becuase during strong winds or gales there would be a severe strain upon the structure, which, if not secured to a firm foundation, might topple over. These logs are kept in place by placing lighter logs crossways, 9 feet apart, letting them in to one another, and securing them by bolts or wooden pins. Upon this foundation the framework may be built of sound timber, roughly squared to take the sap wood off. The bottom should be bolted to the cross-pieces and strengthened by stays. The outside posts are secured at the top by bolting them to stout pieces of timber, bringing them in to about 3 feet apart each way. Cross-pieces are also bolted to the frame at 2 and 4 feet from the top. From the centres of these, other cross-pieces are bolted. The upright frame which supports the sails and tail, and through which the connecting-rod works, is secured to these, and held in position by bolts.

Support of the Sails

A few sound straight slabs will be found useful for this part of the structure. The pieces should be about 10 feet long and trimmed with the adze to about 2 inches thick by 8 in. wide. Two pieces are required. Four other pieces, 8

Elevation of the Windmill

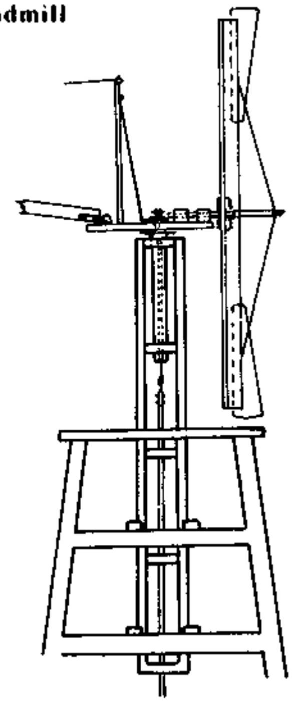


figure 1

Sails

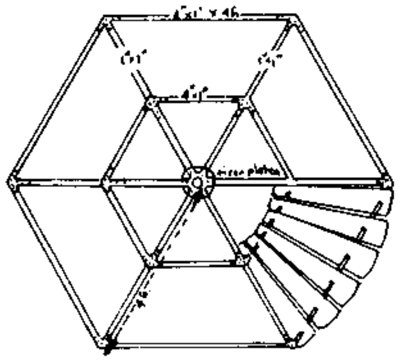


figure 2

Plan of Working Parts

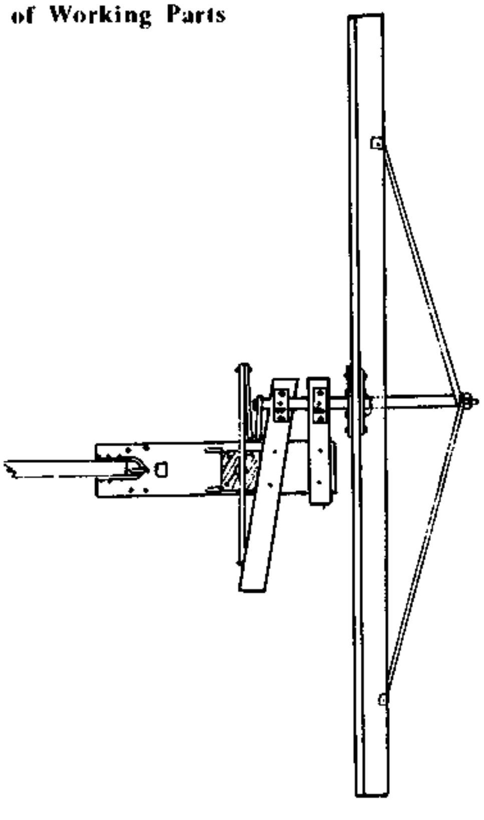


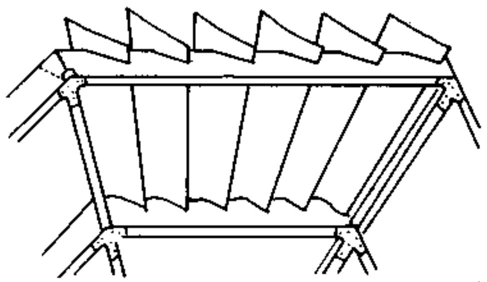
figure 3

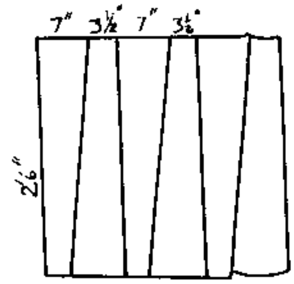
in. x 8 in. are next bored so that an iron rod or wooden connection may pass freely from the crank above to the plunger of the pump beneath. Two of the pieces have holes large enough to admit an iron pipe. These four pieces are placed between the two long pieces and securely fastened together.

The platform to carry the sails should be about 8 in. wide, 2 in. thick, and 4 feet long. In order that the sails may be free to move in any direction as the wind changes, this platform should be arranged so as to admit this movement. It will be necessary to obtain a piece of large-sized piping, about 2 feet long, three iron plates having holes cut to admit the pipe passing through, and an iron ring large enough to fit over the pipe. A hole for the pipe to pass through is bored through the upperplank, a plate is bolted on top and bottom, and another plate on the top of the support. The pipe is inserted through the top, and the top edge is burred to prevent it from falling through. The iron ring is placed between the support and platform, and if this is kept well greased it will be found to move with ease. The sails and platform revolve on this ring, and the pipe, while allowing passage of the connecting rod to work the pump, keeps the top in position.

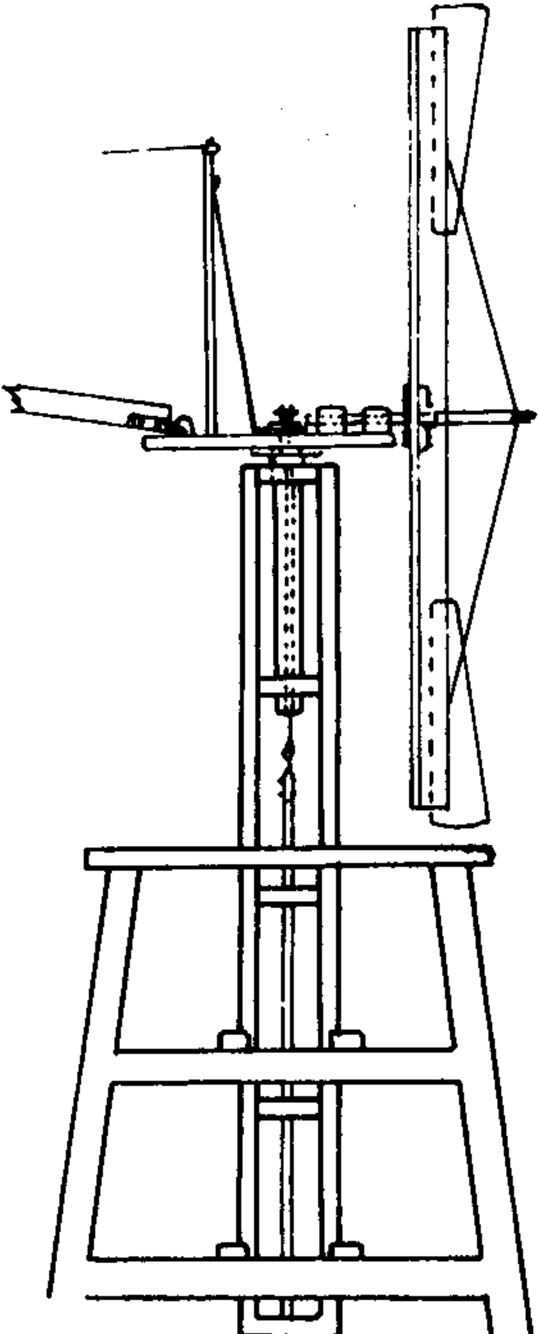
Sails

Six pieces of strong timber 1 in. x 1 in., 4 feet long are fastened to an iron axle by six bolts and two iron plates. Upon these are fastened pieces of timber 4 in. x 1 in., six on the outside and six on the inner side, 2 feet from the end of each arm. Upon these are fixed the fans, which are





best constructed of pieces of galvanized iron 2 ft. 6 in. long, and 3 1/2 inches wide at one end and 7 inches at the other. Thirty-six of these will be required. A piece of iron 2 ft. 6 in. wide should be obtained, and by cutting these as shown in the sketch there will be no loss. To fasten these in frame, make a narrow sawcut about 2 inches deep, at an angle in the outside of the two rows of cross-arms, and let in the fans. These should be curved, and to keep them secure and in position, they may be fastened with a nail and light wedge. The axle extends about a foot in front of the fans, and iron rod stays are fastened at one end to the arms (about a foot from the end), and at the other, to the end of the axle. These, though light, greatly strengthen the arms.



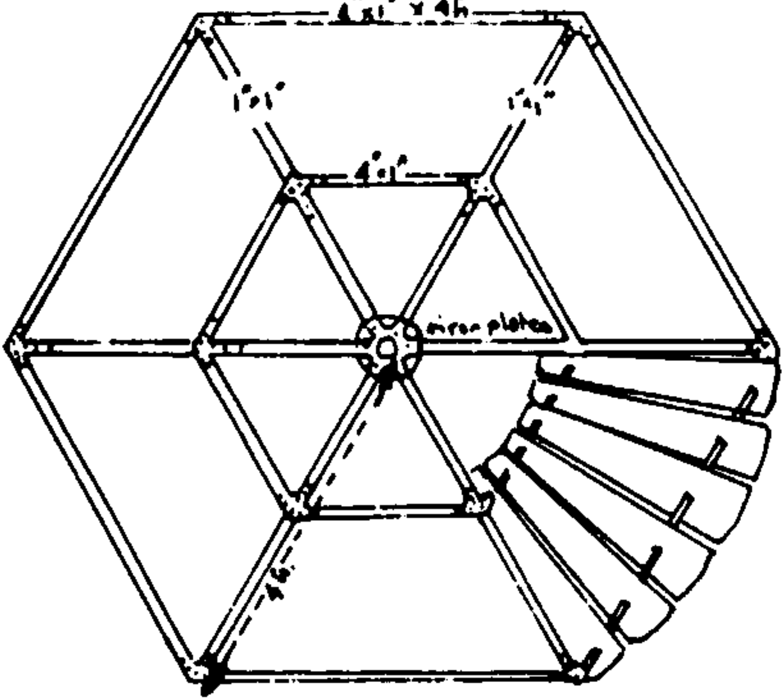

mirror plates

PLATE 6

The flange adaptation for a wooden hub, flat belt or "V" belt pulley, depends on the axle pipe fitting into the nipple pipe, which it should, but does not quite do. You can file the inside of the nipple pipe, which is tedious, or you can drill it out with a one inch drill, which is much easier.

Pipes are always measured by their inside diameters and both water and gas pipes have 1/8" walls, meaning that their outer diameters are always 1/4" greater than their inner diameters. Therefore, a pipe should always be able to fit into another pipe with an inner diameter 1/4" greater than its own. In real life, however, it takes a small amount of urging

Gas pipes are stronger than water pipes. See also plates no. 7, 8, 11, 19, 20, 21 and 24.

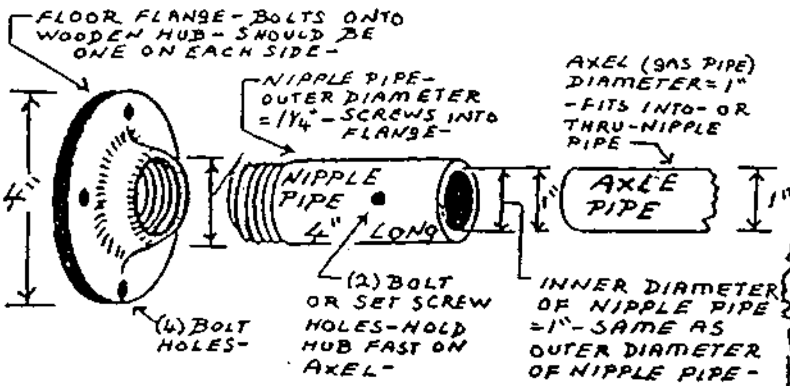
PLATE No. 6

– THE WOODEN MULTIBLADE IV
– THE MAIN HUB – 10" DIAMETER – DETAIL

FLOOR FLANGE – ADAPTATION

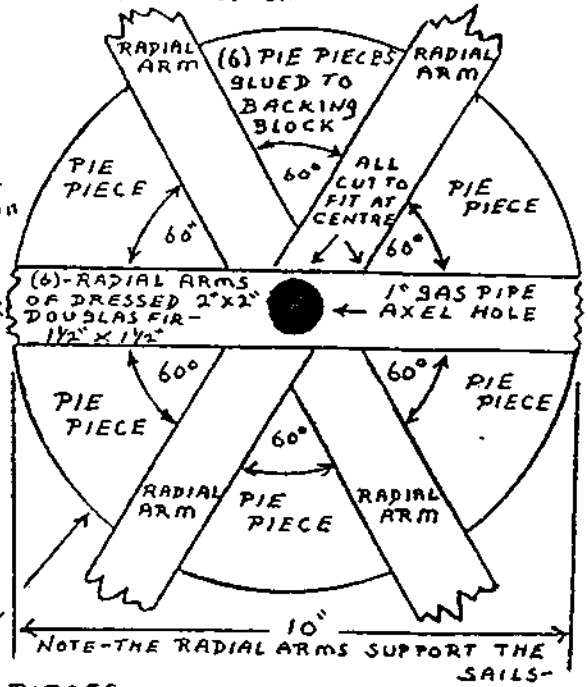
–FLOOR FLANGE HOLDS WOODEN HUB ONTO GAS PIPE AXLE–

(1)



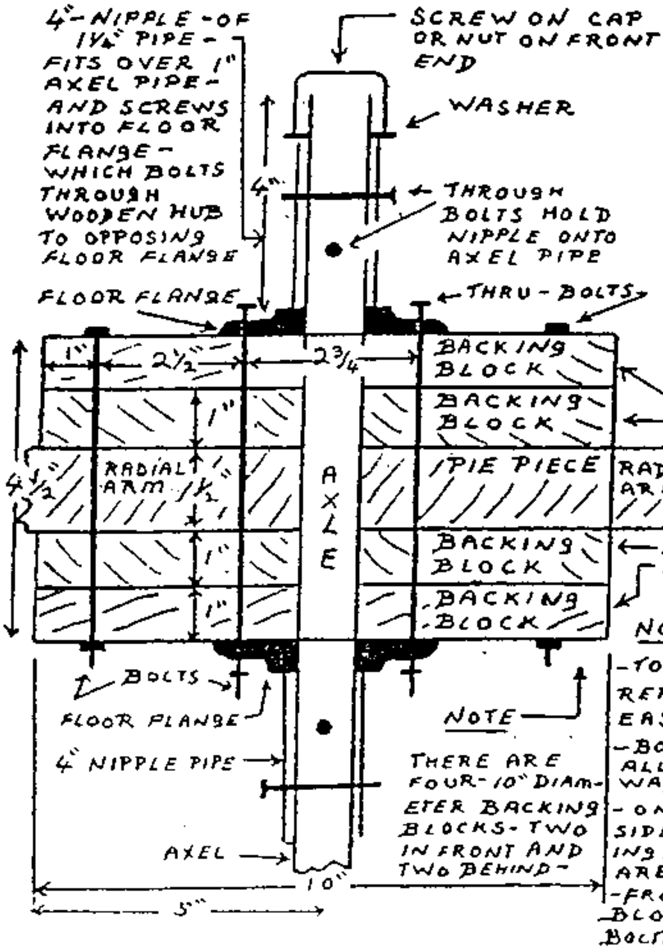
(3) FRONT VIEW – 10" HUB

–SHOWING THE PIE PIECES AND RADIAL ARMS BEFORE THE TWO FRONT BACKING BLOCKS ARE FASTENED ON–



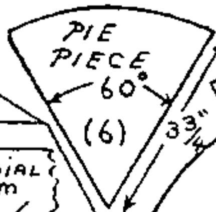
(2)

CROSS SECTION – SIDE VIEW – 10" HUB



(4) (6) – PIE PIECES

SAME THICKNESS AS RADIAL ARMS – GLUE TO BACKING BLOCKS BETWEEN RADIAL ARMS –



(5) FRONT (OR BACK) VIEW – 10" – HUB

WITH BACKING BLOCKS GLUED AND FASTENED OVER PIE PIECES AND ARMS

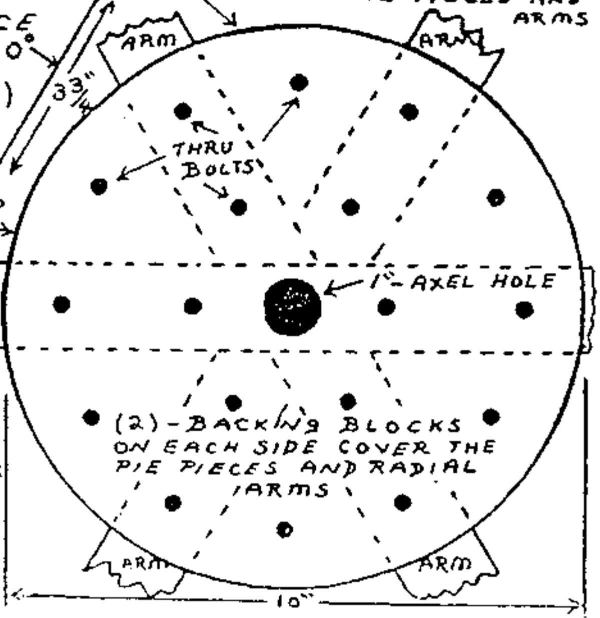


PLATE NO. 7

The floor flange and nipple pipe system work the same as in the main hub shown in plate no. 6.

