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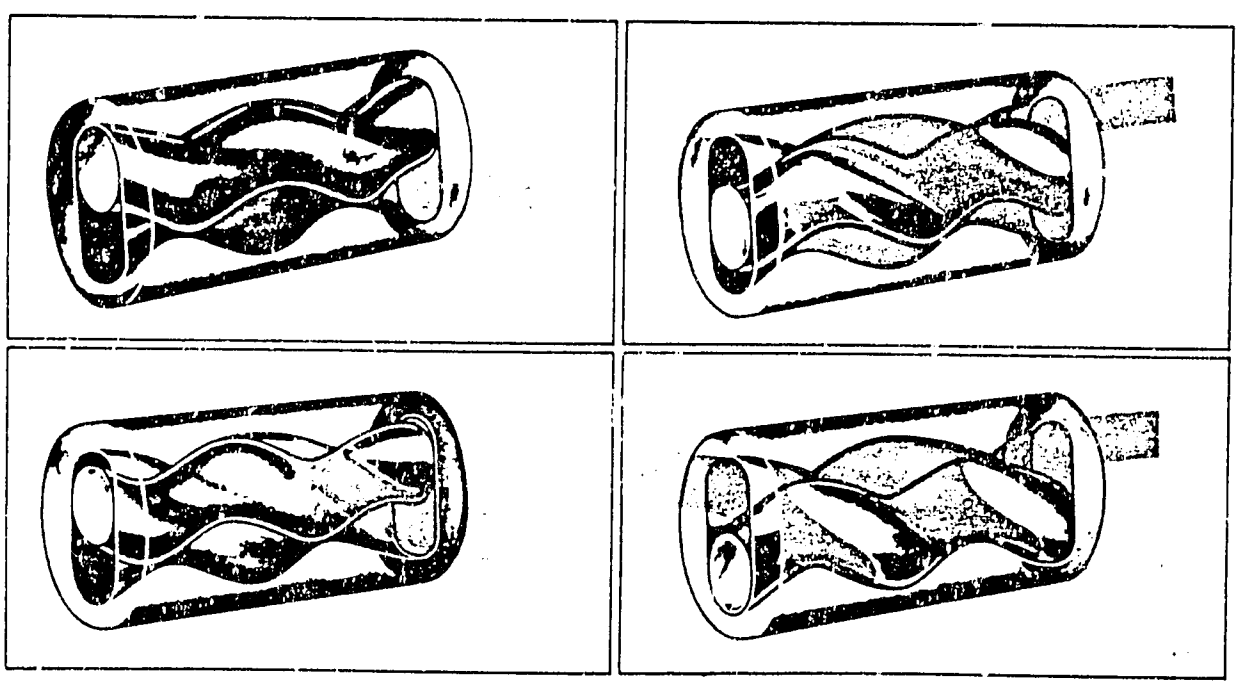
# TEST REPORT OF THE WTGS WINDMILL IN BOTSWANA



TOOL Technical Development Developing Countries

By W. NIJHOFF
May 1986

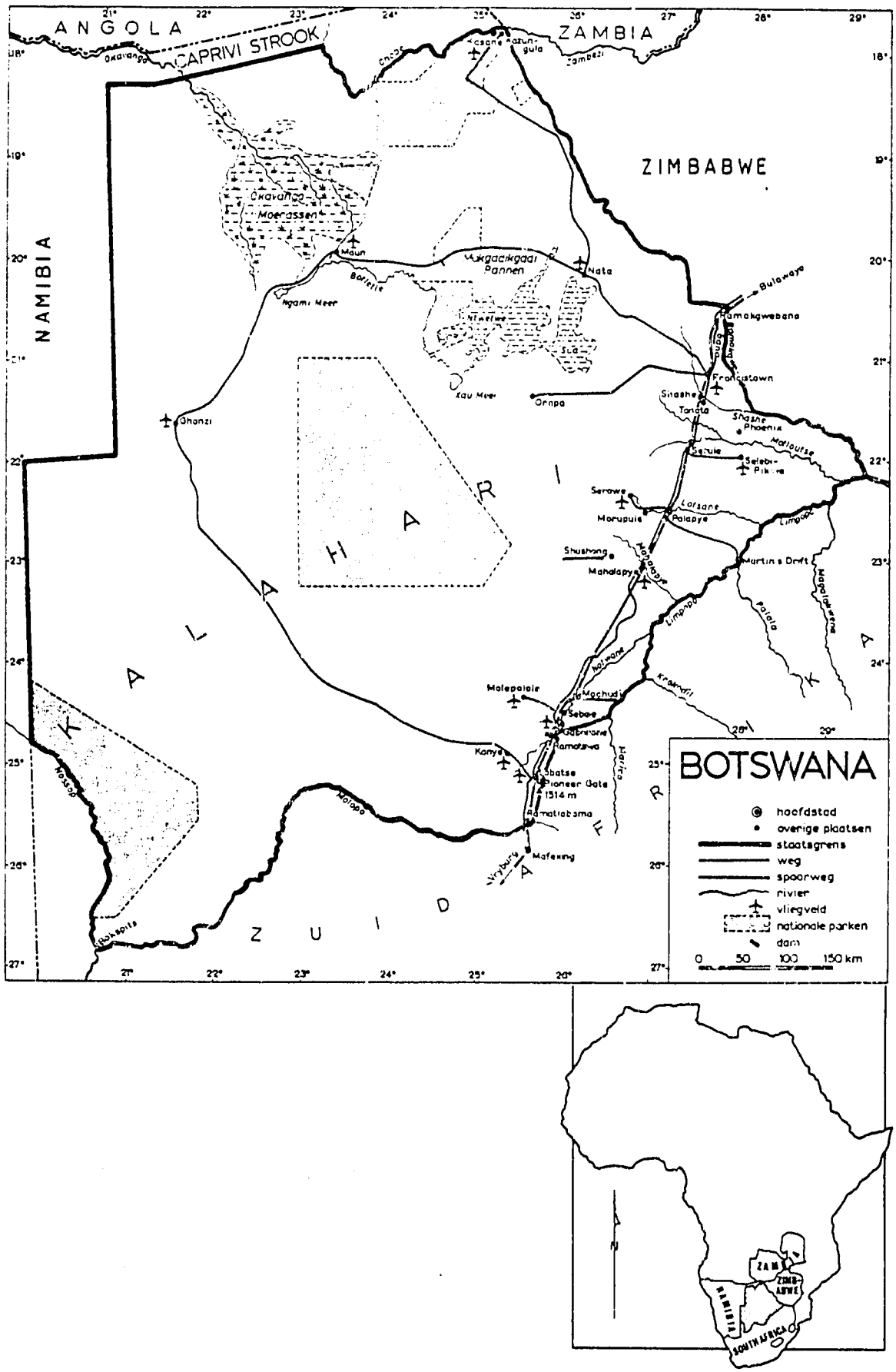



Figure 1 : Map of Botswana.

CONTENTS


| | | page |
|---|---|---|
| 1. | INTRODUCTION | 1 |
| | 1.1 Background of the report | 1 |
| | 1.2 Background of the WTGS | 1 |
| | 1.3 Momoso Engineering Works | 1 |
| | 1.4 Building the windmills | 2 |
| | 1.5 Description of the WTGS windmill | 2 |
| 2. | WIND SPEEDS | 6 |
| | 2.1 Wind speeds in Botswana | 6 |
| | 2.2 Wind speeds at the windmill sites | 6 |
| 3. | CORRECTION FOR ANEMOMETERS | 8 |
| | 3.1 Comparing the various anemometers | 8 |
| | 3.2 Discussion of deviation of anemometers | 12 |
| 4. | TESTING THE WINDMILL | 15 |
| | 4.1 General | 15 |
| | 4.2 The WTGS windmill in Mochudi | 15 |
| | 4.3 Measuring procedure | 15 |
| | 4.4 Processing the raw data | 17 |
| | 4.5 Test results | 17 |
| 5. | MONTHLY PUMPING OUTPUT | 22 |
| | 5.1 Monthly pumping output | 22 |
| | 5.2 Scope for the WTGS windmill | 26 |
| 6. | DISCUSSION OF THE TESTING RESULTS | 27 |
| | 6.1 WTGS windmill in Mochudi | 27 |
| | 6.2 Characteristics of the windmill | 27 |
| | 6.3 Blade design | 31 |
| | 6.4 Transmission ratio | 32 |
| | 6.5 Mono pump | 33 |
| 7. | COSTPRICE WINDMILL | 36 |
| | 7.1 Costprice WTGS windmill | 36 |
| | 7.2 Costprice RIIC windmill | 37 |
| | 7.3 Comparing investment costs of RIIC and WTGS windmill | 37 |
| | 7.4 Costprice reduction of the WTGS windmill | 38 |
| 8. | TESTING RESULTS OF THE CENTRIFUGAL CLUTCH | 39 |
| | 8.1 Introduction | 39 |
| | 8.2 Test procedure | 39 |
| | 8.3 Measuring results | 40 |
| | 8.4 Theoretical model of the clutch | 41 |
| 9. | CONCLUSIONS AND RECOMMENDATIONS | 48 |
| | 9.1 conclusions | 48 |
| | 9.2 recommendations | 49 |
| Appendices | | 50 |