Note especially, that the back up arms are held into their notches at both their top and bottom ends by wire cords so they have a degree of resiliency against the wind and will not break, (see fig. 1 and 5, also plate no. 8, fig. 3).

PLATE No. 7

- THE WOODEN MULTIBLADE V

- THE BACK UP HUB -

-THE BACK-UP HUB BRACES THE BACK UP ARMS - WHICH SUPPORT THE RADIAL ARMS AGAINST WIND PRESSURE

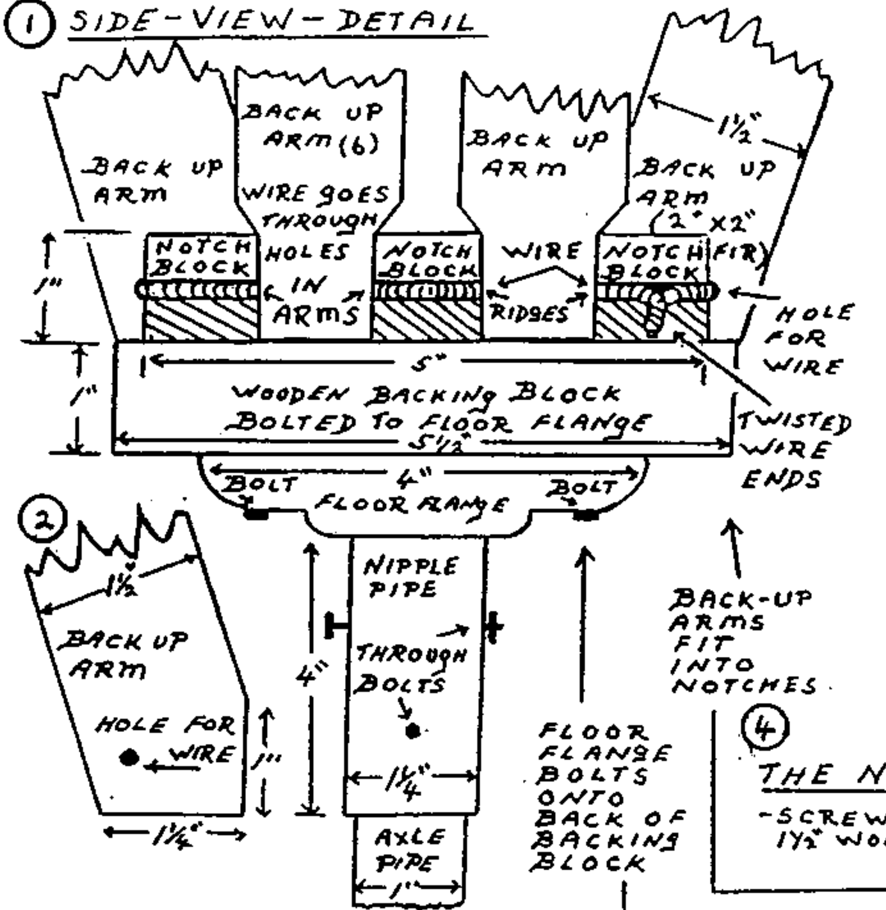
THE BACK-UP HUB IS FITTED ONTO THE AXEL - 12" BEHIND THE MAIN HUB - SEE PLATE No. 7

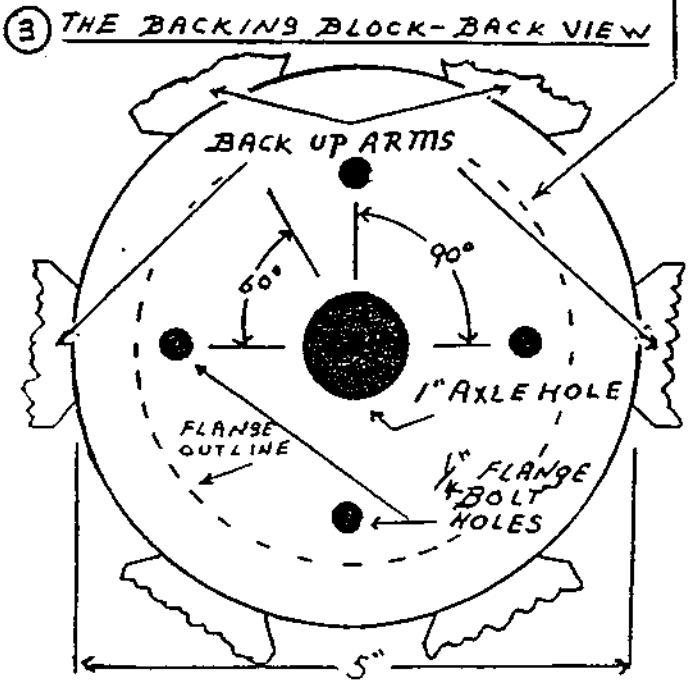
-THE BACK UP BLOCK FITS ONTO AXEL WITH 4" NIPPLE AND FLOOR FLANGE - JUST LIKE THE MAIN HUB-

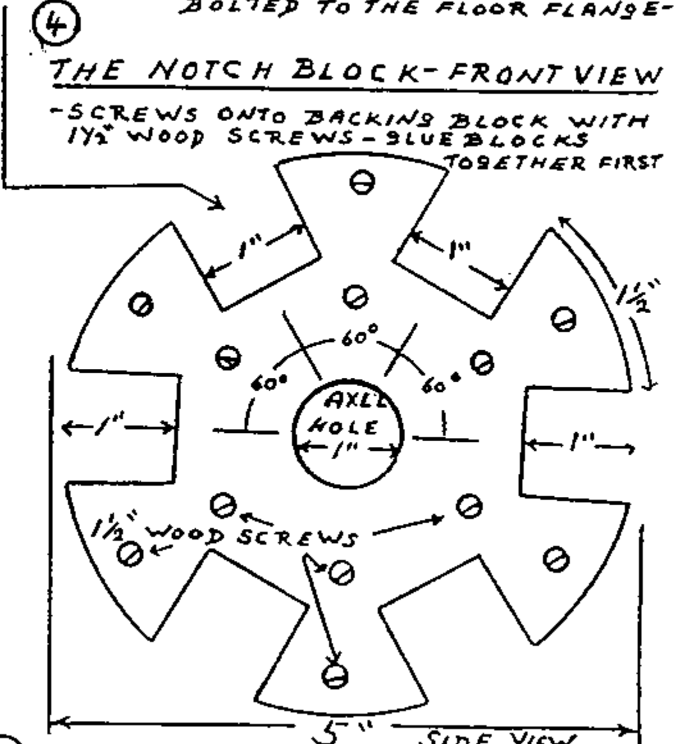
-BACK UP ARMS ARE HELD INTO THE NOTCHES OF THE NOTCH BLOCK (AGAINST THE BACKING BLOCK) BY TIGHT WIRES PASSING THROUGH HOLES IN THE BACK-UP ARMS AND THE 1/4" RIDGES AROUND THE OUTSIDE OF THE NOTCH BLOCK-

-THE NOTCH BLOCK IS GLUED AND SCREWED TO THE BACKING BLOCK-

-THE BACKING BLOCK IS BOLTED TO THE FLOOR FLANGE-







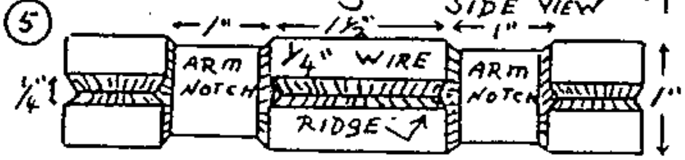


PLATE NO. 8

The 36" blade sails will turn slowly, because, theoretically, the larger the number of sails, the slower will be the R.P.M. Also, a 30° pitch, especially if the blade is flat rather than curved, will reduce the airfoil effect.

This is all discussed with greater detail in the theoretical and rotor blade, (airfoil) sections.

The 36" blade design is especially suited to the eccentric rod application illustrated in plate no. 19, et. al., which works right off the wind shaft axle without any gear down system to slow it's up and down pump rod action.

It may, however, have trouble lifting the eccentric rod to the pump in the case of tower heights of more than fifteen or twenty feet. If this turns out to be so, you can aid the up stroke by the use of springs connected from a point on the eccentric rod to cross pieces on the tower. Four spring connections, to four cross pieces, from the same point on the eccentric rod will be better than one strong spring, because four will hold the rod in its central position.

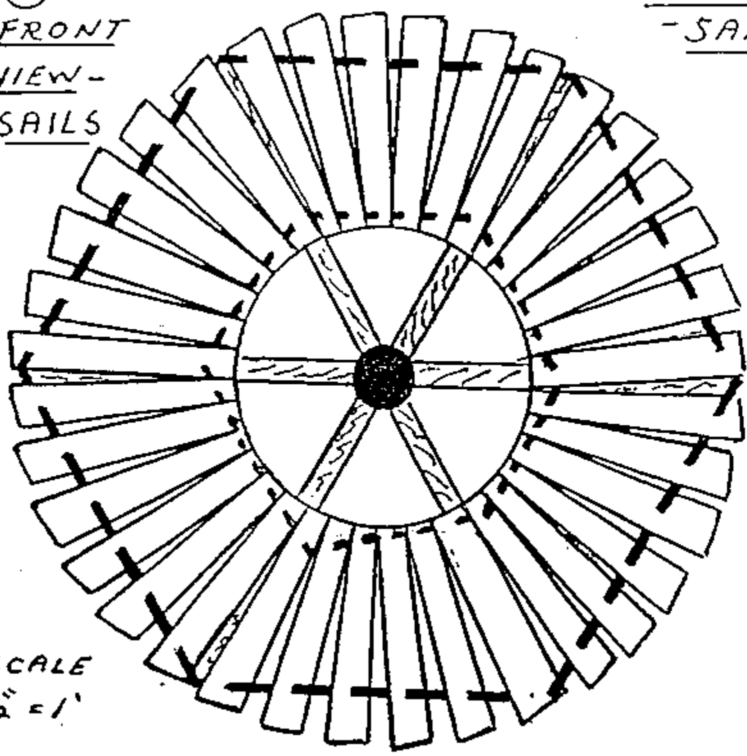
See pump plans, plate no. 61, et. al.

PLATE No. 8

-THE WOODEN MULTIBLADE-VI
-SAILS-I- SAIL FRAMES-I
-36 SAIL BLADES-
-SLOW TURNING-
-8-FOOT DIAMETER

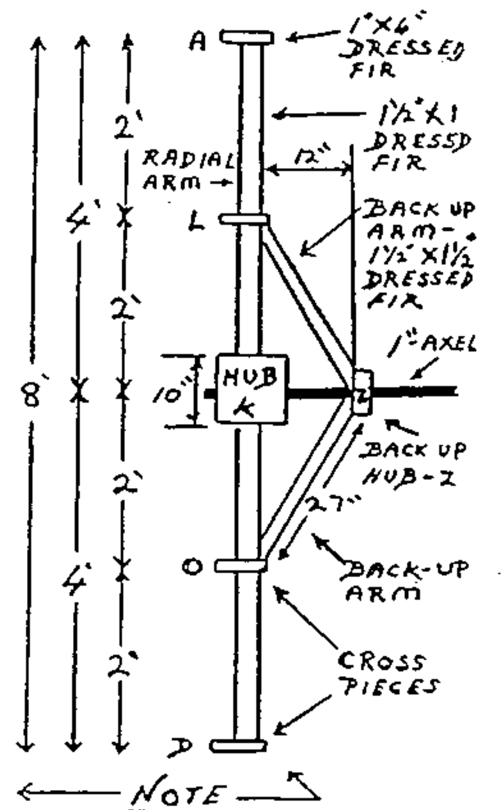
-AXEL CONNECTS DIRECTLY TO ECCENTRIC OR CRANK-

(1) FRONT VIEW- SAILS

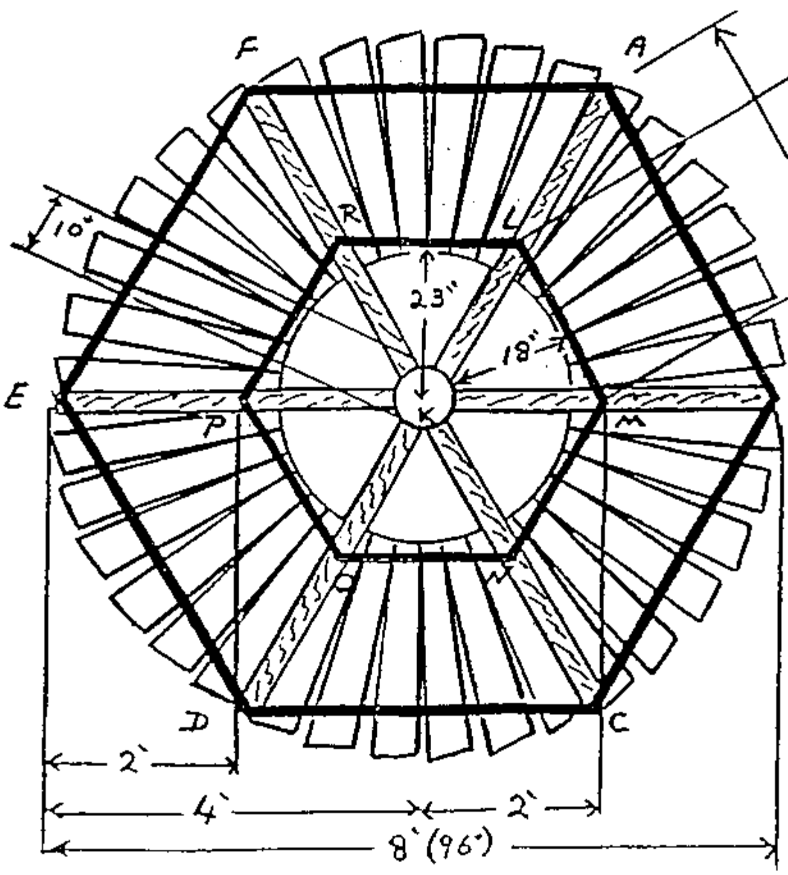


SCALE 1/2" = 1'

(3) FRAME-SIDE VIEW



(2) BACK VIEW - FRAME DETAIL



NOTE

RADIAL ARMS - A-K; B-K; C-K; D-K; E-K AND F-K ARE ALL OF 2"x2" FIR 48"-LONG-DRESSED = 1 1/2"x1 1/2"-

CROSS PIECES - A-B; B-C; C-D; D-E AND E-F ARE ALL MADE FROM 1"x4" DRESSED FIR 48" LONG-

CROSS PIECES - L-M; M-N; N-O O-P; AND P-R ARE ALL MADE FROM 1"x4" DRESSED FIR - 24" LONG-

HUB-K- DIAMETER = 10"

BACK UP HUB-Z- (ABOVE) DIAMETER = 5"

SAIL BLADE - LENGTH = 30"

OVER ALL DIAMETER = 96"

PLATE NO. 9

The sails can be made from plywood, wood, plastic or tin, (galvanized iron). They can also be made from steel drum sections, (see plate no. 54, fig. 3 and plate no. 35, fig. 6), which will give the proper aeronautical curve. If steel drum sections are used, the 30_ pitch angle should be measured from point to point of the inside curve.

The batteries can be made 1/2" instead of one inch thick. In this case, there can be two battens at each station, one above and one below the cross piece. There can then be another one inch batten between the two from the cross piece out. The three pieces can then be glued and bolted to each other and to the cross piece.

PLATE No. 9

- THE WOODEN MULTIBLADE - VII
- THE SAILS II
- SAIL ATTACHMENTS - SHAPES

-SAILS ARE;

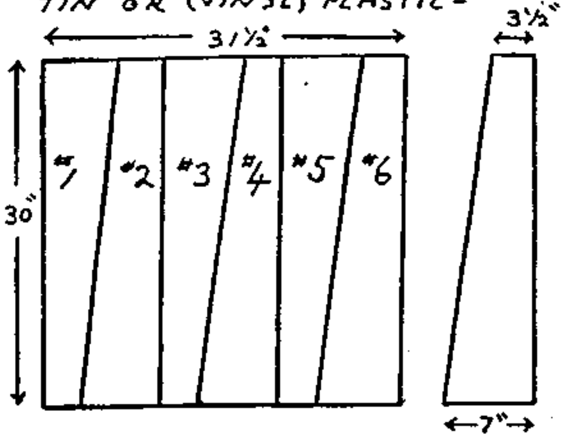
(A) - CUT TO SIZE

(B) - FITTED INTO SLOTS IN CROSS PIECES

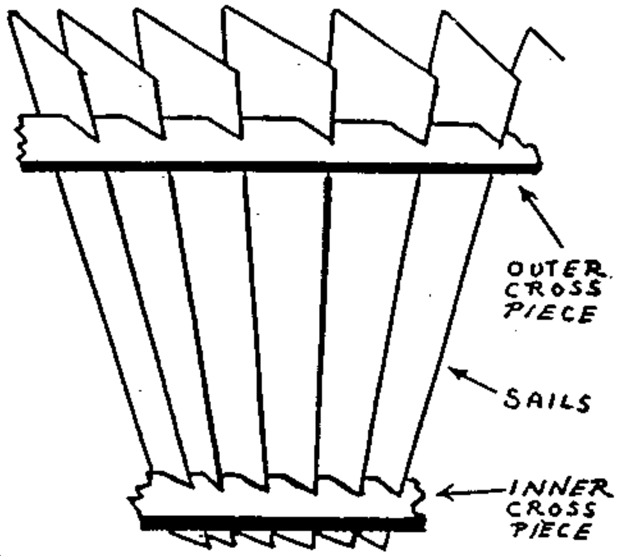
(C) - NAILED TO BATTENS

(1) THE SAILS - SHAPE

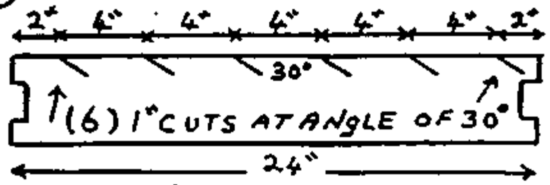
CUT FROM A SINGLE SHEET OF 20 GUAGE GALVANIZED IRON-TIN OR (VINYL) PLASTIC-



(2) SAILS FITTED TO CROSS PIECES

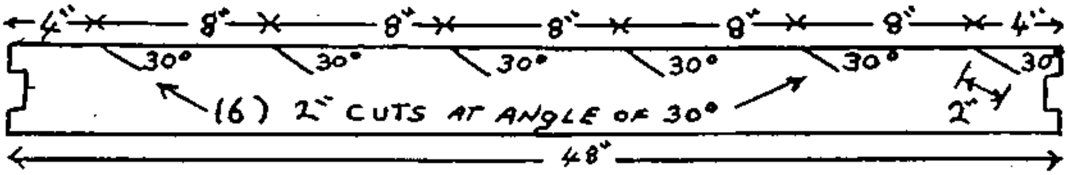


(3) INNER CROSS PIECE

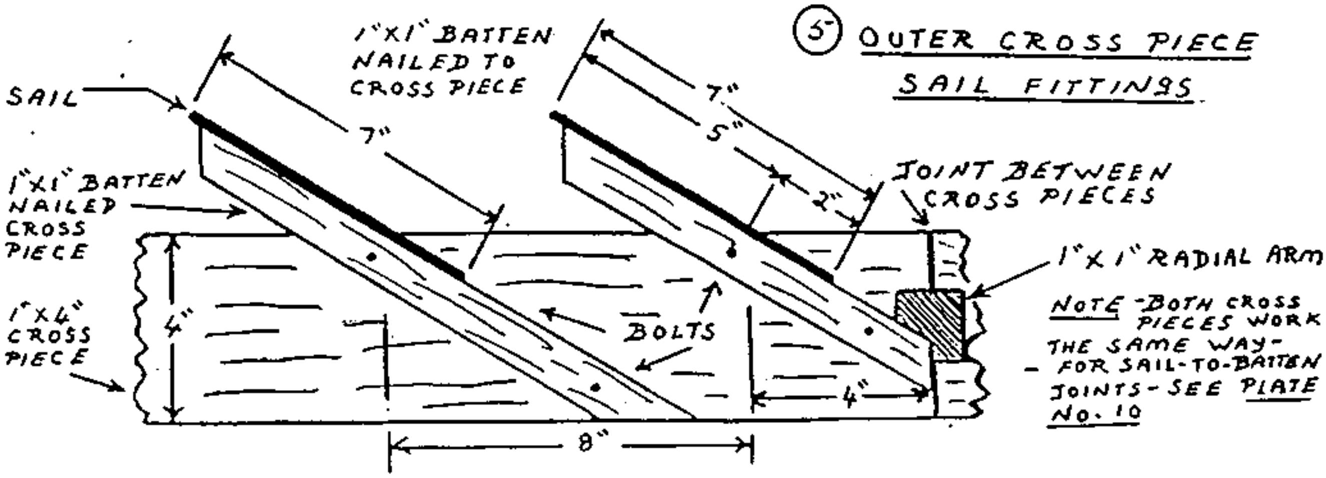


-1"x4"x24" - WITH SIX 2" CUTS AT 30°

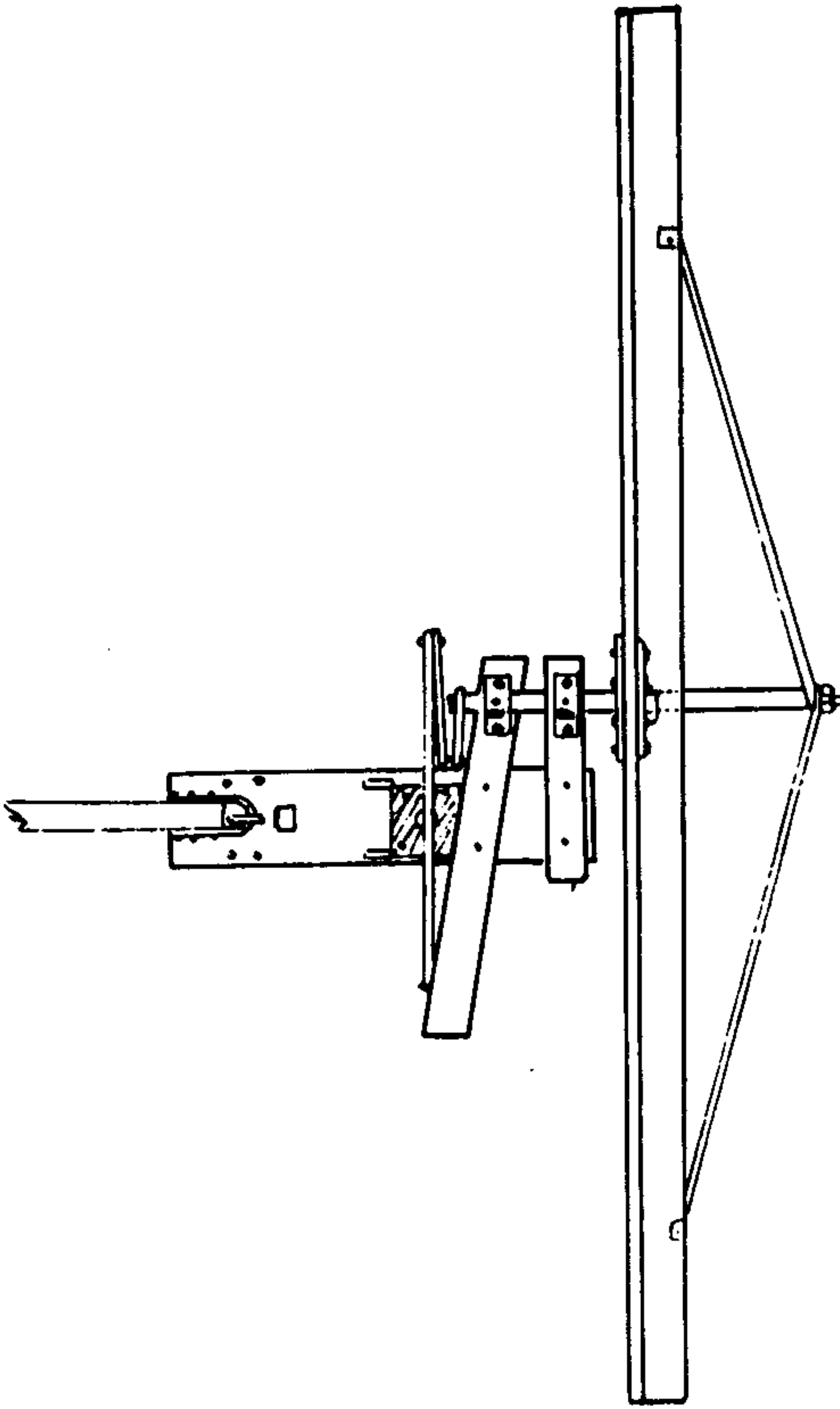
(4) OUTER CROSS PIECE - 1"x4"x48" - WITH SIX 2" CUTS AT 30°

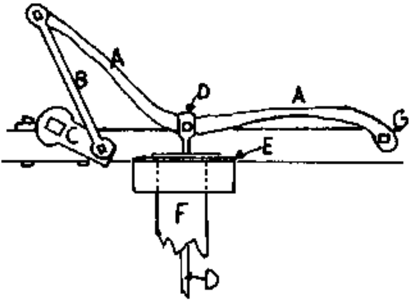


(5) OUTER CROSS PIECE SAIL FITTINGS



NOTE - BOTH CROSS PIECES WORK THE SAME WAY-
- FOR SAIL-TO-BATTEN JOINTS - SEE PLATE No. 10




A
B
C
D
A
G
E
F
D

The other end of the axle is supported on two pieces of 3 x 2 timber, which are securely bolted to the platform. On the end is fastened an arm of iron 4 inches long, and marked C in figure 4. At the free end of C is bolted another arm B, 8 or 9 inches long. A third arm A, 2 feet long, is bolted at one extremity to B and at the other to the 3 x 2 timber at G. The connecting rod is fastened about midway at D. These should all be so bolted as to allow of free movement.

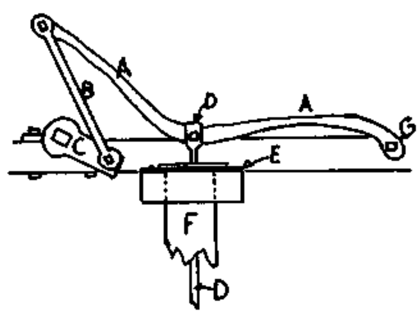


figure 4

Tail

This should be sufficiently large and long enough to keep the sails to the wind. A piece of sheet iron 4 ft. x 2 ft. fastened to a piece of timber 3 in. x 2 in., 9 or 10 feet long, will be found large enough. This may be cut to any desired shape. The end is fastened to the platform with an iron staple, and is also supported by an iron stay stretched over an upright 3 feet high.

The ail is kept in position by having a wooden pin on each side of the long arm. If required to throw it out of gear, the tail may be pulled round upon removal of one pin, and held at right angles by another pin.

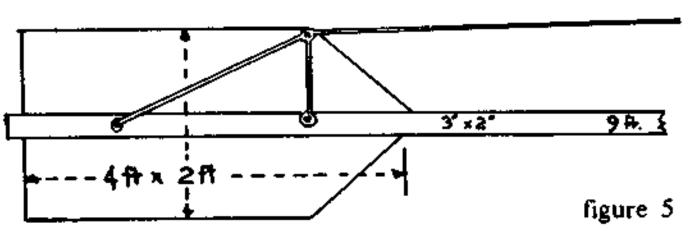


figure 5

In arranging the tail and fans, care should be taken to keep the platform as far as possible evenly balanced on the iron pipe.

The connecting rod is fastened to the plunger of the pump underneath.

The foregoing is one form of home-made windmill, but there are many other ways of arranging the crank, etc., and also the sails.

In utilizing windmill power for driving machinery, it would be necessary to have the sails much larger and stronger in proportion. One having a diameter of 10 feet would develop about one-eighth horse power with a wind blowing 10 miles an hour, while one 22 feet in diameter would develop about one horse power. By means of a fly-wheel and shafting, the power can be transmitted to different parts of the barn as desired.

It will be found, however, that one of the best uses to which a windmill of this kind can be put is that of raising water for various purposes. To raise water by hand entails a great deal of labor and time, and many are the devices used to minimise this. At the present day the ordinary post with a long pole can still be seen in some parts of the countryside while in others the windlass is extensively used. It will be readily seen that where water has to be raised in such small quantities a great deal of time is spent to water a large number of animals. Where water is stored in dams or blind creeks, the stock are often allowed to help themselves, and may be seen wading knee-deep. The consequence is, that not only is the water being kept continuously muddy, but it is also polluted, and one can readily understand that such a state of things is not healthful. Where the supply is limited, it is most important that the source be not contaminated from any preventable cause. This may be accomplished as follows - by fencing off the areas occupied by the water in the case of dams and tanks, and erecting a windmill and suitable troughing, thereby preventing stock from gaining free access to the water. Where a well or tank has to be sunk in order to get a supply, as is the case with some springs, the earth excavated can be utilised in raising the surface of the ground, thus preventing water from around the drinking troughs from running into the well in times of heavy or continuous rains. In places where the water is obtained from a great depth, a lift and force pump would be required, and placed near the surface of the water. This would need extra piping and an extension of the connecting rod. Where the water is only a few feet from the surface, the pump may be set on the surface, or raised a little so that water would flow by gravitation to the trough.

With a little care in the arrangement of the windmill and troughing, the water may be kept at an almost constant level, and little attention is required beyond occasionally oiling and greasing the different parts. Figure 1, as illustrated on page 70, contains a rough idea how this may be done, and shows a tank arranged over the drinking trough, which is kept full. The windmill may be allowed to work continuously, and an overflow pipe is attached near the top of the tank to convey surplus water back to the well. This tank acts as a reservoir and holds a supply ready for flowing into the trough when required, and during times when there is no wind to drive the mill. By having an automatic tap the water may be allowed to run into the trough as fast as it is used. A home-made one may be made as follows: A piece of 1 inch board, 2 ft. 6 in. long, is bolted at one end to a part of the trough or preferably to a frame fitted in the trough, in such a way as to admit the other end moving freely with an upward and downward motion. At 6 inches from the bolted end a flange is fitted, which, when the free end of B rises, covers and completely cuts off the water that passes through the opening in the tank at D. At C a float is arranged—a treacle tin having a patent top will do admirably. The idea is simple. When the float lowers, as it does when the water is used by stock, the flange at E allows the water to escape. The float rises with the water, and when full the supply is again cut off at D. Care should be taken that the flange fits accurately. It is also well to have this covered in, so that stock may not interfere with it.