LIST OF APPENDICES


| | | page |
|---|---|---|
| Appendix 1 | - Job description | 50 |
| 2 | - Histograms of wind speed distribution at eight stations in Botswana<br>- Wind speed distribution at the WTGS windmill site in Mochudi | 51 |
| 3 | - Weekly average wind speeds at the RIIC and WTGS windmill site in Mochudi<br>- Calibration curve of TOOL anemometer assessed by the University of Technology in Eindhoven, August 1984<br>- Simultaneously measured wind speeds at three windmill sites<br>- Calibration certificate of the TOOL anemometer assessed by the KNMI in De Bilt, May 1985 | 53 |
| 4 | - Typical flow accuracy of water meter<br>- Typical pressure drop of water meter<br>- Measured data of the WTGS windmill in Shoshong<br>- Measured data of the RIIC windmill in Mochudi | 56 |
| 5 | - Frequency distribution of wind speeds synthesized with normalized windmill output Table 1 to 6 | 59 |
| 6 | - Correction for air density<br>- Typical pump characteristics of Mono pump | 62 |
| 7 | - Material prices<br>- Details on construction and installation costs of the WTGS windmill | 64 |
| 8 | - Measuring data on the centrifugal clutch | 69 |

## LIST OF ABBREVATIONS

| | |
|---|---|
| BEDU | Botswana Enterprises Development Unit |
| BRET | Botswana Renewable Energy Technology program |
| BTC | Botswana Technology Centre |
| CWD | Consultancy services Windenergy Developing countries |
| DWA | Department of Water Affairs |
| ITDG | Intermediate Technology Development Group |
| KAP | Kleine Ambasade Projecten (Small Dutch embassy projects) |
| KNMI | Royal Netherlands Meteorological Institute |
| MEW | Momoso Engineering Works |
| RIIC | Rural Industries Innovation Centre |
| TOOL | Technical Development with Developing Countries |
| WMO | World Meteorological Organisation |
| WTGS | Windmill Technology Group Serowe |

# 1 INTRODUCTION

## 1.1 Background of the report

This test report is the result of a request of the Windmill Technology Group Serowe (WTGS), Botswana to the TOOL foundation in the Netherlands, to send a windmill expert to test their recently installed prototype windmills.
The mission was financed by the Wild Geese foundation in the Netherlands and was carried out from February 8th upto May 1st 1985. For a detailed Job description see Appendix 1.
The test results, findings, conclusions and recommendations are presented in this report.

The author wishes to express his gratitude to the WTGS group, Momoso, BRET and RIIC for their kind cooperation.
Special thanks are due to Gerrit Jacobs and Jonathan Hodgkin, whose contributions enabled him to carry out his assignment succesfully.

## 1.2 Background of the WTGS

In 1979 a member of the later formed WTGS-group found pieces of raw material intended for the construction of a windmill at the Serowe Farmers Brigade. Originally the windmill would be built by the Sereowe brigade trust, but due to financial problems of the brigades, the project was cancelled. Some of the items originated from RIIC in Kanye and the proposed windmill was part of a six country ITDG collaboration programme. RIIC was the second Botswana collaborator. After several meetings with RIIC it was decided to built the windmill in Serowe. However, rather soon, it was discovered that the design which incorporated a reciprocal transmission and pump was not found appropriate for Botswana conditions.
According to the WTGS-group, prevailing conditions in Botswana, required the design of a rotary transmission coupled to a mono pump, capable of servicing boreholes up to 100 metres. Therefore the WTGS-group was founded, and it was decided that the group should design, build and test their own windmill.

The group consisted that time of seven members of which four were expatriates and three Batswana. All expatriate members of the group were volunteers, who had full time jobs, beside being a member of the WTGS-group. The three Batswana members are the members of Momoso Engineering Works. Momoso started with the assistance of the WTGS-group, financial help from a KAP-project, Botswana Financial Assistance Policy and the Technical School from Meppel, the Netherlands.

At the time of the mission the WTGS-group was diminished to two expatriate members and three Batswana members (from Momoso).

## 1.3 Momoso Engineering Works

Momoso is now a commercial firm, which has specialized in metal work. Some activities are the production of donkey carts, burglar bars, agricultural tools, sheet bending machines, sheet rolling machines, metal shears, erection of ferro-cement tanks, repair of windmills, etc. Besides they have

built the second and third WTGS windmill, modified the first WTGS windmill, installed the second windmill and reinstalled the first windmill. The installation of the third windmill is still due.

## 1.4 Building the windmills

Simultaneously two prototypes of the WTGS windmill have been built. The first prototype (I) was built in Serowe at the Swaneng Hill School by a metalwork teacher (member of the WTGS-group) and his students. This windmill was completed in May 1983. Prototype II was built in Kanye by Momoso with help of two other members of the WTGS-group.
WTGS justifies the simultaneous development/construction of two prototype windmills at different places, that out of the five expatriate members four were about to leave the country as their contracts expired. So priority was given to the transfer of technology/skill to Momoso by building the second windmill before the first one was even tested and proven its capabilities.

Prototype I was installed at Serowe and some input/output measurements were performed (July 1983). Due to several technical problems with the windmill, like loosing a blade, development of cracks in the rotor ring and tail support of the windmill, it was thought to be irresponsible to keep the windmill at that particular site (at the premises of the Swaneng Hill School). Hence the windmill was dismantled.
Because of the closure of the metal work facilities at the Swaneng Hill School, the windmill was transported to Kanye for repair and modifications by Momoso.
This windmill was reinstalled in Shoshong by Momoso in February 1985.

Prototype II was installed at Mochudi in December 1984.

Prototype I is still owned by WTGS, whereas prototype II and III are sold to BRET.

## 1.5 Description of the WTGS windmill.

In this section the second prototype will be described. The third prototype is identical to the second.

### General

The WTGS windmill is a horizontal axis windmill with a 6.2 m diameter rotor on a 9 m high tower. See Photo 1. The rotary transmission drives, via a centrifugal clutch device, a commonly used mono pump to lift water from a borehole. The furling mechanisme of the windmill is based on a inclined tail hinge in combination with a excentrally placed rotor.
All parts of the windmill are discussed more in detail below.

### Rotor

The rotor of the windmill, located up-wind, consists of 8 curved steel sheet blades. The blades are welded with blade supports to the steel tube spokes which are bolted to the disc hub. At the blade root the spokes are inter connected by an angle iron frame which is clamped to the spokes. This framework is supported by steel tubes to a central disc on the extented rotor shaft.

## Blades

The blades are made of 0.7 mm steelsheet and curved with a curveture of 10 %. The blades are 2.2 m long and linearized in chord and blade setting angle. The chord at the root of the blade is 0.60 m and at the tip 0.35 m. The design blade settings are 25° at the bladeroot and 8° at the bladetip. The original parameters of the rotor were based on a tipspeed ratio of 2.5. Because the blades were calculated for a curvature of 7 % which changed for construction reasons into 10 %, the present values for bladechord and setting angles are not optimal. The influence on the rotor efficiency and torque coefficient of this mismatch is calculated in chapter 6.

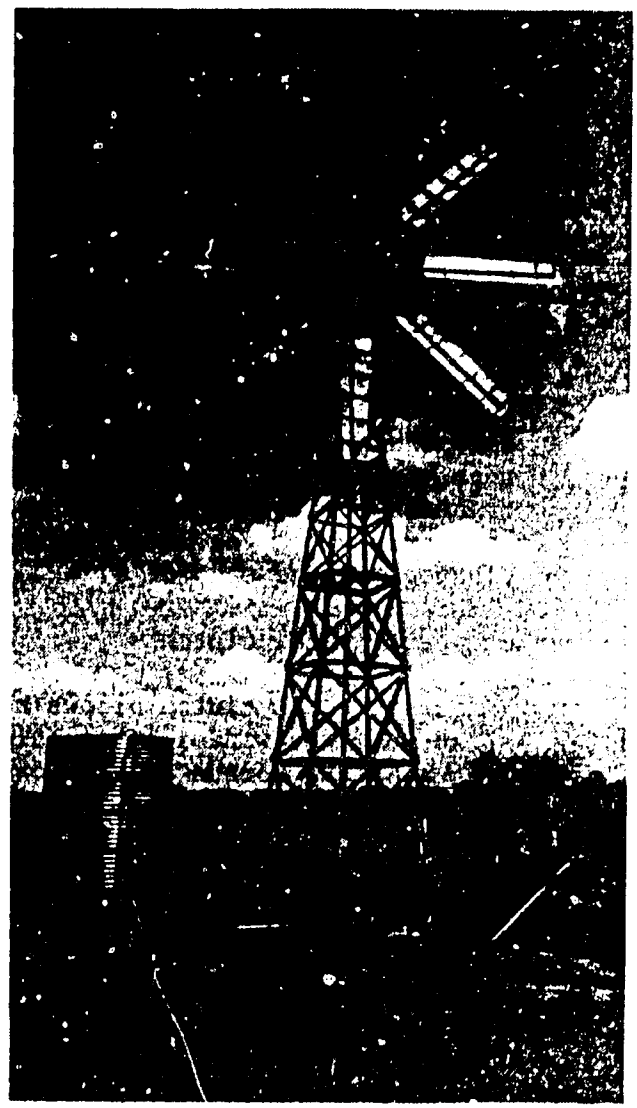


Photo 1 - WTGS windmill in Mochudi (Prototype II)

## Chassis and rotor shaft

The chassis is constructed out of 5 mm steel plate, welded together and is bolted directly to the tower turntable. The chassis supports the rotor shaft, gearbox and rotor assembly.
The rotor shaft is supported by a 65 mm self aligning flange bearing at the chassis front plate and fixed to the bevel gearbox shaft by a rigid coupling with taperlocks and keys. The rotor shaft is excentrially placed on the turntable with an off-set of 5 mm.

## Tail assembly

The tail is a welded steel tube (gas pipe) structure with a sheet metal vane, reinforced with square tubing. The tail is bolted to an inclined pivoting rod which is supported by two self aligning bearing blocks. The bearing blocks are bolted to the chassis frame. A dampening mechanisme has been incorporated in the inclined tail design. At both extreme ends of the tail travel, a stop has been incorporated. The tail travels through an angle of 85°. The length of the tail is 4.5 m and the tailvane area is 4 $m^2$.

## Tower

The tower is a welded, four legged angle iron steel structure, fabricated in two sections which are bolted together. At the bottom and halfway, horizontal angle iron bearing supports are located for the transmission shaft. The tower is cross braced with angle iron on all four tower sides. On the top of the tower the turntable is bolted on a circular cut plate welded to the tower. Two towerlegs are provided with hinges to facilitate

easy erection and lowering of the windmill. The two other towerlegs are provided with foundation plates which are bolted to the foundation as well as the towerleg hinges.
A work platform is located at 1.4 m from the top of the tower all around.

Transmission

The vertical downshaft is constructed from thinwall large diameter steel tube. It is connected to the output side of the gearbox via a flexible coupling, fixed with taperlocks and keys. Just above the half way tower bearing support a second flexible coupling is used. The downshaft is supported by two self aligning flange bearings. On the bottom end of the down shaft a V-belt pulley is fitted for driving the centrifugal clucth and mono pump. The step-up gear ratio of the bevel gearbox is 1:3. The transmission ratio of the V- belt drive is depending on the head (the total head over which the water has to be lifted), the type of mono pump and the windregime, see chapter 6.

The centrifugal clutch

The centrifugal clutch allows the windmill to start unloaded. At a certain speed when the windmill has gained sufficient energy to overcome the very high starting torque of the mono pump, the clutch engages automatically. The automatic clutch consists of a brake drum and two brake shoes (see Photo 2). The brake drum is connected to the pumprod. The brake shoes are mounted on a base plate and are allowed to pivot. They are held in their rest position by adjustable springs. The baseplate is fitted on a pulley of 122 mm diameter, which is turned by the windmill, using 2 B-type V-belts. A ratchet system protects the pump from turning backwards.
See for an analyses of the clutch chapter 8.

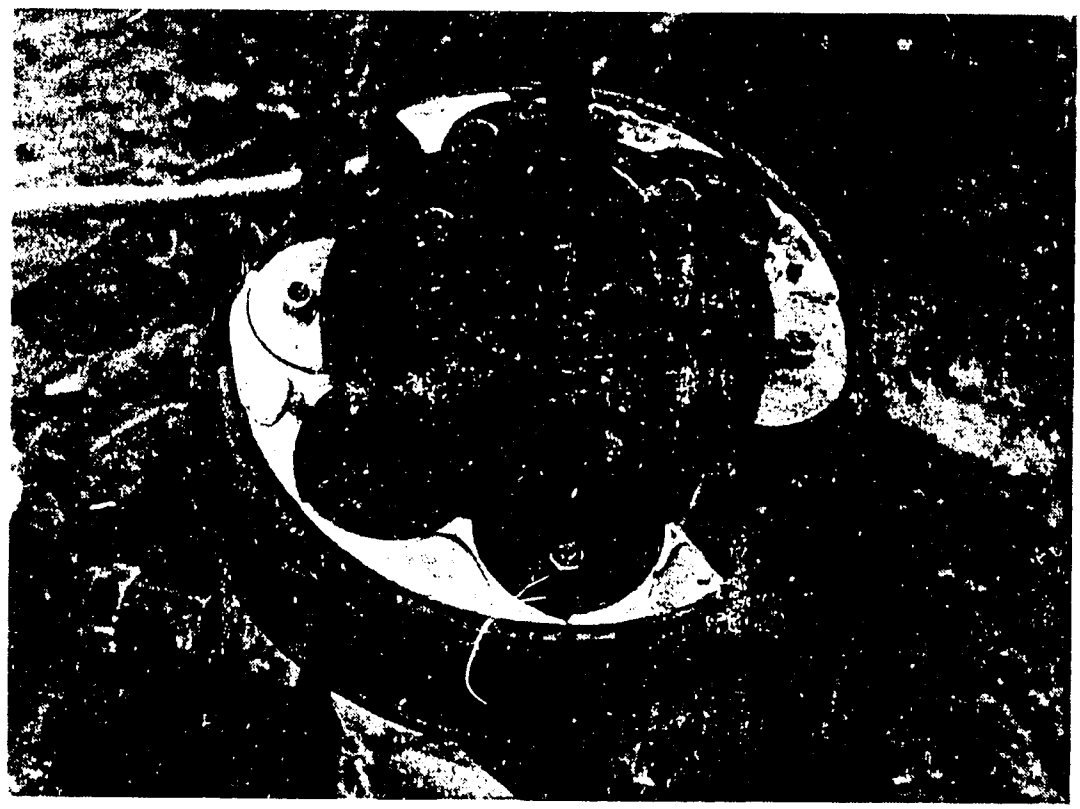


Photo 2 - Automatic centrifugal clutch with removed brake drum

The mono pump.

The mono pumping principle is based on a single moving part, a rotor, within a stator (see figure 2).
The heart of the mono pump is the single scroll metal rotor which rotates eccentrically within a double scrolled resilient stator of twice the pitch length. The rotor, of constant circular cross-section, makes an interference fit inside the stator and creates a continuously forming cavity as it rotates. The cavity progresses towards the discharge end, advancing in front of a continuously forming seal line, and carrying the pumped material with it.

The mono borehole pump can handle salinity, sand and highly corrosive water with relative ease. Units can draw water reliably from depts of 240 metres. Capacities range from a trickle for the hand-operated pumps to more than 100 m3/h for the motor driven models.

The mono pump is extensively used in Botswana and spare parts are country wide available.

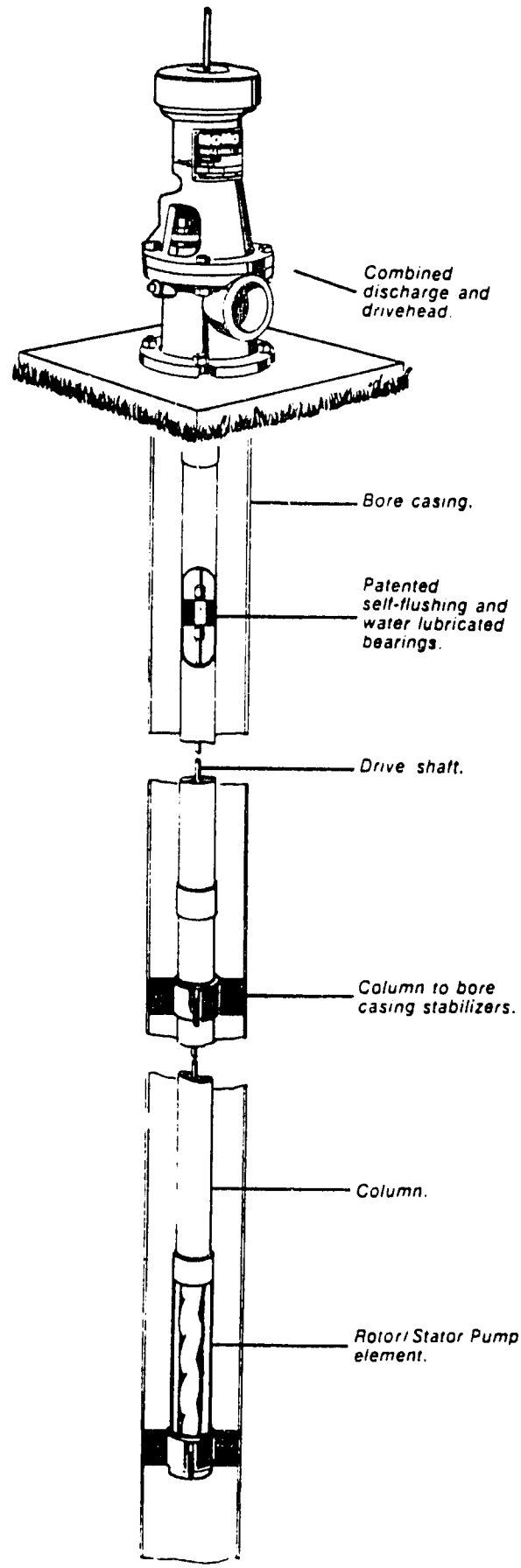



Figure 2 : Mono pump

## 2. WIND SPEEDS

In this chapter some general remarks about the wind speeds in Botswana will be made. The present ongoing wind speed measuring programme coordinated by BRET will be discussed and the wind speeds measured at the three windmill sites will be presented.