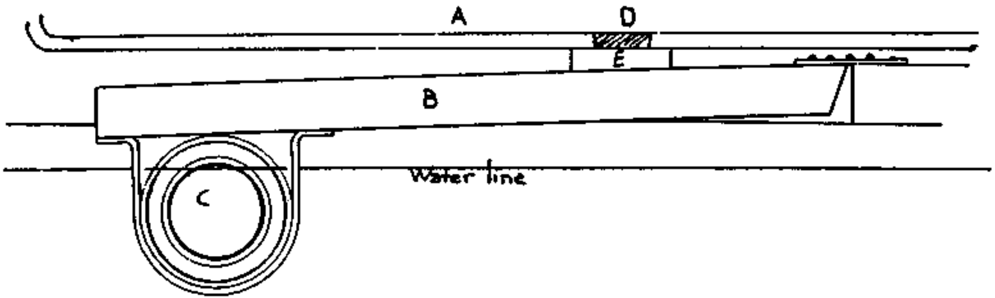


figure 6

For the trough nothing is more substantial than a good hollow log. This, when properly arranged, if firm, is not likely to be removed or overturned. By having a long trough and the tank arranged over the centre, a division fence may be run and the trough used for watering two paddocks.

Where the supply is situated near the homestead, the water may be distributed over the various departments by having a number of tanks raised on proper stands, and conveying it by means of pipes laid underground. By this means not only is the arrangement very convenient for the stables, dairy, piggery, poultry yards, etc., and even the house itself, but it will be found very effective for the flower and kitchen gardens. A week or so of dry weather is often quite sufficient to destroy a fine garden of vegetables and in positions where water may be conveyed as above described, the advantages to be derived from such an arrangement cannot be overestimated.

Reprinted from:

The Agricultural Gazette
of New South Wales
January, 1905

Sail repair

Tears and rips ■ 319

Materials

Thread.

Needles.

Beeswax.

Sewing palm.

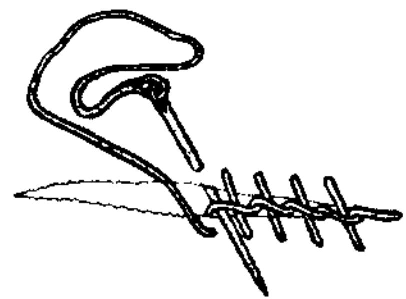
Procedure

Double, even quadruple, the thread.

Wax the thread by drawing it several times across the beeswax.

Make a knot in the end and sew using a sailmaker's darn (herringbone stitch).

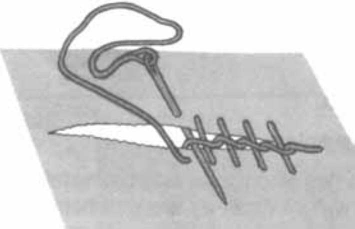
Make 5–6 stitches per 2.5cm.



■ **319** *A sailmaker's darn – herringbone stitch*

Any tear longer than 5cm. which is not along a seam should be patched.

■ **319** *A sailmaker's darn – herringbone stitch*



herringbone

Sewing heavy material like canvas can be as hard on the needle as it is on your hands. If, however, you rub the fabric well with soap before you stitch . . . the job will be a lot more comfortable and the needle will slip through the cloth without nearly so much danger of breaking.

☸ Patching ■ 320, 321, 322

Materials

Thread.

Needles.

Beeswax.

Sewing palm.

Patch: this should be approximately the same weight cloth as the sail being repaired. It should be large enough to extend 5cm. on either side of the tear.

Procedure

If possible, sew the break closed with an overhand stitch ■ **320.**

If the patch is cut from a synthetic fabric, hot seal the edges with an iron, soldering iron, or screwdriver heated on the stove. Failing that, turn the edges under.

If the patch is cut from canvas, turn the edges under.

Place the patch on the sail with its warp and weft lined up with that of the sail.

Hold the patch in place by means of tape, pins, or stitches in the corners ■ **321.**

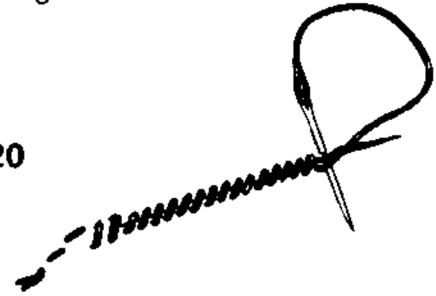
Sew the patch on with an overhand or seam stitch ■ **322.**

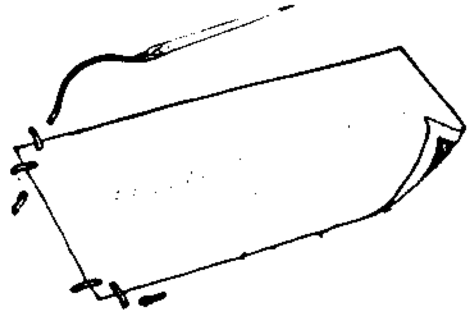
WARNING:

Even though Terylene sails are harder and will take more punishment than canvas, the seams of synthetic fabrics are highly vulnerable. Whereas stitches in cotton or flax tend to sink in and become a part of the cloth, stitches in Terylene stand out, and if too large a thread is used, make little holes of their own. For this reason, three rows of stitches on a seam are required. The two outer ones will hopefully protect the inner one.

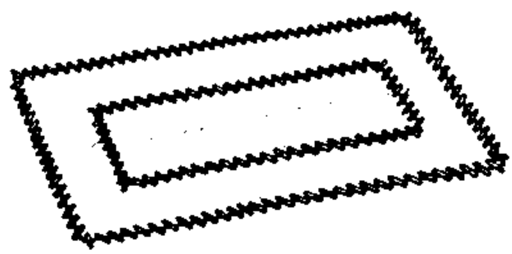
Patching a sail

■ **320**





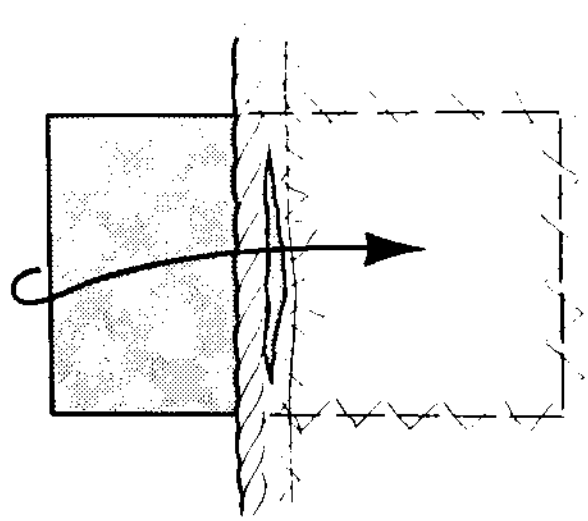
■ **321**



■ **322**

☸ For tears along the bolt rope ■ 323

Wrap the patch around the bolt rope, then sew it through from both sides and along the edge of the rope.

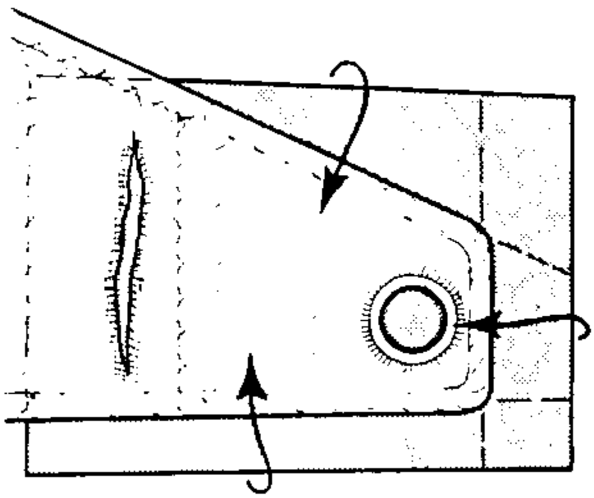


■ **323** *Patching a tear along the bolt rope*

■ 320

For tears along the headboard ■ 324

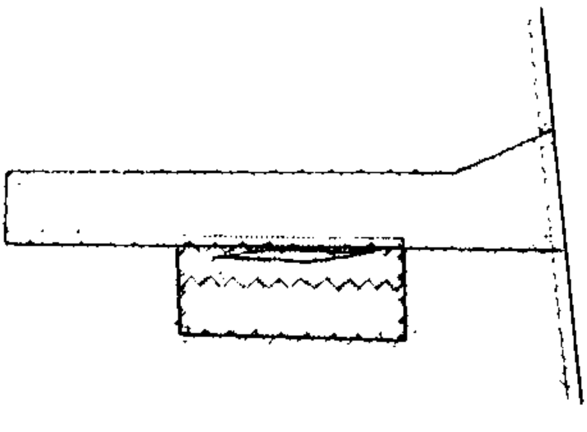
Fold a large patch over the headboard which covers the tear on both sides. Stitch along the base of the headboard, fold in the flaps of the patch, then sew through the headboard holes.



■ **324** *Patching a tear along the headboard*

For tears along a batten pocket ■ 325

Remove the stitches along the edge of the pocket and slide in the patch. Sew the patch on, then re-sew the pocket in place.



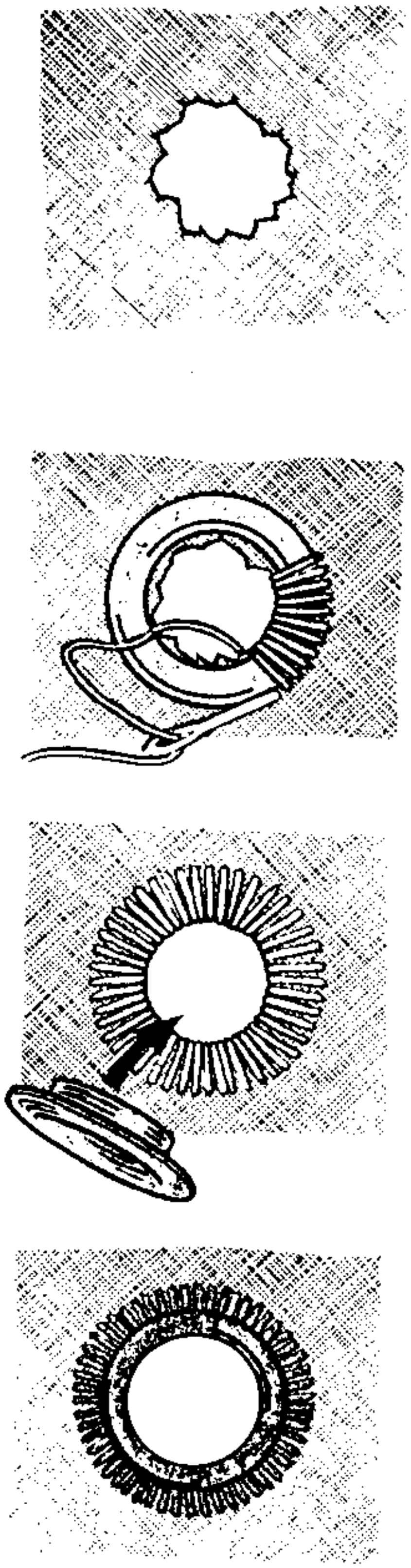
■ **325** *Patching a tear along a batten pocket*

For tears at the tack or clew

METHOD 1 ■ 326

Sew in a round thimble, install the liner, then flare out the edges.

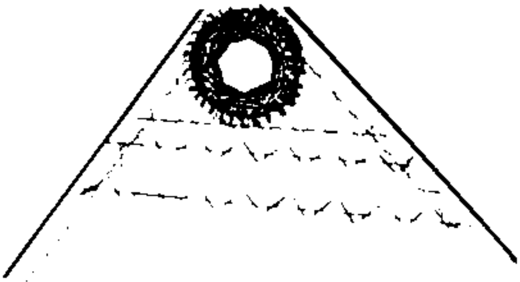
■ **326**



METHOD 2 ■ 327

Sew a piece of rope around the hole either around the rope or, if possible, through it.

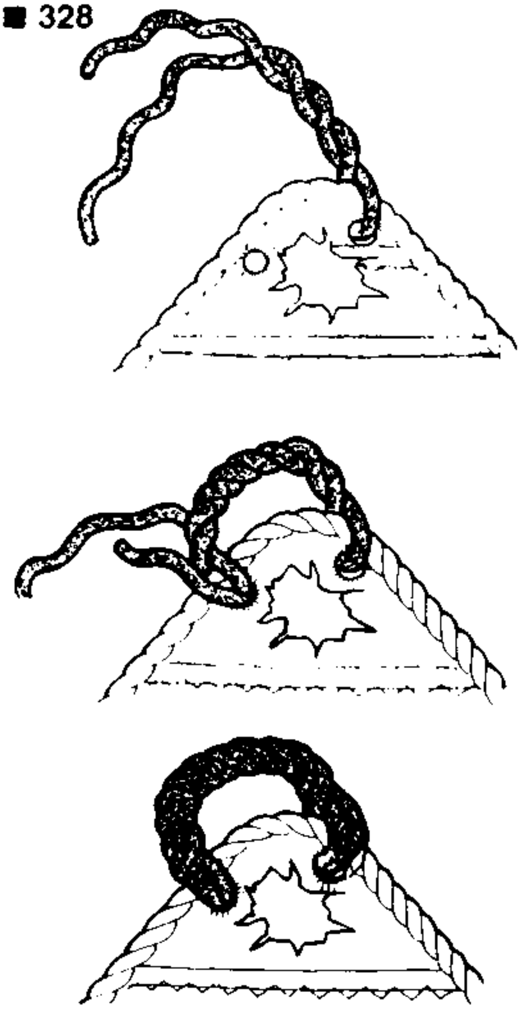
■ 327



METHOD 3 ■ 328

Make a rope cringle around the bolt rope. This can be fabricated as shown from a length of strong line.

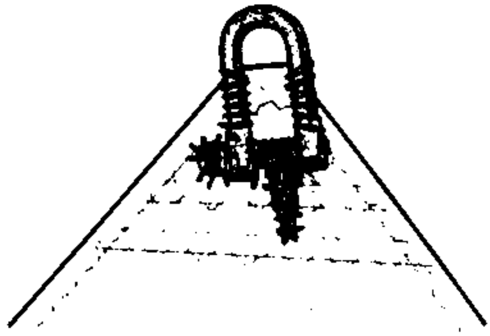
■ 328



METHOD 4 ■ 329

Sew a shackle, either over the hole or to the bolt rope which will serve as a sheet point.

■ 329



NOTE:

To reduce stress, pass the sheet several times through the clew, then secure it with a bowline.

METHOD 5 ■ 330

Fold the clew several times, bunch the sail together and lash it securely.

☸ Long tears, blown-out sails and weakened sailcloth

Materials

A strong, water-resistant contact glue.

Patching material. If not enough is available, a sailbag makes a good substitute.

Procedure

Clean the glueing surfaces with fresh water and let them dry.