### 2.1 The wind speeds in Botswana

Till recently not much was known about the wind speeds in Botswana. Although wind speed measurements were made for a period of more than 20 years already at eight stations in Botswana, these measurements are taken at 2 m height. These wind speed averages per month are given in Figure 2.1, Appendix 2. In this figure the wind speeds at 10 m height are also displayed. These wind speeds, however, are extrapolated from those at 2 m heigth, whereby the wind speeds at 10 m height are assumed to be 60 % more than the measured wind speeds at 2 m height. This is a very "tricky" assumption; the increment is strongly depending on the surface roughness i.e. the overgrowth around the station.

For achieving an accurate wind climate survey of the whole country, for the purpose of assessing the feasibility of windmills for example, reliable estimates of the wind-potential at around 10 m height are needed and hence the need for wind data at 10 m height from a rather dense network.
Such an observation network was planned already in 1980 by BTC, DWA and Met. Services; later on also in cooperation with BRET. The stations were chosen in connection to the plans for strengthening the Met. station network as it was planned in the WMO report "Met. forecasting in Botswana" 1980. The network will ultimately consist of some 40 stations, some of which at windmill test sites included in a waterpumping comparison program.

Started late 1982 with establishing these stations at 10 m height, the last ones will be in operation in 1985.

The monitoring and analysing part of this rather dense network has already been started up by BRET and will be taken over by Met. Services later on. Ultimately all wind data will be stored at Met. Services in their computer data base.

### 2.2 Wind speeds at the windmill sites

In the framework of the waterpumping comparison program, BRET will have some 13 water pumping windmills under test.
All these windmills are or will be equiped with monitoring equipment; see for a description of this equipment chapter 4.2. The wind speeds at the windmill test sites are measured by a cupanemometer at a distance of about 3 times the rotor diameter and at the same height as the rotor centre, see Photo 3.

The wind speed data from the WTGS windmill site in Mochudi are listed in table 2.1, Appendix 2, and displayed in histograms in Figure 3. Because the readings were taken each week, normally at the same day, the histograms do not cover exacly a full month.

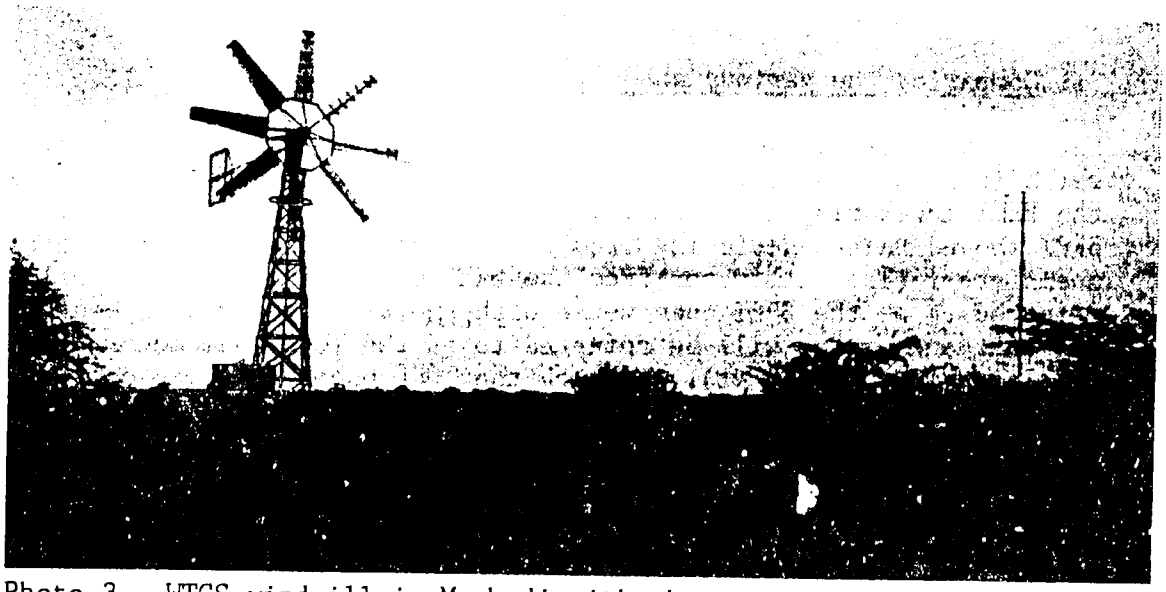


Photo 3 - WTGS windmill in Mochudi with the anemometers at a distance of about 3 times the rotor diameter.

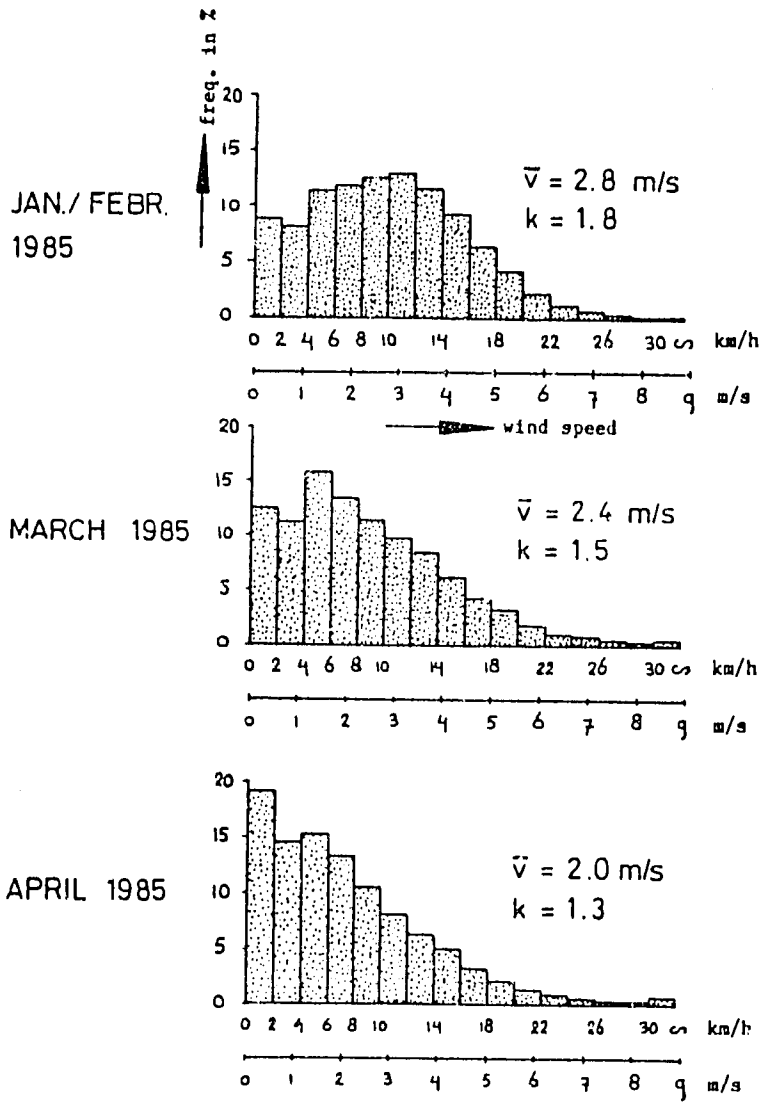



Figure 3 : Wind speed distribution at the WTGS windmill site in Mochudi with the monthly average wind speeds and the determined Weibull shape parameters (k-values).

# 3 CORRECTION FOR ANEMOMETERS

## 3.1 Comparing the various anemometers

During the first windmill measurements at the WTGS windmill in Mochudi, which is also under the testing scheme of BRET and therefore equiped with the BRET monitoring equipment, it was discovered that the anemometer from BRET showed values deviating from the values obtained from the test anemometer. (The anemometer from the BRET monitoring equipment will be referred to as the BRET anemometer with the displayed wind speeds vb and the test anemometer will be referred to as the TOOL anemometer with the displayed wind speeds vt). Although the TOOL anemometer was calibrated in August 1985 by CWD in the Netherlands (see Appendix 3, Figure 3.1 for the calibration curve), who recommended to increase all readings by 0.5 m/s, this was not found satisfactory and did also not equalize the differences in readings found.
Further research revealed that the wind speeds measured by BRET at the nearby RIIC windmill with uniform equipment deviated highly from those measured at the WTGS windmill.
The weekly average wind speeds as monitored by the BRET equipment during 7 weeks is shown in Figure 4 (The values are listed in Table 3.1, Appendix 3).

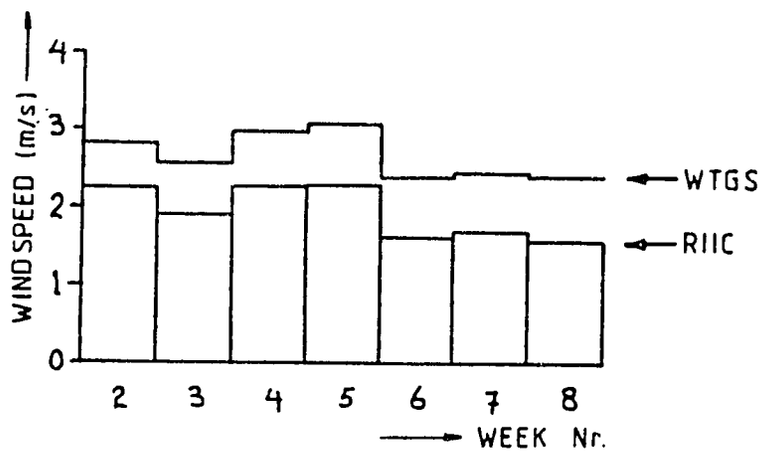



Figure 4 : Simultaneously monitored weekly average wind speeds at the WTGS and RIIC windmill sites in Mochudi

Whereas these windmills were in the same plain area at a distance of only approx. 2 km from each other without any difference in terrain roughness or vegetation, it is safe to assume that the real prevailing wind speeds should be exactly the same at both sides.
In order to find an explanation for these unacceptable high deviations it was decided to compare both anemometers with the TOOL anemometer.
Therefore the TOOL anemometer was placed on the same pole as the BRET anemometers at the same height and at a mutual distance of 0.6 m as shown in Photo 4.
At one hour intervals the windrun of both anemometers were read and converted into average wind speeds in m/s.
This procedure has been carried out for the WTGS windmill and the RIIC windmill in Mochudi and for the WTGS windmill in Shoshong. The results are presented in Figure 5. (The values are listed in Table 3.2, Appendix 3).
However, these results are of limited use as long as the calibration curve of the TOOL anemometer is not known.
Therefore, after the mission, the TOOL anemometer has been calibrated in a

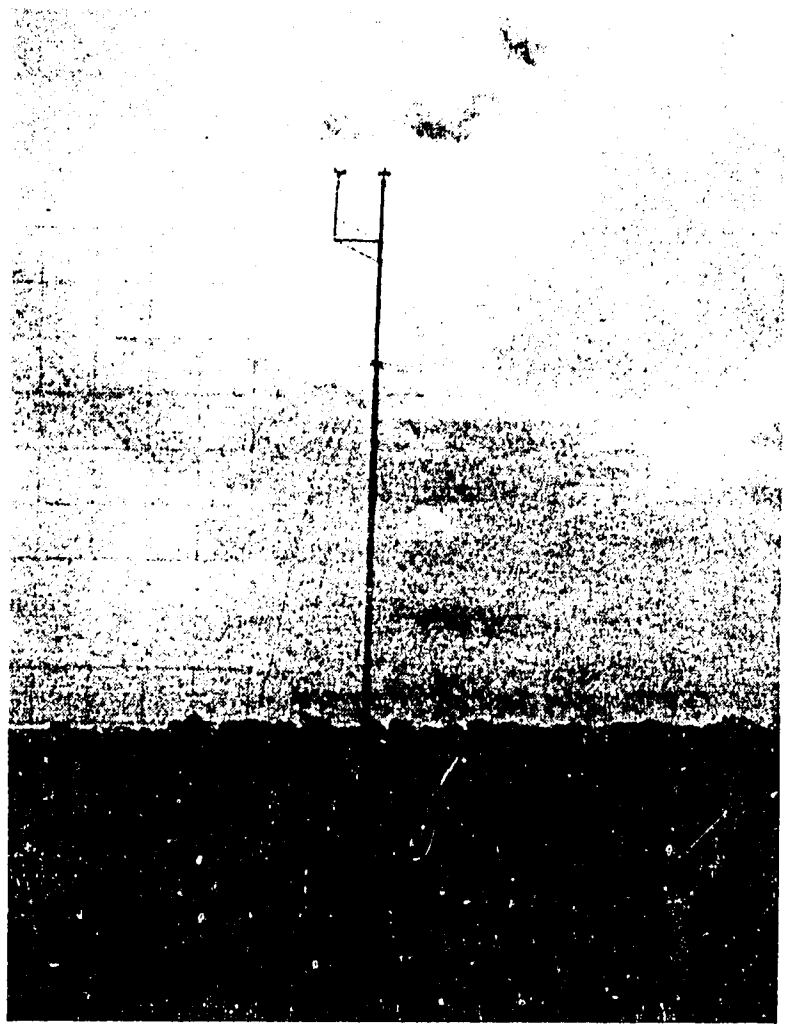


Photo 4 - Comparing the anemometers

windtunnel of the Royal Netherlands Meteorological Institute (KNMI).
The calibration curve is presented in Figure 6, with the calibration values listed in Appendix 3, Table 3.3.
From these calibration values the following correction formula has been derived with regression analyses:

$$v = 0.98 \text{ v display} + 0.3 \quad \text{m/s}$$

whereby v refers to the real wind speed and v display refers to the wind speed as displayed by the TOOL anemometer.

This correction formula has been used for the wind speeds measured by the TOOL anemometer at the three windmill sites. The justification of using this calibration instead of the CWD calibration is explained in Chapter 3.2.
The values of the simultaneously monitored wind speeds at the three sites are listed below in Table 1, whereby v represents the real wind speed (is equal to the corrected TOOL anemometer readings) and vb represents the displayed values of the BRET anemometers; both converted into m/s.
Again with regression analyses the regression lines have been computed to derive the correction formulaes to be used for the wind speeds measured by the BRET anemometers. The regression line expressions are also presented in Table 1 along with the correction formulaes. The correction formula is just a rounded off version of the regression line expressions for practical

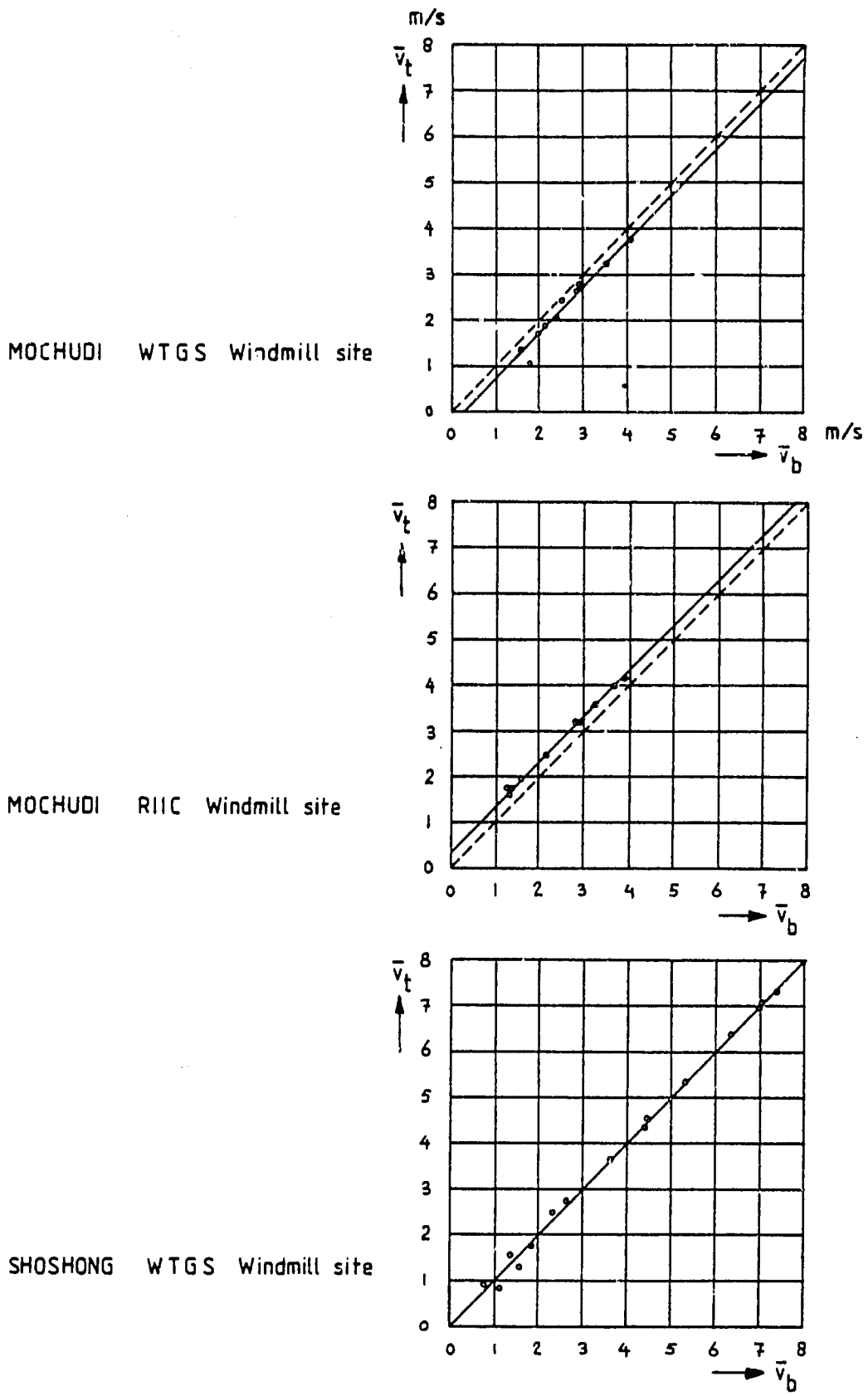



Figure 5 : Simultaneously measured wind speeds with the BRET and the TOOL anemometer at the three windmill sites