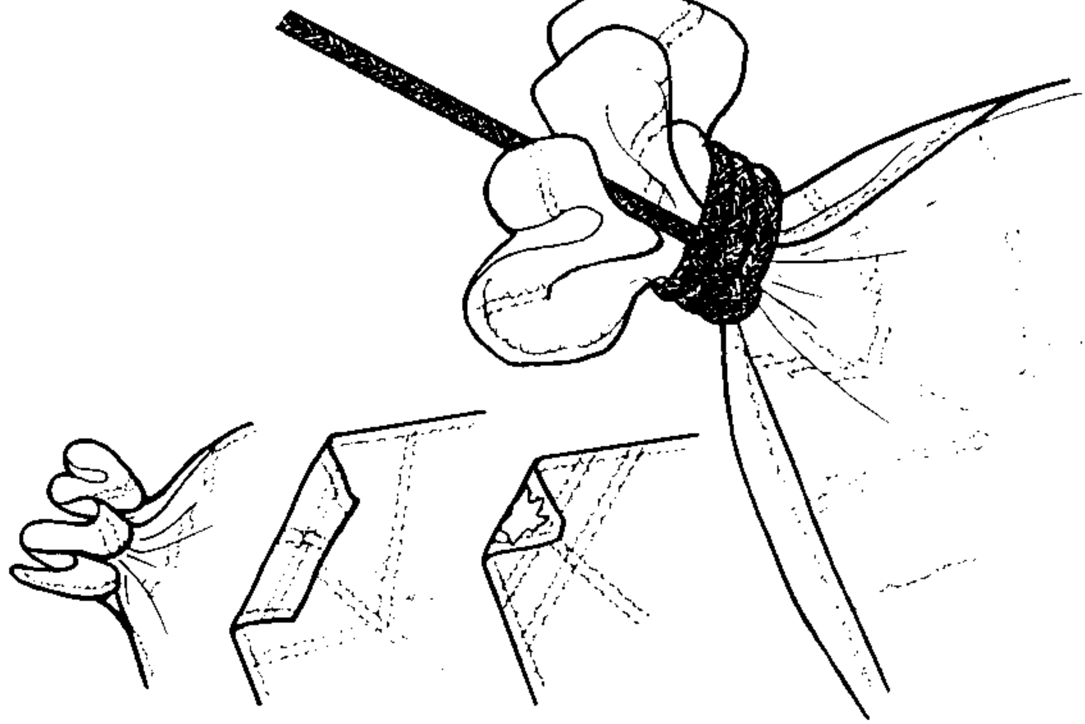
If the break is along a seam, don't use a patch.

Spread the glue evenly on both surfaces and let it nearly dry.

Press the two surfaces together.

To make a solid bond, pound the entire joint with a block of wood and a hammer.

■ 330

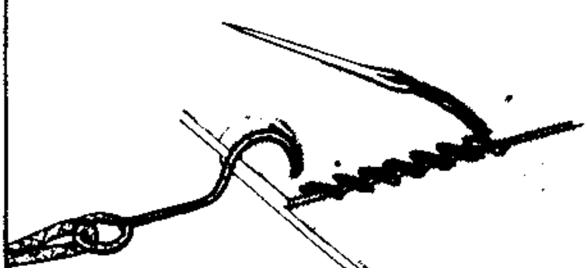


For easy sewing

Lay the sail and patch over a cutting board across your knees, and place the seam along the edge.

Hold the sail taut by means of a shock cord and hook **■ 331.**

■ **331** *Holding the sail taut with a shock cord and hook*



For fast sewing on heavy cloth

Hold the sail vertically, and with a man on either side, each armed with a sewing palm and a pair of pliers, push and pull the needles back and forth.

☸ Chafe

On the seams

Cover both sides of the seam with sail tape (nylon or Terylene) and stitch it lightly in place.

On sails

Once a chafe mark appears, cover the area on *both* sides with a patch of light Terylene.

Prevention

Rig a boom vang so that the sail will lose its tendency to ride up and down on the shrouds and spreaders.

Cover spreader ends with tape, a leather bag or tennis balls.

Cover turnbuckles with tape, plastic hose, or rags.

See: Baggywrinkle

Baggywrinkle

See also: Chafe, Sail repair

Materials

For one metre of baggywrinkle – about three metres of 3.5–4cm. old rope.

Two lengths of strong twine.

Procedure

Unlay the rope and cut it into 10cm strands.

Tie two lengths of twine in a vertical position between two fittings.

Take a strand of rope, hold it crossways, bring the ends up outside the twine, then pass them inside ■ **40**.

Slide the strand up firmly against the knot.

Take the next strand . . . and so on.

Press the strands tightly against each other and knot the twine to hold them in place.

Unhitch the twine ■ **41**.

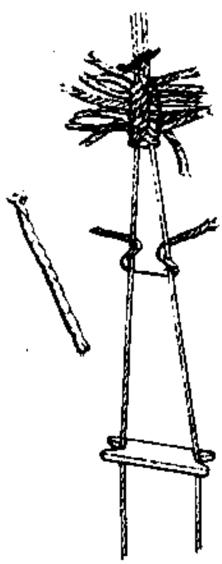
Tape the sections of shroud where the baggywrinkle is lashed so it will not slip down ■ **42**.

NOTE:

Instant baggywrinkle can be fabricated from paint rollers.

■ **42**

■ **40** *Baggywrinkle*



■ **41**

Canoe Finishing

Canvas canoes take a good finish, and remain not only water-tight but also attractive over a considerable period — if the job is done right.

1. Wash inside and out; then dry thoroughly.

2. Remove old paint, using any standard varnish remover according to the manufacturer's directions.

3. Dry entire canoe thoroughly. For this use a small motor-driven blower, taking warm air from around a heater improvised from one of the common "air-tight" wood-burning stoves. This warm dry air is blown gently into a canvas-covered box completely covering the canoe, the blower being tied in at the end while the other end is left open as a vent. After partially drying the canoe with the stern toward the blower lift the cover, turn the canoe halfway around, and complete the drying.

4. After making sure that the canoe is dry, and regardless of the final colour desired, prime it with a thin coating — little more than a wash — of aluminum paint, using a long-oil varnish as the vehicle.

5. Then the canoe is given two colour coats of best grade marine paint, the material for each coat being cut with the addition of one-half pint of turpentine or wood spirits to the gallon as received. After the first coat has dried thoroughly, it is sanded lightly to assure a better bond with the following coat.

6. The job is finished with a coating of spar varnish. The varnish is flowed on with as little brushing as possible, beginning at the keel and working toward the gunwales.

Where any lettering, initials or decorative design is desired, it is put on over the last coat of color and covered with the spar varnish along with the rest of the canvas.

Jobs turned out in the manner outlined last from three to five years, depending upon usage (care being taken to drain the craft after each trip) and the amount of abrasion suffered from sandy beaches and rocky shoals.

Appendix

Metric conversion charts

Metric prefixes and abbreviations

The metre is used as an example below. The same prefixes apply to litres (l or lit) and grams (g). The abbreviation lit is used for litre when unqualified to avoid confusion with the numeral 1.

millimetre (mm)	0.001	one thousandth metre
centimetre (cm)	0.01	one hundredth metre
decimetre (dm)	0.1	one tenth metre
metre (m)	**1**	one metre
decametre (dam)	10	ten metres
hectometre (hm)	100	one hundred metres
kilometre (km)	1000	one thousand metres

Length (linear measure)

Fractions of 1 inch in millimetres

Thirty-seconds, sixteenths, eighths, quarters and one half

in	*mm*
1/32	0.8
1/16	1.6
3/32	2.4
1/8	3.2
5/32	4.0
3/16	4.8
7/32	5.6
1/4	6.3
9/32	7.1
5/16	7.9
11/32	8.7
3/8	9.5
13/32	10.3
7/16	11.1
15/32	11.9
1/2	12.7
17/32	13.5
9/16	14.3
19/32	15.1
5/8	15.9
21/32	16.7
11/16	17.5
23/32	18.3
3/4	19.0
25/32	19.8
13/16	20.6
27/32	21.4
7/8	22.2
29/32	23.0
15/16	23.8
31/32	24.6
1 inch	25.4

Twelfths, sixths and thirds

in	*mm*
1/12	2.1
1/6	4.2
1/4	6.3
1/3	8.5
5/12	10.6
1/2	12.7
7/12	14.8
2/3	16.9
3/4	19.0
5/6	21.2
11/12	23.3
1 inch	25.4

Note

Find the Imperial figure you wish to convert in the **heavy** type central column and read off the metric equivalent in the right-hand column and vice versa.
For example:
10 inches = 254 millimetres and 10mm = 0.39in.

Conversion from inches is only taken up to 40 in the chart below, see next chart for continuation.

Inches/millimetres

in		*mm*
0.04	**1**	25.4
0.08	**2**	50.8
0.12	**3**	76.2
0.16	**4**	101.6
0.20	**5**	127.0
0.24	**6**	152.4
0.28	**7**	177.8
0.31	**8**	203.2
0.35	**9**	228.6
0.39	**10**	254.0
0.43	**11**	279.4
0.47	**12**	304.8
0.51	**13**	330.2
0.55	**14**	355.6
0.59	**15**	381.0
0.63	**16**	406.4
0.67	**17**	431.8
0.71	**18**	457.2
0.75	**19**	482.6
0.79	**20**	508.0
0.83	**21**	533.4
0.87	**22**	558.8
0.91	**23**	584.2
0.94	**24**	609.6
0.98	**25**	635.0
1.02	**26**	660.4
1.06	**27**	685.8
1.10	**28**	711.2
1.14	**29**	736.6
1.18	**30**	762.0
1.22	**31**	787.4
1.26	**32**	812.8
1.30	**33**	838.2
1.34	**34**	863.6
1.38	**35**	889.0
1.42	**36**	914.4
1.46	**37**	939.8
1.50	**38**	965.2
1.54	**39**	990.6
1.57	**40**	1016.0
1.97	**50**	
2.36	**60**	
2.76	**70**	
3.15	**80**	
3.54	**90**	
3.94	**100**	
7.87	**200**	
11.81	**300**	
15.75	**400**	
19.68	**500**	
23.62	**600**	
27.56	**700**	
31.50	**800**	
35.43	**900**	
39.37	**1000**	

Imperial measurements are expressed below in yards, feet and inches rather than in decimals for convenience if converting with rulers or measuring tapes which do not include decimal readings.

Feet/metres

ft	*in*		*m*
3	3	**1**	0.30
6	7	**2**	0.61
9	10	**3**	0.91
13	1	**4**	1.22
16	5	**5**	1.52
19	8	**6**	1.83
23	0	**7**	2.13
26	3	**8**	2.44
29	6	**9**	2.74
32	10	**10**	3.05
65	7	**20**	6.10
98	5	**30**	9.14
131	3	**40**	12.19
164	0	**50**	15.24
196	10	**60**	18.29
229	8	**70**	21.34
262	6	**80**	24.38
295	3	**90**	27.43
328	1	**100**	30.48

Yards/metres

yd	*ft*	*in*		*m*
1	0	3	**1**	0.9
2	0	7	**2**	1.8
3	0	10	**3**	2.7
4	1	1	**4**	3.7
5	1	5	**5**	4.6
6	1	8	**6**	5.5
7	2	0	**7**	6.4
8	2	3	**8**	7.3
9	2	6	**9**	8.2
10	2	10	**10**	9.1
21	2	7	**20**	18.3
32	2	5	**30**	27.4
43	2	3	**40**	36.6
54	2	0	**50**	45.7
65	1	10	**60**	54.9
76	1	8	**70**	64.0
87	1	6	**80**	73.2
98	1	3	**90**	82.3
109	1	1	**100**	91.4

Quick conversion factors – length

Terms are set out in full in the left-hand column except where clarification is necessary.

1 inch (in)	= 25.4mm/2.54cm
1 foot (ft)/12in	= 304.8mm/30.48cm/0.3048m
1 yard (yd)/3ft	= 914.4mm/91.44cm/0.9144m
1 mile (mi)/1760yd	= 1609.344m/1.609km
1 millimetre (mm)	= 0.0394in
1 centimetre (cm)/10mm	= 0.394in
1 metre (m)/100cm	= 39.37in/3.281ft/1.094yd
1 kilometre (km)/1000m	= 1093.6yd/0.6214mi

Quick conversion factors – area

1 square inch (sq in)	= 645.16sq mm/ 6.4516sq cm
1 square foot (sq ft)/144sq in	= 929.03sq cm
1 square yard (sq yd)/9sq ft	= 8361.3sq cm/ 0.8361sq m
1 acre (ac)/4840sq yd	= 4046.9sq m/0.4047ha
1 square mile (sq mi)640ac	= 259ha
1 square centimetre (sq cm)/ 100 square millimetre (sq mm)	= 0.155sq in
1 square metre (sq m)/ 10,000sq cm	= 10.764sq ft/1.196sq yd
1 are (a)/100sq m	= 119.60sq yd/0.0247ac
1 hectare (ha)/100a	= 2.471ac/0.00386sq mi

Quick conversion factors – volume

1 cubic inch (cu in)	= 16.3871cu cm
1 cubic foot (cu ft)/ 1728cu in	= 28.3168cu dm/0.0283cu m
1 cubic yard (cu yd)/ 27cu ft	= 0.7646cu m
1 cubic centimetre (cu cm)/ 1000 cubic millimetres (cu mm)	= 0.0610cu in
1 cubic decimetre (cu dm)/ 1000cu cm	= 61.024cu in/0.0353cu ft
1 cubic metre (cu m)/ 1000cu dm	= 35.3146cu ft/1.308cu yd
1cu cm	= 1 millilitre (ml)
1cu dm	= 1 litre (lit) See **Capacity**

Area (square measure)

As millimetre numbers would be unwieldy for general use, square or cubic inches have been converted to square or cubic centimetres. Conversion from square inches is only taken up to 150 in the first chart below; see next chart for continuation.

Square inches/square centimetres

sq in		*sq cm*
0.2	**1**	6.5
0.3	**2**	12.9
0.5	**3**	19.4
0.6	**4**	25.8
0.8	**5**	32.3
0.9	**6**	38.7
1.1	**7**	45.2
1.2	**8**	51.6
1.4	**9**	58.1
1.6	**10**	64.5
3.1	**20**	129.0
4.7	**30**	193.5
6.2	**40**	258.1
7.8	**50**	322.6
9.3	**60**	387.1
10.9	**70**	451.6
12.4	**80**	516.1
14.0	**90**	580.6
15.5	**100**	645.2
17.1	**110**	709.7
18.6	**120**	774.2
20.2	**130**	838.7
21.7	**140**	903.2
23.3	**150**	967.7
31.0	**200**	
46.5	**300**	
62.0	**400**	
77.5	**500**	
93.0	**600**	
108.5	**700**	
124.0	**800**	
139.5	**900**	
155.0	**1000**	

Square feet/square metres

sq ft		*sq m*
10.8	**1**	0.09
21.5	**2**	0.19
32.3	**3**	0.28
43.1	**4**	0.37
53.8	**5**	0.46
64.6	**6**	0.56
75.3	**7**	0.65
86.1	**8**	0.74
96.9	**9**	0.84
107.6	**10**	0.93
215.3	**20**	1.86
322.9	**30**	2.79
430.6	**40**	3.72
538.2	**50**	4.65
645.8	**60**	5.57
753.5	**70**	6.50
861.1	**80**	7.43
968.8	**90**	8.36
1076.4	**100**	9.29

Square yards/square metres

sq yd		*sq m*
1.2	**1**	0.8
2.4	**2**	1.7
3.6	**3**	2.5
4.8	**4**	3.3
6.0	**5**	4.2
7.2	**6**	5.0
8.4	**7**	5.9
9.6	**8**	6.7
10.8	**9**	7.5
12.0	**10**	8.4
23.9	**20**	16.7
35.9	**30**	25.1
47.8	**40**	33.4
59.8	**50**	41.8
71.8	**60**	50.2
83.7	**70**	58.5
95.7	**80**	66.9
107.6	**90**	75.3
119.6	**100**	83.6

Volume (cubic measure)

Cubic inches/cubic centimetres

cu in		*cu cm*
0.06	**1**	16.4
0.12	**2**	32.8
0.18	**3**	49.2
0.24	**4**	65.5
0.31	**5**	81.9
0.37	**6**	98.3
0.43	**7**	114.7
0.49	**8**	131.1
0.55	**9**	147.5
0.61	**10**	163.9
1.22	**20**	327.7
1.83	**30**	491.6
2.44	**40**	655.5
3.05	**50**	819.4
3.66	**60**	983.2
4.27	**70**	1147.1/1.15cu dm
4.88	**80**	1311.0/1.31cu dm
5.49	**90**	1474.8/1.47cu dm
6.10	**100**	1638.7/1.64cu dm
12.20	**200**	3277.4/3.28cu dm
18.31	**300**	4916.1/4.92cu dm
24.41	**400**	6554.8/6.55cu dm
30.51	**500**	8193.5/8.19cu dm
36.61	**600**	9832.2/9.83cu dm
42.72	**700**	11470.9/11.47cu dm
48.82	**800**	13109.7/13.11cu dm
54.92	**900**	14748.4/14.75cu dm
61.02	**1000**	16387.1/16.39cu dm
122.05	**2000**	32774.1/32.77cu dm