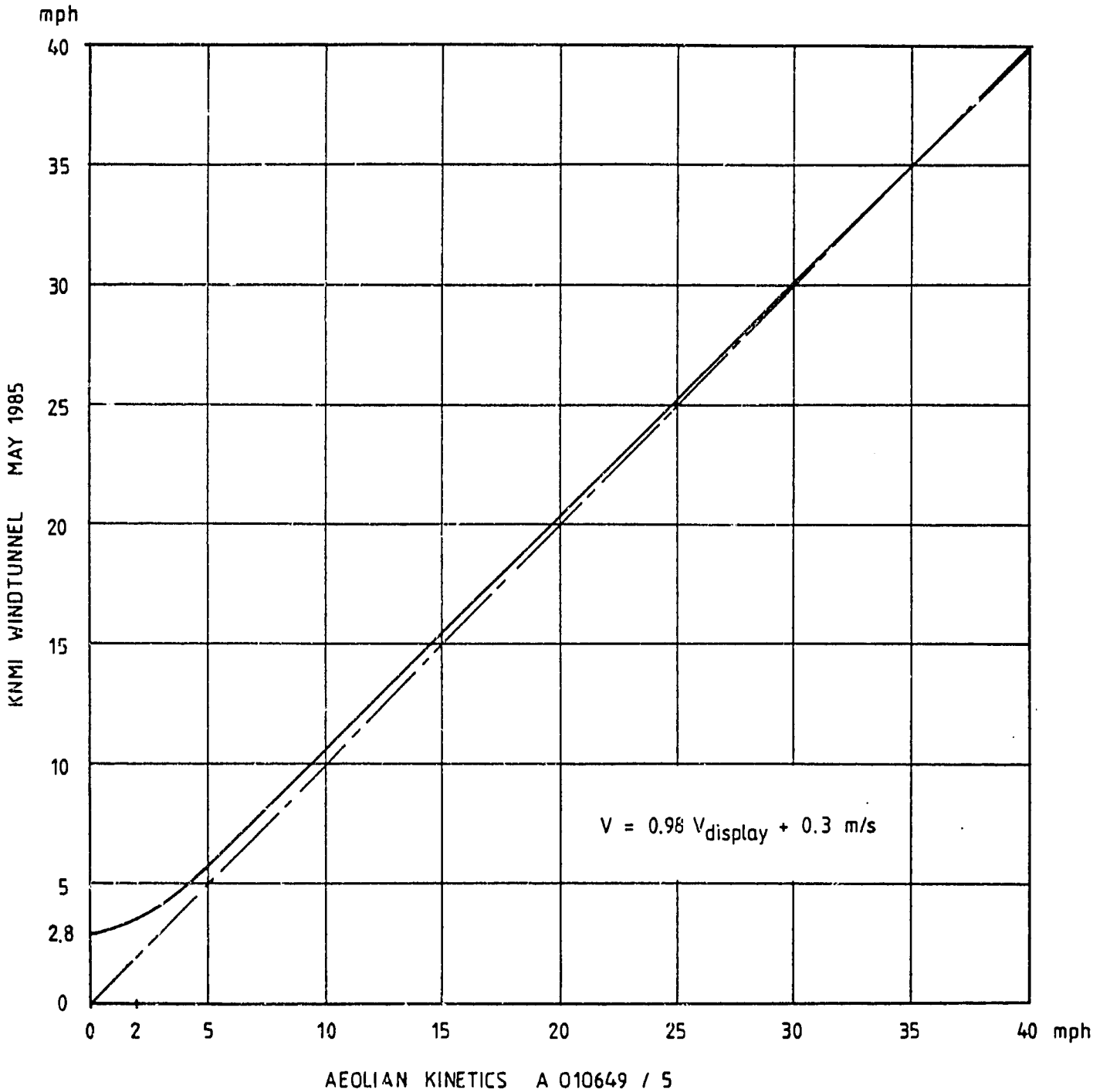



Figure 6 : Calibration curve of the TOOL anemometer assessed by the KNMI

reasons and to prevent the impression of a too high accuracy of callibration and/or anemometers.
Therefore it was also decided to neglect the very small deviation in the WTGS-Mochudi readings whereby the theoretical correction is most probably within the inaccuracy or tolerance of the equipment. Hence, no correction has been made for the WTGS-Mochudi readings. The correction made for the RIIC-Mochudi readings is v = 0.94 vb + 0.8 m/s and the correction made for WTGS-Shoshong is v = 0.98 vb + 0.3 m/s.
The results are shown in Figure 7, whereby on the vertical axis the corrected values of the TOOL anemometer is set (representing the real wind speed) and on the horizontal axis the corrected values of the BRET

| WTGS vb m/s | Mochudi v m/s | RIIC vb m/s | Mochudi v m/s | WTGS vb m/s | Shoshong v m/s |
|---|---|---|---|---|---|
| 2.37 | 2.37 | 1.27 | 2.02 | 0.78 | 1.20 |
| 3.55 | 3.48 | 3.69 | 4.22 | 2.32 | 2.72 |
| 1.61 | 1.61 | 3.89 | 4.42 | 2.63 | 3.01 |
| 4.09 | 4.02 | 3.28 | 3.84 | 1.85 | 2.00 |
| 2.16 | 2.13 | 2.14 | 2.73 | 1.35 | 1.81 |
| 2.87 | 2.89 | 2.89 | 3.44 | 4.44 | 4.74 |
| 2.00 | 1.97 | 2.83 | 3.46 | 7.02 | 7,23 |
| 1.78 | 1.35 | 1.57 | 2.25 | 5.30 | 5.50 |
| 2.94 | 3.02 | 1.34 | 2.03 | 3.61 | 3.91 |
| 2.54 | 2.67 | 1.31 | 1.95 | 1.56 | 1.57 |
| 2.93 | 3.01 | | | 1.13 | 1.13 |
| 2.54 | 2.62 | | | 4.40 | 4.53 |
| 2.53 | 2.56 | | | 7.36 | 7.44 |
| 2.64 | 2.65 | | | 6.99 | 7.10 |
| | | | | 6.33 | 6.54 |
| regression line: v=1.046 vb-0.13 | | regression line: v=0.935 vb+0.77 | | regression line: v=0.982 vb+0.29 | |
| no correction will be made v = vb | | correction to be made: v = 0.94 vb + 0.8 | | correction to be made: v = 0.98 vb + 0.3 | |

Table 1 : Comparison and correction of anemometers

anemometers at the three different sites.
As can be seen, the result is quite satisfactory.

All wind speeds used in other chapters of this report are the, with the above given correction formulaes, calculated values and thus represent the real wind speed.

## 3.2 Discussion of deviation of anemometers

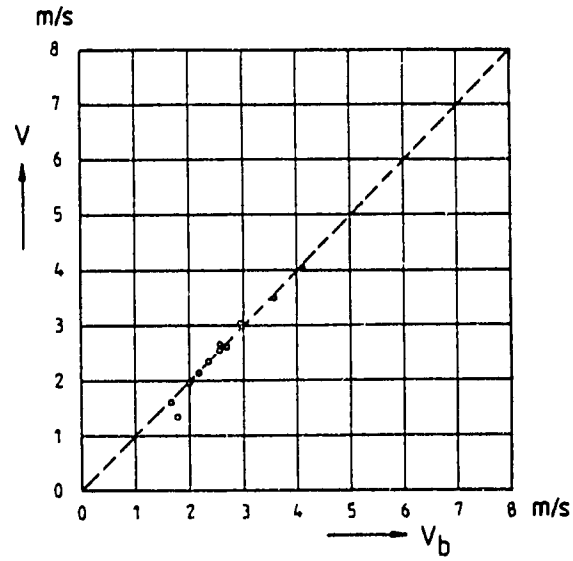
Although the above corrected wind speeds are now of significant value and are of workable use, it is interesting to know what makes the anemometers differ so much.
In case of the TOOL anemometer, it was found that one bearing (the bottom trust bearing) was worn out and the bearings were very dirty.
After the first calibration by the KMNI with the anemometer in the same condition as used in Botswana, the anemometer was revised. The wornout bearing was replaced by a new one and the bearings were cleaned and correctly lubricated and then again calibrated. The result of this calibration with the revised anemometer is shown in Figure 8. It can be seen that the deviation from the "normal" is minimized with regard to the situation before revision. This is clearly a result of reduced friction in the bearings of the anemometer.
The conclusion might be valid that if an anemometer is in a mechanically good shape, well cleaned and proper lubricated, the displayed wind speeds or windrun have likely a neglectable deviation from the real wind speeds.