Cubic feet/cubis decimetres

cu ft		*cu dm*
.04	**1**	28.3
0.07	**2**	56.6
0.11	**3**	85.0
0.14	**4**	113.3
0.18	**5**	141.6
0.21	**6**	169.9
0.25	**7**	198.2
0.28	**8**	226.5
0.32	**9**	254.9
0.35	**10**	283.2
0.71	**20**	566.3
1.06	**30**	849.5
1.41	**40**	1132.7/1.13cu m
1.77	**50**	1415.8/1.42cu m
2.12	**60**	1699.0/1.70cu m
2.47	**70**	1982.2/1.98cu m
2.83	**80**	2265.3/2.27cu m
3.18	**90**	2548.5/2.55cu m
3.53	**100**	2831.7/2.83cu m

Cubic yards/cubic metres

cu yd		*cu m*
1.3	**1**	0.8
2.6	**2**	1.5
3.9	**3**	2.3
5.2	**4**	3.1
6.5	**5**	3.8
7.8	**6**	4.6
9.2	**7**	5.4
10.5	**8**	6.1
11.8	**9**	6.9
13.1	**10**	7.6
26.2	**20**	15.3
39.2	**30**	22.9
52.3	**40**	30.6
65.4	**50**	38.2
78.5	**60**	45.9
91.6	**70**	53.5
104.6	**80**	61.2
117.7	**90**	68.8
130.8	**100**	76.5

Capacity

Fluid ounces/millilitres

fl oz		
0.04	**1**	28.4
0.07	**2**	56.8
0.11	**3**	85.2
0.14	**4**	113.6
0.18	**5**	142.1
0.21	**6**	170.5
0.25	**7**	198.9
0.28	**8**	227.3
0.32	**9**	255.7
0.35	**10**	284.1
0.70	**20**	568.2
1.06	**30**	852.4
1.41	**40**	1136.5/1.136 lit
1.76	**50**	1420.6/1.421 lit

Pints/litres

pt		*lit*
1.8	**1**	0.6/568ml
3.5	**2**	1.1
5.3	**3**	1.7
7.0	**4**	2.3
8.8	**5**	2.8
10.6	**6**	3.4
12.3	**7**	4.0
14.1	**8**	4.5
15.8	**9**	5.1
17.6	**10**	5.7

Gallons/litres

gal		*lit*
0.2	**1**	4.5
0.4	**2**	9.1
0.7	**3**	13.6
0.9	**4**	18.2
1.1	**5**	22.7
1.3	**6**	27.3
1.5	**7**	31.8
1.8	**8**	36.4
2.0	**9**	40.9
2.2	**10**	45.5
4.4	**20**	90.9
6.6	**30**	136.4
8.8	**40**	181.8
11.0	**50**	227.3
13.2	**60**	272.8
15.4	**70**	318.2
17.6	**80**	363.7
19.8	**90**	409.1
22.0	**100**	454.6

Weight

Ounces/grams

oz		*g*
0.04	**1**	28.3
0.07	**2**	56.7
0.11	**3**	85.0
0.14	**4**	113.4
0.18	**5**	141.7
0.21	**6**	170.1
0.25	**7**	198.4
0.28	**8**	226.8
0.32	**9**	255.1
0.35	**10**	283.5
0.39	**11**	311.8
0.42	**12**	340.2
0.46	**13**	368.5
0.49	**14**	396.9
0.53	**15**	425.2
0.56	**16**	453.6
0.71	**20**	567.0
1.06	**30**	850.5
1.41	**40**	1134.0
1.76	**50**	1417.5
2.12	**60**	1701.0
2.47	**70**	1984.5
2.82	**80**	2268.0
3.17	**90**	2551.5
3.53	**100**	2835.0

Pounds/kilograms

lb		*kg*
2.2	**1**	0.5
4.4	**2**	0.9
6.6	**3**	1.4
8.8	**4**	1.8
11.0	**5**	2.3
13.2	**6**	2.7
15.4	**7**	3.2
17.6	**8**	3.6
19.8	**9**	4.1
22.0	**10**	4.5
44.1	**20**	9.1
66.1	**30**	13.6
88.2	**40**	18.1
110.2	**50**	22.7
132.3	**60**	27.2
154.3	**70**	31.8
176.4	**80**	36.3
198.4	**90**	40.8
220.5	**100**	45.4

Quick conversion factors – capacity

1 fluid ounce (fl oz)	= 28.4ml
1 gill (gi)/5fl oz	= 142.1ml
1 pint (pt)/4gi	= 568.2ml/0.568 lit
1 quart (qt)/2pt	= 1.136 lit
1 gallon (gal)/4pt	= 4.546 lit
1 millilitre (ml)	= 0.035fl oz
1 litre (lit)	= 1.76pt/0.22gal
1ml	= 1 cubic centimetre (cu cm)
1 lit	= 1 cubic decimetre (cu dm) See **Volume**
1 US pint	= 5/6 Imperial pt/473.2ml/0.473 lit
1 US gallon	= 5/6 Imperial gal/3.785 lit

Quick conversion factors – weight

1 ounce (oz)	= 28.35g
1 pound (lb)/16oz	= 453.59g/0.4536kg
1 stone/14lb	= 6.35kg
1 hundredweight (cwt)/ 8 stone/112lb	= 50.80kg
1 ton/20cwt	= 1016.05kg/1.016t
1 gram (g)	= 0.035oz
1 kilogram (kg)/1000g	= 35.274oz/2.2046lb/ 2lb 3.274oz
1 tonne (t)/1000kg	= 2204.6lb/0.9842 ton

Metric conversion tables

Inches	Decimals	Millimetres	Millimetres to Inches		Inches to Millimetres	
			mm	Inches	Inches	mm
1/64	0.015625	0.3969	0.01	0.00039	0.001	0.0254
1/32	0.03125	0.7937	0.02	0.00079	0.002	0.0508
3/64	0.046875	1.1906	0.03	0.00118	0.003	0.0762
1/16	0.0625	1.5875	0.04	0.00157	0.004	0.1016
5/64	0.078125	1.9844	0.05	0.00197	0.005	0.1270
3/32	0.09375	2.3812	0.06	0.00236	0.006	0.1524
7/64	0.109375	2.7781	0.07	0.00276	0.007	0.1778
1/8	0.125	3.1750	0.08	0.00315	0.008	0.2032
9/64	0.140625	3.5719	0.09	0.00354	0.009	0.2286
5/32	0.15625	3.9687	0.1	0.00394	0.01	0.254
11/64	0.171875	4.3656	0.2	0.00787	0.02	0.508
3/16	0.1875	4.7625	0.3	0.01181	0.03	0.762
13/64	0.203125	5.1594	0.4	0.01575	0.04	1.016
7/32	0.21875	5.5562	0.5	0.01969	0.05	1.270
15/64	0.234375	5.9531	0.6	0.02362	0.06	1.524
1/4	0.25	6.3500	0.7	0.02756	0.07	1.778
17/64	0.265625	6.7469	0.8	0.03150	0.08	2.032
9/32	0.28125	7.1437	0.9	0.03543	0.09	2.286
19/64	0.296875	7.5406	1	0.03937	0.1	2.54
5/16	0.3125	7.9375	2	0.07874	0.2	5.08
21/64	0.328125	8.3344	3	0.11811	0.3	7.62
11/32	0.34375	8.7312	4	0.15748	0.4	10.16
23/64	0.359375	9.1281	5	0.19685	0.5	12.70
3/8	0.375	9.5250	6	0.23622	0.6	15.24
25/64	0.390625	9.9219	7	0.27559	0.7	17.78
13/32	0.40625	10.3187	8	0.31496	0.8	20.32
27/64	0.421875	10.7156	9	0.35433	0.9	22.86
7/16	0.4375	11.1125	10	0.39370	1	25.4
29/64	0.453125	11.5094	11	0.43307	2	50.8
15/32	0.46875	11.9062	12	0.47244	3	76.2
31/64	0.484375	12.3031	13	0.51181	4	101.6
1/2	0.5	12.7000	14	0.55118	5	127.0
33/64	0,515625	13.0969	15	0.59055	6	152.4
17/32	0.53125	13.4937	16	0.62992	7	177.8
35/64	0.546875	13.8906	17	0.66929	8	203.2
9/16	0.5625	14.2875	18	0.70866	9	228.6
37/64	0.578125	14.6844	19	0.74803	10	254.0
19/32	0.59375	15.0812	20	0.78740	11	279.4
39/64	0.609375	15.4781	21	0.82677	12	304.8
5/8	0.625	15.8750	22	0.86614	13	330.2
41/64	0.640625	16.2719	23	0.90551	14	355.6
21/32	0.65625	16.6687	24	0.94488	15	381.0
43/64	0.671875	17.0656	25	0.98425	16	406.4
11/16	0.6875	17.4625	26	1.02362	17	431.8
45/64	0.703125	17.8594	27	1.06299	18	457.2
23/32	0.71875	18.2562	28	1.10236	19	482.6
47/64	0.734375	18.6531	29	1.14173	20	508.0
3/4	0.75	19.0500	30	1.18110	21	533.4
49/64	0.765625	19.4469	31	1.22047	22	558.8
25/32	0.78125	19.8437	32	1.25984	23	584.2
51/64	0.796875	20.2406	33	1.29921	24	609.6
13/16	0.8125	20.6375	34	1.33858	25	635.0
53/64	0.828125	21.0344	35	1.37795	26	660.4
27/32	0.84375	21.4312	36	1.41732	27	685.8
55/64	0.859375	21.8281	37	1.4567	28	711.2
7/8	0.875	22.2250	38	1.4961	29	736.6
57/64	0.890625	22.6219	39	1.5354	30	762.0
29/32	0.90625	23.0187	40	1.5748	31	787.4
59/64	0.921875	23.4156	41	1.6142	32	812.8
15/16	0.9375	23.8125	42	1.6535	33	838.2
61/64	0.953125	24.2094	43	1.6929	34	863.6
31/32	0.96875	24.6062	44	1.7323	35	889.0
63/64	0.984375	25.0031	45	1.7717	36	914.4

VIII. Decimal Equivalents of Common Fractions

8ths	16ths	32ds	64ths		8ths	16ths	32ds	64ths	
			1	.015625				33	.515625
		1	2	.03125			17	34	.53125
			3	.046875				35	.546875
	1	2	4	.0625		9	18	36	.5625
			5	.078125				37	.578125
		3	6	.09375			19	38	.59375
			7	.109375				39	.609375
1	2	4	8	.125	5	10	20	40	.625
			9	.140625				41	.640625
		5	10	.15625			21	42	.65625
			11	.171875				43	.671875
	3	6	12	.1875		11	22	44	.6875
			13	.203125				45	.703125
		7	14	.21875			23	46	.71875
			15	.234375				47	.734375
2	4	8	16	.25	6	12	24	48	.75
			17	.265625				49	.765625
		9	18	.28125			25	50	.78125
			19	.296875				51	.796875
	5	10	20	.3125		13	26	52	.8125
			21	.328125				53	.828125
		11	22	.34375			27	54	.84375
			23	.359375				55	.859375
3	6	12	24	.375	7	14	28	56	.875
			25	.390625				57	.890625
		13	26	.40625			29	58	.90625
			27	.421875				59	.921875
	7	14	28	.4375		15	30	60	.9375
			29	.453125				61	.953125
		15	30	.46875			31	62	.96875
			31	.484375				63	.984375
4	8	16	32	.5	8	16	32	64	1

Table D-1. Fraction, Decimal, and Metric Equivalents

Fractions	Decimal In.	Metric mm.	Fractions	Decimal In.	Metric mm.
1/64	.015625	.397	33/64	.515625	13.097
1/32	.03125	.794	17/32	.53125	13.494
3/64	.046875	1.191	35/64	.546875	13.891
1/16	.0625	1.588	9/16	.5625	14.288
5/64	.078125	1.984	37/64	.578125	14.684
3/32	.09375	2.381	19/32	.59375	15.081
7/64	.109375	2.778	39/64	.609375	15.478
1/8	.125	3.175	5/8	.625	15.875
9/64	.140625	3.572	41/64	.640625	16.272
5/32	.15625	3.969	21/32	.65625	16.669
11/64	.171875	4.366	43/64	.671875	17.066
3/16	.1875	4.763	11/16	.6875	17.463
13/64	.203125	5.159	45/64	.703125	17.859
7/32	.21875	5.556	23/32	.71875	18.256
15/64	.234375	5.953	47/64	.734375	18.653
1/4	.250	6.35	3/4	.750	19.05
17/64	.265625	6.747	49/64	.765625	19.447
9/32	.28125	7.144	25/32	.78125	19.844
19/64	.296875	7.54	51/64	.796875	20.241
5/16	.3125	7.938	13/16	.8125	20.638
21/64	.328125	8.334	53/64	.828125	21.034
11/32	.34375	8.731	27/32	.84375	21.431
23/64	.359375	9.128	55/64	.859375	21.828
3/8	.375	9.525	7/8	.875	22.225
25/64	.390625	9.922	57/64	.890625	22.622
13/32	.40625	10.319	29/32	.90625	23.019
27/64	.421875	10.716	59/64	.921875	23.416
7/16	.4375	11.113	15/16	.9375	23.813
29/64	.453125	11.509	61/64	.953125	24.209
15/32	.46875	11.906	31/32	.96875	24.606
31/64	.484375	12.303	63/64	.984375	25.003
1/2	.500	12.7	1	1.00	25.4

Inches	Millimeters	Inches	Millimeters	Inches	Millimeters
0.001	0.0254	0.010	0.2540	0.019	0.4826
0.002	0.0508	0.011	0.2794	0.020	0.5080
0.003	0.0762	0.012	0.3048	0.021	0.5334
0.004	0.1016	0.013	0.3302	0.022	0.5588
0.005	0.1270	0.014	0.3556	0.023	0.5842
0.006	0.1524	0.015	0.3810	0.024	0.6096
0.007	0.1778	0.016	0.4064	0.025	0.6350
0.008	0.2032	0.017	0.4318		
0.009	0.2286	0.018	0.4572		

Table D-4. Feet to Meters Conversion Table

Feet – metres 1 foot = 0.3048 m			
ft.	met.	ft.	met.
1	0,305	31	9,449
2	**0,610**	**32**	**9,754**
3	0,914	33	10,058
4	**1,219**	**34**	**10,363**
5	1,524	35	10,668
6	**1,829**	**36**	**10,973**
7	2,134	37	11,278
8	**2,438**	**38**	**11,582**
9	2,743	39	11,887
10	**3,048**	**40**	**12,192**
11	3,353	41	12,497
12	**3,658**	**42**	**12,802**
13	3,962	43	13,106
14	**4,267**	**44**	**13,441**
15	4,572	45	13,716
16	**4,877**	**46**	**14,021**
17	5,182	47	14,326
18	**5,486**	**48**	**14,630**
19	5,791	49	14,935
20	**6,096**	**50**	**15,240**
21	6,401	51	15,545
22	**6,706**	**52**	**15,850**
23	7,010	53	16,154
24	**7,315**	**54**	**16,459**
25	7,620	55	16,764
26	**7,925**	**56**	**17,069**
27	8,230	57	17,374
28	**8,534**	**58**	**17,678**
29	8,839	59	17,983
30	**9,144**	**60**	**18,288**

Table D-5. Meters to Feet Conversion Table

Metres – Feet 1 metre = 3.2808 feet	
met.	feet
1	3,28
2	**6,56**
3	9,84
4	**13,12**
5	16,40
6	**19,69**
7	22,97
8	**26,25**
9	29,53
10	**32,81**
11	36,09
12	**39,37**
13	42,65
14	**45,93**
15	49,21
16	**52,49**
17	55,77
18	**59,06**
19	62,34
20	**65,62**

Table D-6. Inches to Centimeters Conversion Table

Inches – centimetres 1 inch = 2.54 cm	
inches	cm
1	2,54
2	**5,08**
3	7,62
4	**10,16**
5	12,70
6	**15,24**
7	17,78
8	**20,32**
9	22,86
10	**25,40**
11	27,94
12	**30,48**

Conversions: length

Use of the tables: the number to be converted, which is made up by adding the unit at the side of a line to the unit at the head of a column, is converted to the number in the position where line and column meet. For example, 11 in = 10 in + 1 in = 27.940 cm