The reason for the much too low values displayed by the "RIIC anemometer" and the less lower values of the WTGS-Shoshong anemometer might be well be

CORRECTION MADE FOR TOOL ANEMOMETER: $V = 0.98\ V_t + 0.3$ m/s

WTGS MOCHUDI

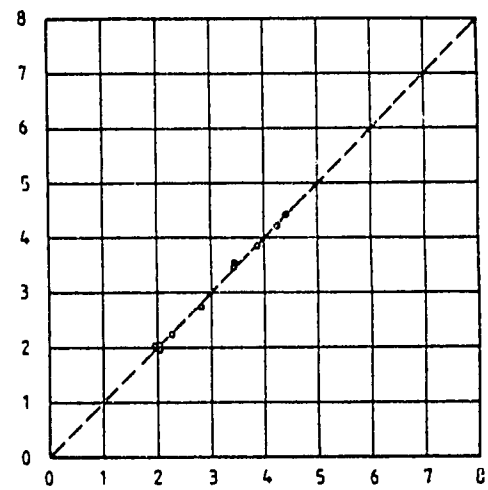
NO CORRECTION FOR BRET ANEMOMETER




RIIC MOCHUDI

CORRECTION MADE FOR BRET ANEMOMETER:

$V = 0.94\ V_b + 0.8$ m/s




WTGS SHOSHONG

CORRECTION MADE FOR BRET ANEMOMETER:

$V = 0.98\ V_b + 0.3$ m/s

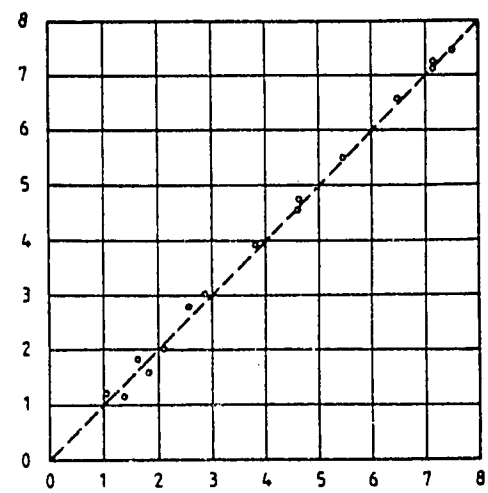



Figure 7 : Simultaneously measured wind speeds with the BRET and TOOL anemometers after applying the individual correction formulaes for all the anemometers.

a mechanical defect in the bearing(s) and/or dirty not properly lubricated rotary parts.
It should be worthwile to revise these anemometers and check the new behaviour.

In general it is advised by the KNMI (and practised also with their own anemometers) to revise all anemometers each year or in case the environment is highly poluted every half year.

The discrepancy in calibration results between the calibration carried out by CWD in August 1984 and the KNMI in May 1985 on the same anemometer (see Figure 3.1, Appendix 3 and Figure 6, page 11) could not be explained by CWD. The KNMI suggested that the measuring method and/or equipment of CWD might not have been correct.
Because the last (KNMI) calibration showed a smaller deviation than the previous CWD calibration, whereby the starting speed of the anemometer was the same, it may be concluded that the anemometer performance has not deteriorated in the mean time. On the other hand, since no manipulations with the anemometer have been done, it is safe to assume that the performance of the anemometer has not changed in a positive sense.
Therefore, the KNMI calibration has been assumed correct and valid for the whole duration of the mission.

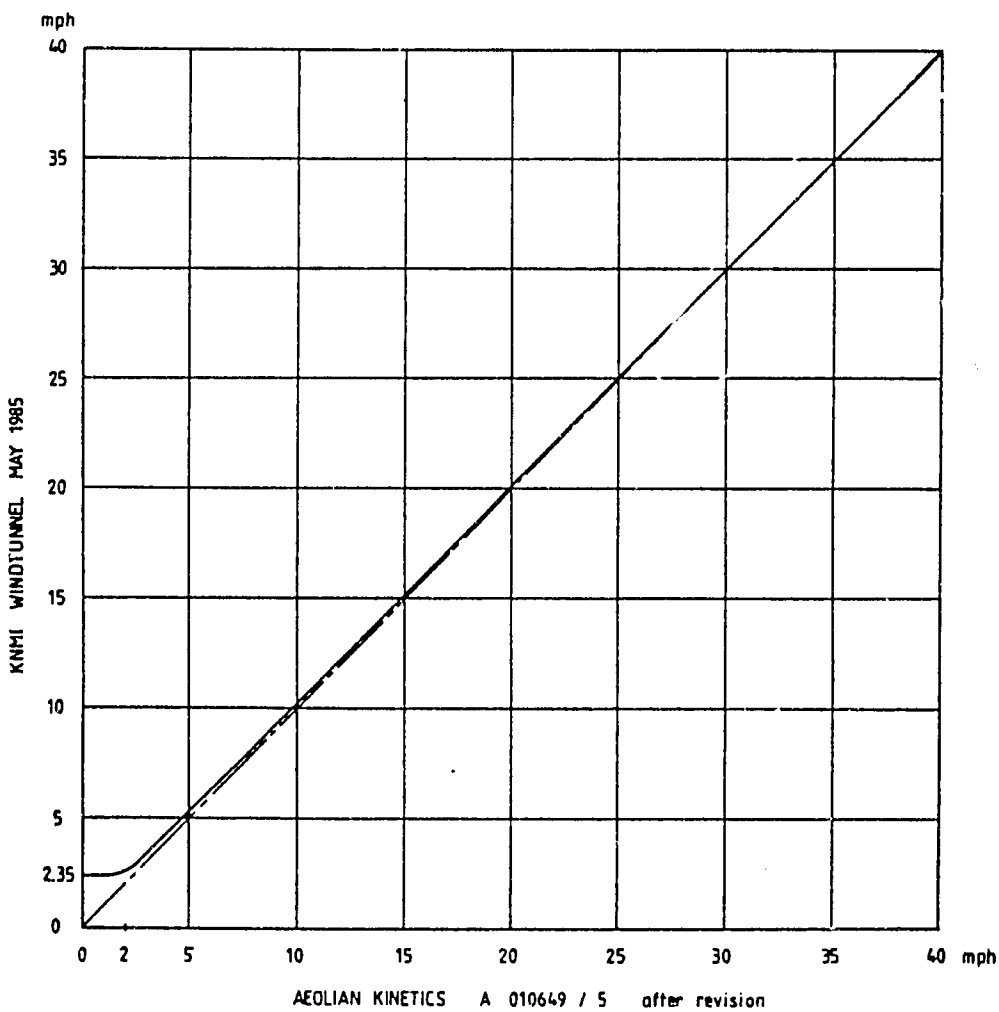



Figure 8 : Calibration curve of the TOOL anemometer assessed by the KNMI after revision of the anemometer

# 4 TESTING THE WINDMILLS

## 4.1 General

First of all I would like to point to the very low wind speeds, especially in Mochudi, during my stay which made measuring on the windmills a cumbersome undertaking.

Most of the measurements are performed on the WTGS windmill in Mochudi. The determination of the influence of the blade angles on the starting behaviour and overall efficiency of the system could only be performed at the WTGS windmill in Shoshong because this prototype only had an adjustable bladesetting construction. Unfortunately this windmill was not functioning untill the last week of my stay, although not proper. Hence it was not possible to carry out this measurements. However, some remarks will be made based on other (windtunnel) measurements later on.
Also some measurements were carried out on the RIIC windmill in Mochudi. As both windmills (RIIC and WTGS windmill in Mochudi) have the same size rotor and both drive a monopump but use an other system to overcome the high starting torque of the mono pump, it is interesting to see which system performs best; of course also in relation with the reliability and costs of both systems.
The big handicap, however, was lack of wind, especially during the measurements at the RIIC windmill. Therefore the results of the measurements at the RIIC windmill only indicate the behaviour of the system at very low wind speeds. Apart from all other complications, conclusions about comparing the two windmill systems are only tentative and should be interpreted carefully.

## 4.2 The WTGS windmill in Mochudi

This windmill was installed in December 1984 and functioned well ever since. The windmill was bought by BRET in the framework of their long term testing programme and was thus equiped with the BRET monitoring equipment (see Photo 5).
The monitoring equipment totals the pumped quantity of water, the number of revolutions of the vertical downshaft of the windmill and is keeping track of the elapsed time. It also monitors the wind speed whereby not only the total windrun is displayed, but also the momentaneous wind speed every 2 seconds and the wind speed distribution in intervals of 2 km/h ranging from 0 to 30 km/h and more than 30 km/h. Besides the equipment is keeping track of the pump-on time. The displayed totals are read each week and analysed by BRET.
For the short term measurements to be performed to establish the windmill characteristics this equipment could not be used because of a too small resolution.
For establishing the monthly wind speed distribution and monthly average wind speeds the BRET data are used. (See Chapter 2).

## 4.3 Measuring procedure

Every 10 minutes the windrun, the number of revolutions of the vertical downshaft and the pumped amount of water was recorded. In addition the speed at which the clutch engaged or disengaged as well as the speed range

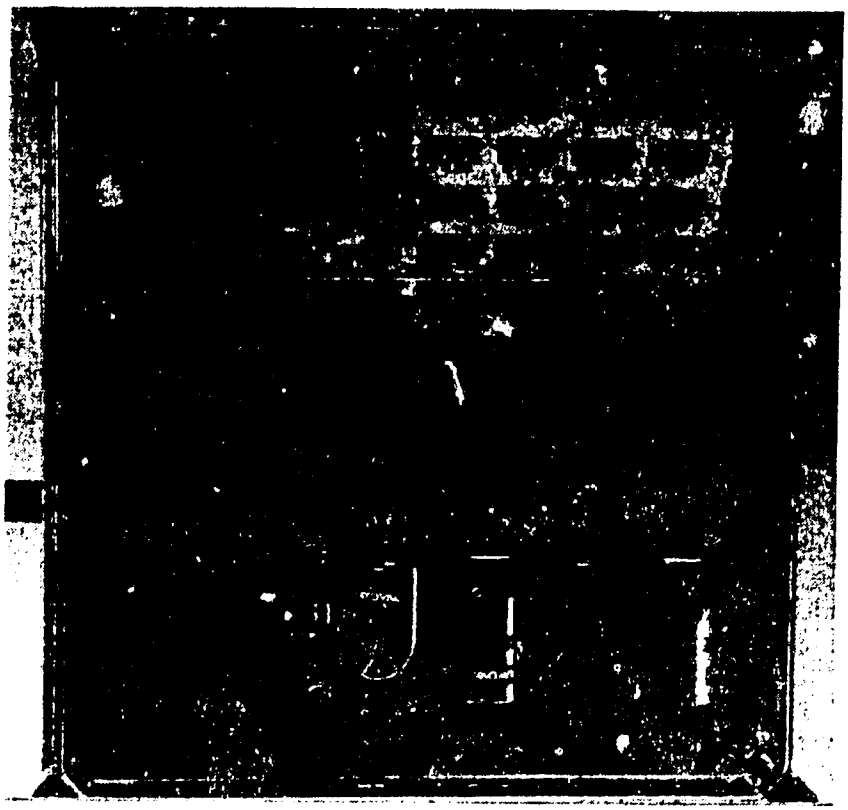


Photo 5 - The BRET monitoring equipment

over which the clutch slipped was recorded momentaneously with help of a tachometer (see Photo 6).