Inches to Centimetres   1 in = 2.54 cm

in → / ↓	0	1	2	3	4	5	6	7	8	9	← in / ↓
	cm	cm	cm	cm	cm	cm	cm	cm	cm	cm	
0	0.000	2.540	5.080	7.620	10.160	12.700	15.240	17.780	20.320	22.860	0
10	25.400	27.940	30.480	33.020	35.560	38.100	40.640	43.180	45.720	48.260	10
20	50.800	53.340	55.880	58.420	60.960	63.500	66.040	68.580	71.120	73.660	20
30	76.200	78.740	81.280	83.820	86.360	88.900	91.440	93.980	96.520	99.060	30
40	101.600	104.140	106.680	109.220	111.760	114.300	116.840	119.380	121.920	124.460	40
50	127.000	129.540	132.080	134.620	137.160	139.700	142.240	144.780	147.320	149.860	50
60	152.400	154.940	157.480	160.020	162.560	165.100	167.640	170.180	172.720	175.260	60
70	177.800	180.340	182.880	185.420	187.960	190.500	193.040	195.580	198.120	200.660	70
80	203.200	205.740	208.280	210.820	213.360	215.900	218.440	220.980	223.520	226.060	80
90	228.600	231.140	233.680	236.220	238.760	241.300	243.840	246.380	248.920	251.460	90
100	254.000										100

in → / ↓	0	10	20	30	40	50	60	70	80	90	← in / ↓
	cm	cm	cm	cm	cm	cm	cm	cm	cm	cm	
0	0.000	25.400	50.800	76.200	101.600	127.000	152.400	177.800	203.200	228.600	0
100	254.000	279.400	304.800	330.200	355.600	381.000	406.400	431.800	457.200	482.600	100
200	508.000	533.400	558.800	584.200	609.600	635.000	660.400	685.800	711.200	736.600	200
300	762.000	787.400	812.800	838.200	863.600	889.000	914.400	939.800	965.200	990.600	300
400	1016.000	1041.400	1066.800	1092.200	1117.600	1143.000	1168.400	1193.800	1219.200	1244.600	400
500	1270.000	1295.400	1320.800	1346.200	1371.600	1397.000	1422.400	1447.800	1473.200	1498.600	500
600	1524.000	1549.400	1574.800	1600.200	1625.600	1651.000	1676.400	1701.800	1727.200	1752.600	600
700	1778.000	1803.400	1828.800	1854.200	1879.600	1905.000	1930.400	195 .800	1981.200	2006.600	700
800	2032.000	2057.400	2082.800	2108.200	2133.600	2159.000	2184.400	2209.800	2235.200	2260.600	800
900	2286.000	2311.400	2336.800	2362.200	2387.600	2413.000	2438.400	2463.800	2489.200	2514.600	900
1000	2540.000										1000

Centimetres to Inches   1 cm = 0.393 701 in

cm → / ↓	0	1	2	3	4	5	6	7	8	9	← cm / ↓
	in	in	in	in	in	in	in	in	in	in	
0	0.000	0.394	0.787	1.181	1.575	1.969	2.362	2.756	3.150	3.543	0
10	3.937	4.331	4.724	5.118	5.512	5.906	6.299	6.693	7.087	7.480	10
20	7.874	8.268	8.661	9.055	9.449	9.843	10.236	10.630	11.024	11.417	20
30	11.811	12.205	12.598	12.992	13.386	13.780	14.173	14.567	14.961	15.354	30
40	15.748	16.142	16.535	16.929	17.323	17.717	18.110	18.504	18.898	19.291	40
50	19.685	20.079	20.472	20.866	21.260	21.654	22.047	22.441	22.835	23.228	50
60	23.622	24.016	24.409	24.803	25.197	25.591	25.984	26.378	26.772	27.165	60
70	27.559	27.953	28.346	28.740	29.134	29.528	29.921	30.315	30.709	31.102	70
80	31.496	31.890	32.283	32.677	33.071	33.465	33.858	34.252	34.646	35.039	80
90	35.433	35.827	36.220	36.614	37.008	37.402	37.795	38.189	38.583	38.976	90
100	39.370										100

cm → / ↓	0	10	20	30	40	50	60	70	80	90	← cm / ↓
	in	in	in	in	in	in	in	in	in	in	
0	0.000	3.937	7.874	11.811	15.748	19.685	23.622	27.559	31.496	35.433	0
100	39.370	43.307	47.244	51.181	55.118	59.055	62.992	66.929	70.866	74.803	100
200	78.740	82.677	86.614	90.551	94.488	98.425	102.362	106.299	110.236	114.173	200
300	118.110	122.047	125.984	129.921	133.858	137.795	141.732	145.669	149.606	153.543	300
400	157.480	161.417	165.354	169.291	173.228	177.165	181.102	185.039	188.976	192.913	400
500	196.850	200.787	204.724	208.661	212.598	216.535	220.472	224.409	228.346	232.283	500
600	236.220	240.157	244.094	248.031	251.969	255.906	259.843	263.780	267.717	271.654	600
700	275.591	279.528	283.465	287.402	291.339	295.276	299.213	303.150	307.087	311.024	700
800	314.961	318.898	322.835	326.772	330.709	334.646	338.583	342.520	346.457	350.394	800
900	354.331	358.268	362.205	366.142	370.079	374.016	377.953	381.890	385.827	389.764	900
1000	393.701										1000

Use of the tables: the number to be converted, which is made up by adding the unit at the side of a line to the unit at the head of a column, is converted to the number in the position where line and column meet.
For example, 11 in = 10 in + 1 in = 279.400 mm

Inches to Millimetres   1 in = 25.4 mm

Note. This table can also be used for converting milli-inches (mils or 'thou') to micrometres ('microns')

in → ↓	0	1	2	3	4	5	6	7	8	9 ←	in ↓
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
0	0.000	25.400	50.800	76.200	101.600	127.000	152.400	177.800	203.200	228.600	0
10	254.000	279.400	304.800	330.200	355.600	381.000	406.400	431.800	457.200	482.600	10
20	508.000	533.400	558.800	584.200	609.600	635.000	660.400	685.800	711.200	736.600	20
30	762.000	787.400	812.800	838.200	863.600	889.000	914.400	939.800	965.200	990.600	30
40	1016.000	1041.400	1066.800	1092.200	1117.600	1143.000	1168.400	1193.800	1219.200	1244.600	40
50	1270.000	1295.400	1320.800	1346.200	1371.600	1397.000	1422.400	1447.800	1473.200	1498.600	50
60	1524.000	1549.400	1574.800	1600.200	1625.600	1651.000	1676.400	1701.800	1727.200	1752.600	60
70	1778.000	1803.400	1828.800	1854.200	1879.600	1905.000	1930.400	1955.800	1981.200	2006.600	70
80	2032.000	2057.400	2082.800	2108.200	2133.600	2159.000	2184.400	2209.800	2235.200	2260.600	80
90	2286.000	2311.400	2336.800	2362.200	2387.600	2413.000	2438.400	2463.800	2489.200	2514.600	90
100	2540.000										100

in → ↓	0	10	20	30	40	50	60	70	80	90 ←	in ↓
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
0	0.000	254.000	508.000	762.000	1016.000	1270.000	1524.000	1778.000	2032.000	2286.000	0
100	2540.000	2794.000	3048.000	3302.000	3556.000	3810.000	4064.000	4318.000	4572.000	4826.000	100
200	5080.000	5334.000	5588.000	5842.000	6096.000	6350.000	6604.000	6858.000	7112.000	7366.000	200
300	7620.000	7874.000	8128.000	8382.000	8636.000	8890.000	9144.000	9398.000	9652.000	9906.000	300
400	10160.000	10414.000	10668.000	10922.000	11176.000	11430.000	11684.000	11938.000	12192.000	12446.000	400
500	12700.000	12954.000	13208.000	13462.000	13716.000	13970.000	14224.000	14478.000	14732.000	14986.000	500
600	15240.000	15494.000	15748.000	16002.000	16256.000	16510.000	16764.000	17018.000	17272.000	17526.000	600
700	17780.000	18034.000	18288.000	18542.000	18796.000	19050.000	19304.000	19558.000	19812.000	20066.000	700
800	20320.000	20574.000	20828.000	21082.000	21336.000	21590.000	21844.000	22098.000	22352.000	22606.000	800
900	22860.000	23114.000	23368.000	23622.000	23876.000	24130.000	24384.000	24638.000	24892.000	25146.000	900
1000	25400.000										1000

Millimetres to Inches   1 mm = 0.039 370 in

Note. This table can also be used for converting micrometres ('microns') to milli-inches (mils or 'thou')

mm → ↓	0	1	2	3	4	5	6	7	8	9 ←	mm ↓
	in	in	in	in	in	in	in	in	in	in	
0	0.000	0.039	0.079	0.118	0.157	0.197	0.236	0.276	0.315	0.354	0
10	0.394	0.433	0.472	0.512	0.551	0.591	0.630	0.669	0.709	0.748	10
20	0.787	0.827	0.866	0.906	0.945	0.984	1.024	1.063	1.102	1.142	20
30	1.181	1.220	1.260	1.299	1.339	1.378	1.417	1.457	1.496	1.535	30
40	1.575	1.614	1.654	1.693	1.732	1.772	1.811	1.850	1.890	1.929	40
50	1.969	2.008	2.047	2.087	2.126	2.165	2.205	2.244	2.283	2.323	50
60	2.362	2.402	2.441	2.480	2.520	2.559	2.598	2.638	2.677	2.717	60
70	2.756	2.795	2.835	2.874	2.913	2.953	2.992	3.031	3.071	3.110	70
80	3.150	3.189	3.228	3.268	3.307	3.346	3.386	3.425	3.465	3.504	80
90	3.543	3.583	3.622	3.661	3.701	3.740	3.780	3.819	3.858	3.898	90
100	3.937										100

mm → ↓	0	10	20	30	40	50	60	70	80	90 ←	mm ↓
	in	in	in	in	in	in	in	in	in	in	
0	0.000	0.394	0.787	1.181	1.575	1.969	2.362	2.756	3.150	3.543	0
100	3.937	4.331	4.724	5.118	5.512	5.906	6.299	6.693	7.087	7.480	100
200	7.874	8.268	8.661	9.055	9.449	9.843	10.236	10.630	11.024	11.417	200
300	11.811	12.205	12.598	12.992	13.386	13.780	14.173	14.567	14.961	15.354	300
400	15.748	16.142	16.535	16.929	17.323	17.717	18.110	18.504	18.898	19.291	400
500	19.685	20.079	20.472	20.866	21.260	21.654	22.047	22.441	22.835	23 228	500
600	23.622	24.016	24.409	24.803	25.197	25.591	25.984	26.378	26.772	27.165	600
700	27.559	27.953	28.346	28.740	29.134	29.528	29.921	30.315	30.709	31.102	700
800	31.496	31.890	32.283	32.677	33.071	33.465	33.858	34.252	34.646	35.039	800
900	35.433	35.827	36.220	36.614	37.008	37.402	37.795	38.189	38.583	38.976	900
1000	39.370										1000

Conversions: length

Use of the table: the number of inches to be converted, which is made up by the number of inches at the head of a column and the fraction at the side of a line, is converted to the number in the position where line and column meet.
For example, 1 1/64 in = 1 in + 1/64 in = 25.797 mm

Inches and fractions of an inch to Millimetres 1 in = 25.4 mm

in → ↓	0	1	2	3	4	5	6	7	8	9	10	11	← in ↓
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
0	0.000	25.400	50.800	76.200	101.600	127.000	152.400	177.800	203.200	228.600	254.000	279.400	0
1/64	0.397	25.797	51.197	76.597	101.997	127.397	152.797	178.197	203.597	228.997	254.397	279.797	1/64
1/32	0.794	26.194	51.594	76.994	102.394	127.794	153.194	178.594	203.994	229.394	254.794	280.194	1/32
3/64	1.191	26.591	51.991	77.391	102.791	128.191	153.591	178.991	204.391	229.791	255.191	280.591	3/64
1/16	1.588	26.988	52.388	77.788	103.188	128.588	153.988	179.388	204.788	230.188	255.588	280.988	1/16
5/64	1.984	27.384	52.784	78.184	103.584	128.984	154.384	179.784	205.184	230.584	255.984	281.384	5/64
3/32	2.381	27.781	53.181	78.581	103.981	129.381	154.781	180.181	205.581	230.981	256.381	281.781	3/32
7/64	2.778	28.178	53.578	78.978	104.378	129.778	155.178	180.578	205.978	231.378	256.778	282.178	7/64
1/8	3.175	28.575	53.975	79.375	104.775	130.175	155.575	180.975	206.375	231.775	257.175	282.575	1/8
9/64	3.572	28.972	54.372	79.772	105.172	130.572	155.972	181.372	206.772	232.172	257.572	282.972	9/64
5/32	3.969	29.369	54.769	80.169	105.569	130.969	156.369	181.769	207.169	232.569	257.969	283.369	5/32
11/64	4.366	29.766	55.166	80.566	105.966	131.366	156.766	182.166	207.566	232.966	258.366	283.766	11/64
3/16	4.762	30.162	55.562	80.962	106.362	131.762	157.162	182.562	207.962	233.362	258.762	284.162	3/16
13/64	5.159	30.559	55.959	81.359	106.759	132.159	157.559	182.959	208.359	233.759	259.159	284.559	13/64
7/32	5.556	30.956	56.356	81.756	107.156	132.556	157.956	183.356	208.756	234.156	259.556	284.956	7/32
15/64	5.953	31.353	56.753	82.153	107.553	132.953	158.353	183.753	209.153	234.553	259.953	285.353	15/64
1/4	6.350	31.750	57.150	82.550	107.950	133.350	158.750	184.150	209.550	234.950	260.350	285.750	1/4
17/64	6.747	32.147	57.547	82.947	108.347	133.747	159.147	184.547	209.947	235.347	260.747	286.147	17/64
9/32	7.144	32.544	57.944	83.344	108.744	134.144	159.544	184.944	210.344	235.744	261.144	286.544	9/32
19/64	7.541	32.941	58.341	83.741	109.141	134.541	159.941	185.341	210.741	236.141	261.541	286.941	19/64
5/16	7.938	33.338	58.738	84.138	109.538	134.938	160.338	185.738	211.138	236.538	261.938	287.338	5/16
21/64	8.334	33.734	59.134	84.534	109.934	135.334	160.734	186.134	211.534	236.934	262.334	287.734	21/64
11/32	8.731	34.131	59.531	84.931	110.331	135.731	161.131	186.531	211.931	237.331	262.731	288.131	11/32
23/64	9.128	34.528	59.928	85.328	110.728	136.128	161.528	186.928	212.328	237.728	263.128	288.528	23/64
3/8	9.525	34.925	60.325	85.725	111.125	136.525	161.925	187.325	212.725	238.125	263.525	288.925	3/8
25/64	9.922	35.322	60.722	86.122	111.522	136.922	162.322	187.722	213.122	238.522	263.922	289.322	25/64
13/32	10.319	35.719	61.119	86.519	111.919	137.319	162.719	188.119	213.519	238.919	264.319	289.719	13/32
27/64	10.716	36.116	61.516	86.916	112.316	137.716	163.116	188.516	213.916	239.316	264.716	290.116	27/64
7/16	11.112	36.512	61.912	87.312	112.712	138.112	163.512	188.912	214.312	239.712	265.112	290.512	7/16
29/64	11.509	36.909	62.309	87.709	113.109	138.509	163.909	189.309	214.709	240.109	265.509	290.909	29/64
15/32	11.906	37.306	62.706	88.106	113.506	138.906	164.306	189.706	215.106	240.506	265.906	291.306	15/32
31/64	12.303	37.703	63.103	88.503	113.903	139.303	164.703	190.103	215.503	240.903	266.303	291.703	31/64
1/2	12.700	38.100	63.500	88.900	114.300	139.700	165.100	190.500	215.900	241.300	266.700	292.100	1/2
33/64	13.097	38.497	63.897	89.297	114.697	140.097	165.497	190.897	216.297	241.697	267.097	292.497	33/64
17/32	13.494	38.894	64.294	89.694	115.094	140.494	165.894	191.294	216.694	242.094	267.494	292.894	17/32
35/64	13.891	39.291	64.691	90.091	115.491	140.891	166.291	191.691	217.091	242.491	267.891	293.291	35/64
9/16	14.288	39.688	65.088	90.488	115.888	141.288	166.688	192.088	217.488	242.888	268.288	293.688	9/16
37/64	14.684	40.084	65.484	90.884	116.284	141.684	167.084	192.484	217.884	243.284	268.684	294.084	37/64
19/32	15.081	40.481	65.881	91.281	116.681	142.081	167.481	192.881	218.281	243.681	269.081	294.481	19/32
39/64	15.478	40.878	66.278	91.678	117.078	142.478	167.878	193.278	218.678	244.078	269.478	294.878	39/64
5/8	15.875	41.275	66.675	92.075	117.475	142.875	168.275	193.675	219.075	244.475	269.875	295.275	5/8
41/64	16.272	41.672	67.072	92.472	117.872	143.272	168.672	194.072	219.472	244.872	270.272	295.672	41/64
21/32	16.669	42.069	67.469	92.869	118.269	143.669	169.069	194.469	219.869	245.269	270.669	296.069	21/32
43/64	17.066	42.466	67.866	93.266	118.666	144.066	169.466	194.866	220.266	245.666	271.066	296.466	43/64
11/16	17.462	42.862	68.262	93.662	119.062	144.462	169.862	195.262	220.662	246.062	271.462	296.862	11/16
45/64	17.859	43.259	68.659	94.059	119.459	144.859	170.259	195.659	221.059	246.459	271.859	297.259	45/64
23/32	18.256	43.656	69.056	94.456	119.856	145.256	170.656	196.056	221.456	246.856	272.256	297.656	23/32
47/64	18.653	44.053	69.453	94.853	120.253	145.653	171.053	196.453	221.853	247.253	272.653	298.053	47/64
3/4	19.050	44.450	69.850	95.250	120.650	146.050	171.450	196.850	222.250	247.650	273.050	298.450	3/4
49/64	19.447	44.847	70.247	95.647	121.047	146.447	171.847	197.247	222.647	248.047	273.447	298.847	49/64
25/32	19.844	45.244	70.644	96.044	121.444	146.844	172.244	197.644	223.044	248.444	273.844	299.244	25/32
51/64	20.241	45.641	71.041	96.441	121.841	147.241	172.641	198.041	223.441	248.841	274.241	299.641	51/64
13/16	20.638	46.038	71.438	96.838	122.238	147.638	173.038	198.438	223.838	249.238	274.638	300.038	13/16
53/64	21.034	46.434	71.834	97.234	122.634	148.034	173.434	198.834	224.234	249.634	275.034	300.434	53/64
27/32	21.431	46.831	72.231	97.631	123.031	148.431	173.831	199.231	224.631	250.031	275.431	300.831	27/32
55/64	21.828	47.228	72.628	98.028	123.428	148.828	174.228	199.628	225.028	250.428	275.828	301.228	55/64
7/8	22.225	47.625	73.025	98.425	123.825	149.225	174.625	200.025	225.425	250.825	276.225	301.625	7/8
57/64	22.622	48.022	73.422	98.822	124.222	149.622	175.022	200.422	225.822	251.222	276.622	302.022	57/64
29/32	23.019	48.419	73.819	99.219	124.619	150.019	175.419	200.819	226.219	251.619	277.019	302.419	29/32
59/64	23.416	48.816	74.216	99.616	125.016	150.416	175.816	201.216	226.616	252.016	277.416	302 816	59/64
15/16	23.812	49.212	74.612	100.012	125.412	150.812	176.212	201.612	227.012	252.412	277.812	303.212	15/16
61/64	24.209	49.609	75.009	100.409	125.809	151.209	176.609	202.009	227.409	252.809	278.209	303.609	61/64
31/32	24.606	50.006	75.406	100.806	126.206	151.606	177.006	202.406	227.806	253.206	278.606	304.006	31/32
63/64	25.003	50.403	75.803	101.203	126.603	152.003	177.403	202.803	228.203	253.603	279.003	304.403	63/64

Fractions to Decimals

Fraction	Decimal equivalent	Fraction	Decimal equivalent
1/2	0.5	1/32	0.031 25
1/3	0.333 333	1/33	0.030 303
1/4	0.25	1/34	0.029 412
1/5	0.2	1/35	0.028 571
1/6	0.166 667	1/36	0.027 778
1/7	0.142 857	1/37	0.027 027
1/8	0.125	1/38	0.026 316
1/9	0.111 111	1/39	0.025 641
1/10	0.1	1/40	0.025
1/11	0.090 909	1/41	0.024 390
1/12	0.083 333	1/42	0.023 810
1/13	0.076 923	1/43	0.023 256
1/14	0.071 429	1/44	0.022 727
1/15	0.066 667	1/45	0.022 222
1/16	0.062 5	1/46	0.021 739
1/17	0.058 824	1/47	0.021 277
1/18	0.055 556	1/48	0.020 833
1/19	0.052 632	1/49	0.020 408
1/20	0.05	1/50	0.02
1/21	0.047 619	1/51	0.019 608
1/22	0.045 455	1/52	0.019 231
1/23	0.043 478	1/53	0.018 868
1/24	0.041 667	1/54	0.018 519
1/25	0.04	1/55	0.018 182
1/26	0.038 462	1/56	0.017 857
1/27	0.037 037	1/57	0.017 544
1/28	0.035 714	1/58	0.017 241
1/29	0.034 483	1/59	0.016 949
1/30	0.033 333	1/60	0.016 667
1/31	0.032 258		

Note. For the decimal equivalent of other fractions with 1 as numerator, and a number from 0.01 to 100.9 as denominator, see reciprocals, pages 144–147.

Fractions 3rds	6ths	12ths	24ths	Decimal equivalent
			1	0.041 667
		1	2	0.083 333
			3	0.125
	1	2	4	0.166 667
			5	0.208 333
		3	6	0.25
			7	0.291 667
1	2	4	8	0.333 333
			9	0.375
		5	10	0.416 667
			11	0.458 333
	3	6	12	0.5
			13	0.541 667
		7	14	0.583 333
			15	0.625
2	4	8	16	0.666 667
			17	0.708 333
		9	18	0.75
			19	0.791 667
	5	10	20	0.833 333
			21	0.875
		11	22	0.916 667
			23	0.958 333
3	6	12	24	1

Fractions 1/2's	1/4's	8ths	16ths	32nds	64ths	Decimal equivalent (all figures are exact)
					1	0.015 625
				1	2	0.031 25
					3	0.046 875
			1	2	4	0.062 5
					5	0.078 125
				3	6	0.093 75
					7	0.109 375
		1	2	4	8	0.125
					9	0.140 625
				5	10	0.156 25
					11	0.171 875
			3	6	12	0.187 5
					13	0.203 125
				7	14	0.218 75
					15	0.234 375
	1	2	4	8	16	0.25
					17	0.265 625
				9	18	0.281 25
					19	0.296 875
			5	10	20	0.312 5
					21	0.328 125
				11	22	0.343 75
					23	0.359 375
		3	6	12	24	0.375
					25	0.390 625
				13	26	0.406 25
					27	0.421 875
			7	14	28	0.437 5
					29	0.453 125
				15	30	0.468 75
					31	0.484 375
1	2	4	8	16	32	0.5
					33	0.515 625
				17	34	0.531 25
					35	0.546 875
			9	18	36	0.562 5
					37	0.578 125
				19	38	0.593 75
					39	0.609 375
		5	10	20	40	0.625
					41	0.640 625
				21	42	0.656 25
					43	0.671 875
			11	22	44	0.687 5
					45	0.703 125
				23	46	0.718 75
					47	0.734 375
	3	6	12	24	48	0.75
					49	0.765 625
				25	50	0.781 25
					51	0.796 875
			13	26	52	0.812 5
					53	0.828 125
				27	54	0.843 75
					55	0.859 375
		7	14	28	56	0.875
					57	0.890 625
				29	58	0.906 25
					59	0.921 875
			15	30	60	0.937 5
					61	0.953 125
				31	62	0.968 75
					63	0.984 375
2	4	8	16	32	64	1

CONVERSION TABLE
Feet to Inches

	2 Ft.	3 Ft.	4 Ft.	5 Ft.	6 Ft.
0″	24″	36″	48″	60″	72″
1″	25	37	49	61	
2″	26	38	50	62	
3″	27	39	51	63	
4″	28	40	52	64	
5″	29	41	53	65	
6″	30	42	54	66	
7″	31	43	55	67	
8″	32	44	56	68	
9″	33	45	57	69	
10″	34	46	58	70	
11″	35	47	59	71	

TABLE — DECIMALS OF A FOOT

For Each Sixteenth of An Inch

	0	1	2	3	4	5	6	7	8	9	10	11
0		.0833	.1667	.250	.3333	.4167	.5000	.5833	.6667	.7500	.8333	.9167
$\frac{1}{16}$	.0052	.0885	.1719	.2552	.3385	.4219	.5052	.5885	.6719	.7552	.8385	.9219
$\frac{1}{8}$	.0104	.0937	.1771	.2604	.3437	.4271	.5104	.5937	.6771	.7604	.8437	.9271
$\frac{3}{16}$	.0156	.0990	.1823	.2656	.3490	.4323	.5156	.5990	.6823	.7656	.8490	.9323
$\frac{1}{4}$	.0208	.1042	.1875	.2708	.3542	.4375	.5208	.6042	.6875	.7708	.8542	.9375
$\frac{5}{16}$	.0260	.1094	.1927	.2760	.3594	.4427	.5260	.6094	.6927	.7760	.8594	.9427
$\frac{3}{8}$	.0312	.1146	.1979	.2812	.3646	.4479	.5339	.6172	.7005	.7839	.8672	.9505
$\frac{7}{16}$	.0365	.1198	.2031	.2865	.3698	.4531	.5365	.6198	.7031	.7865	.8698	.9531
$\frac{1}{2}$	.0417	.1250	.2083	.2917	.3750	.4583	.5417	.6250	.7083	.7917	.8750	.9583
$\frac{9}{16}$	.0469	.1302	.2135	.2969	.3802	.4635	.5469	.6302	.7135	.7969	.8802	.9635
$\frac{5}{8}$	.0521	.1354	.2188	.3021	.3854	.4688	.5521	.6354	.7188	.8021	.8854	.9688
$\frac{11}{16}$	.0573	.1406	.2240	.3073	.3906	.4740	.5573	.6406	.7240	.8073	.8906	.9740
$\frac{3}{4}$	.0625	.1458	.2292	.3125	.3958	.4792	.5625	.6458	.7292	.8125	.8958	.9792
$\frac{13}{16}$	.0677	.1510	.2344	.3177	.4010	.4844	.5677	.6510	.7344	.8177	.9010	.9844
$\frac{7}{8}$	.0729	.1562	.2396	.3229	.4062	.4896	.5729	.6562	.7396	.8229	.9062	.9896
$\frac{15}{16}$	.0781	.1615	.2448	.3281	.4115	.4948	.5781	.6615	.7448	.8281	.9115	.9949

MEASURING NUTS AND BOLTS

Nuts and bolts come in a great variety of sizes. The size of the head of a bolt or nut is measured between the flat sides of the hexagon. In standard American nuts and bolts these sizes usually follow one another in 1/16" steps. Thus you have 1/2" (8/16") bolts and 9/16" bolts and 5/8" (10/16") bolts, but you don't find 2/3" bolts. Foreign cars use metric-sized nuts and bolts which are measured in the same way from flat side to flat side, but in millimeters instead of sixteenths of an inch. Some English cars use yet another way of measuring head sizes known as the "Whitworth system." Instead of measuring from flat to flat of the hexagon, Whitworth sizes measure from point to point. Fortunately most British manufacturers have switched over to metric sizes or standard American sizes.

Unfortunately, head size isn't all there is to measuring nuts and bolts. Bolts are also measured by diameter—that is, through the threads. Thus you could have a bolt with a 1/2" head and a diameter of 1/4" or one with a 1/2" head and a 3/16" diameter. Nuts are measured for diameter across the widest opening the threads make.

As if this weren't enough, nuts and bolts (and studs and screws as well) are also measured according to how coarse or fine their threads are. This measurement is made in "threads per inch." A bolt with 16 threads per inch is rather coarsely threaded. Twenty threads per inch is a fine thread.

Once in a while you will run into a nut or a bolt which has **left-hand thread**. This means it screws in counterclockwise and screws out clockwise. Often left-hand thread nuts and bolts have a little "L" marked on them. Sometimes they don't—then you just have to try turning the "wrong" way and see what happens.

WRENCH SIZES

The size of a wrench refers to the size of the nut or bolt it fits (see Appendix, p. 92, on measuring sizes of nuts and bolts). Most sets of American wrenches start at 3/8" and go up in steps of 1/16". The largest wrench in a set might be anywhere from 3/4" to 1-5/16". (What we call "American" wrenches are also known as SAE [Society of Automotive Engineers] wrenches.) Wrenches smaller than 3/8" are called "miniatures" or "ignition" wrenches. There are also metric wrenches, which you will need if you want to work on foreign cars.

Americans spend a good deal of time in school learning a chaotic system of weights and measures and forget most of it rapidly. Most of us remember that there are 12 inches in a foot and 3 feet in a yard and even that there are 5,280 feet in a mile. Hardly anyone knows how big an acre is or how many pints there are in a gallon or . . .

Most of our units of weight and measure had different origins at different times. An inch was three barleycorns laid end to end. A foot was the length of Charlemagne's foot (he had big feet). A yard was the distance from the tip of Henry I's nose to the tip of his outstretched arm. Roman legions used to count off paces as they marched—a thousand paces (*mille passuum*) was roughly 5,000 feet and the English changed the name to "mile."

As you can see, our system of measure has its roots in Roman imperialism, feudal class structure and an agricultural economy. Not very relevant to a technological industrial society.

Most countries had different and equally illogical systems of measure until the French Revolution came along. The French revolutionaries decided they needed a more orderly and convenient system and chose the meter (3.28 feet) as the standard unit of measure ("meter" comes from the Greek word for measure). They then derived all other units of measure from the meter in multiples of 10 or 1/10. A centimeter is 1/100 of a meter and a millimeter is 1/1000 of a meter. A kilometer is 1000 meters. A liter is 1000 cubic centimeters and a kilo ("key" for short) is the weight of a liter of water. Neat and easy.

Over the years other countries adopted the metric system or had it forced upon them by imperialist colonizers from one European state or another, until only the English-speaking countries were holding out. Now Great Britain and the Commonwealth are in the middle of a ten-year switchover, leaving the U.S. as the lone non-metric nation in the world. In every other country school children can learn their system of measure in a month. In the U.S. we spend years getting a partial grip on our system of measure.

What all this means to you as an auto mechanic is that you may need two sets of wrenches—one for American-built cars and another for foreign makes. Most English cars are using metric nuts and bolts by now (although a few still use the Whitworth system—see Appendix, p. 92).

Metric wrench sets start with 6 or 7 mm. (millimeters) and go up to 19 mm. in 1 mm. intervals. Sixteen and 18 mm. wrenches are not usually included in metric sets. Fortunately, 16 and 18 mm. nuts and bolts are not usually included on cars.

If you are going to do a lot of work on foreign cars you have to get yourself a set of metric combination wrenches and sockets. If it's just a question of tightening one nut on a Volkswagen, you may find that you can fake it with your American wrenches. Several sizes in the American and metric systems are close enough to be almost interchangeable. Unfortunately most of these switches work in one direction only: you can use a wrench which is slightly too big on a bolt, but you can't use one which is a little too small. The table shows you which fakes you can get away with. Try not to use it just because you're too lazy to fetch the right wrench out of your tool box!

MICKEY MOUSE'S METRIC CONVERSION CHART

	WRENCH SIZE	FITS	BOLT SIZE
American to metric	3/8		9 mm
	7/16		11 mm
	9/16		14 mm
	11/16		17 mm
	3/4		19 mm
Metric to American	10 mm		3/8
	11 mm		7/16*
	13 mm		1/2
	17 mm		5/8
	19 mm		3/4*
	21 mm		13/16

* *sometimes*