The windrun was measured with a Aeolien kinetics WP 4000 wind prospector in combination with a maximum cup anemometer, which displayed the windrun in 0.01 mile.

The number of revolutions of the vertical downshaft were measured with a second wind prospector which was put in the "counting pulses mode". The pulses were generated by a reed switch controlled by a magnet fixed on the shaft. Each shaft revolution gave one count on the display unit.

The pumped amount of water was read directly from the water flow meter. The water flow was displayed in US Gallons and could be read conveniently in 0.5 US Gallons. The accuracy of the flow meter is a function of the flow rate but is better than 1 % according to the manufacturer; see Figure 4.1, Appendix 4 for the typical flow accuracy. Anyhow no correction has been applied for these deviations. The pressure drop over the flow meter is also a function of the flow rate; see Figure 4.2, Appendix 4 for the typical pressure drop over the flow meter. In the range of the flow rate pumped by the windmill the pressure drop is less than 0.5 m water collumn. At flow rates around the starting speed of the windmill the pressure drop is even less than 0.1 m water collumn, which can be completely neglected if related to the total head over which the water is lifted.

The 10 minutes intervals were measured with a stopwatch. During all measurering sessions, visual observations were made of the behaviour of the furling mechanisme and the overall behaviour of the windmill.

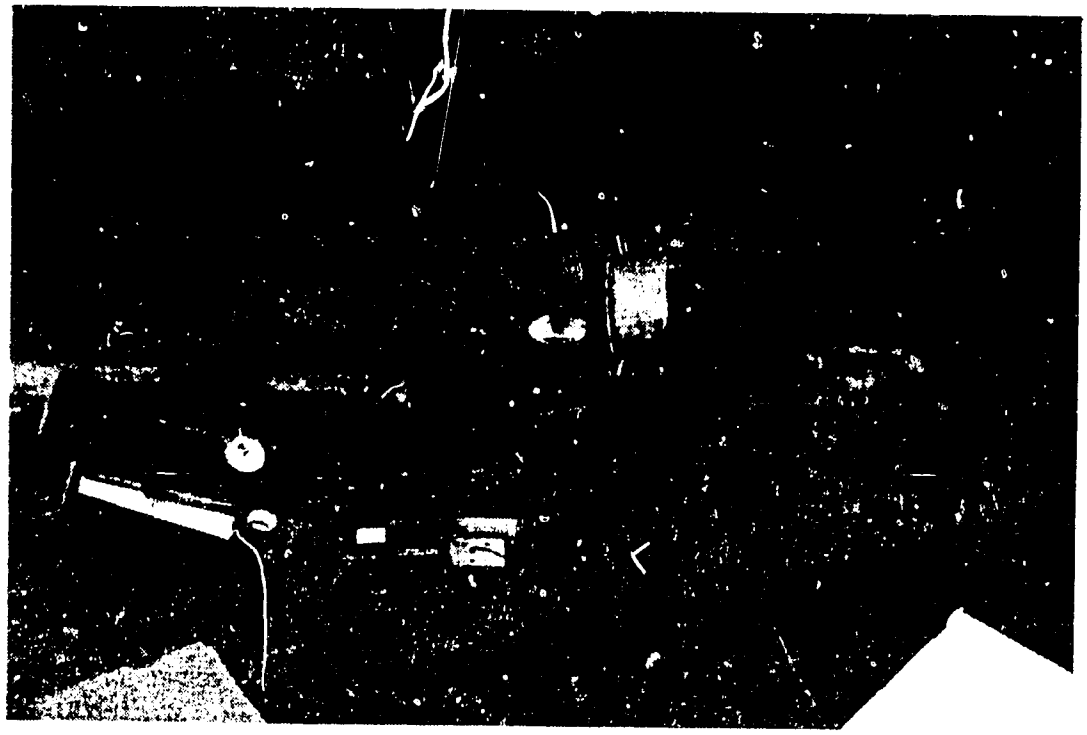


Photo 6 - Testing equipment arrangement

## 4.4 Processing the raw data

By subtracting all readings from the previous ones and deviding them by the elapsed time since the last reading, the 10 minutes average values were found. These averages were converted into m/s for the wind speed, rpm for the rotor speed and m3/h for the water flow rate.
Finally all measurements were grouped in wind speed bins of a 0.5 m/s width and the average of all measured values were calculated.
These average values for different situations and windmills are presented in this report whereby also the number of samples is indicated on which they are based.

## 4.5 Test results

The WTGS windmill in Mochudi has been tested twice. First the windmill was tested "as it was". After making modifications on the clutch and experimenting with the transmission ratio the windmill was tested again. These two tests will be referred to as I and II respectively. The test results are presented in Table 2.
The flow rate versus wind speed is graphicaly presented in Figure 9, curve I. The dotted curve is a reference curve calculated for a total system efficiency of 10 % , see Chapter 6. Curve II represents the situation after the modifications on the clutch and with a higher transmission ratio; see further on.
In Table 3 the testing results are presented after the modifications on the clutch and with a higher transmission ratio.
The flow rate versus pump drive speed is graphicaly presented in Figure 10. It is stressed here that the pump drive speed is not identical with the pump speed.
This would only be the case if the clutch was engaged continuously, which was certainly not the case in situation I. It can however be concluded that the rate of engagement at a wind speed of arround 6 m/s was at its maximum (relative). At higher wind speeds the influence of the (too quick acting) furling mechanisme is visible. At lower (10 minutes average) wind speeds

| wind speed m/s | rotor speed rpm | pump drive speed rpm | water flow rate m3/h |
|---|---|---|---|
| 1.9 | 13.8 | 118 | - |
| 3.0 | 14.2 | 121 | 0.01 |
| 3.6 | 19.7 | 168 | 0.05 |
| 4.0 | 25.5 | 217 | 0.31 |
| 4.4 | 30.2 | 257 | 0.57 |
| 5.0 | 35.7 | 304 | 0.99 |
| 5.5 | 41.1 | 350 | 1.21 |
| 5.9 | 43.2 | 368 | 1.37 |
| 6.9 | 57.2 | 487 | 1.84 |

Table 2 : Measuring results I WTGS windmill Mochudi
Total head: 36.5 m

| wind speed m/s | rotor speed rpm | pump drive speed rpm | water flow rate m3/h |
|---|---|---|---|
| 2.6 | 10.0 | 106 | 0.18 |
| 3.0 | 11.3 | 120 | 0.20 |
| 3.5 | 14.3 | 151 | 0.37 |
| 4.0 | 18.3 | 194 | 0.57 |
| 4.6 | 24.7 | 260 | 0.94 |
| 5.0 | 27.7 | 292 | 1.07 |

Table 3 : Measuring results II WTGS windmill Mochudi.
Total head: 36.5 m

the engagement ratio is also decreasing because the portion of time within those 10 minutes the wind speed is below the minimum required for keeping the clutch engaged or to engage it again is increasing. The "higher" situated curve of situation II also indicates a higher ratio of engagement; when this curve is more straightly shaped it indicates a better starting behaviour, or in other words: the clutch works better.

The test results of the WTGS windmill in Shoshong are presented in Table 4.1, Appendix 4. In this case the measured values are not grouped into wind speed bins because of the low number of samples and the very high scatter in the measured values; see Figure 11. The very low values for the flow at higher wind speeds are fully due to the mal functioning of the furling mechanisme of this windmill.
The flow rate versus pump drive speed is visualized in Figure 12.

The test results of the RIIC windmill at Mochudi are listed in Table 4.2, Appendix 4 and visualized in Figure 13 and 14.
The interpretation of these measuring results is very complicated because of the continously variable transmission ratio. At very low wind speeds the transmission ratio is minimal. With increasing wind speeds or better with increasing drive shaft speeds, the transmission ratio is increased to a maximum value of 4.2 times the ratio it had at start wind speeds (The manufacturer of the variable V-belt transmission gave for this maximum value 6.2 times. However, at the RIIC windmill in Mochudi a value of 4.2 was measured).
This maximum is reached at wind speeds of about 5 m/s.
A more comprehensive discussion of the testing results is given in Chapter 6.

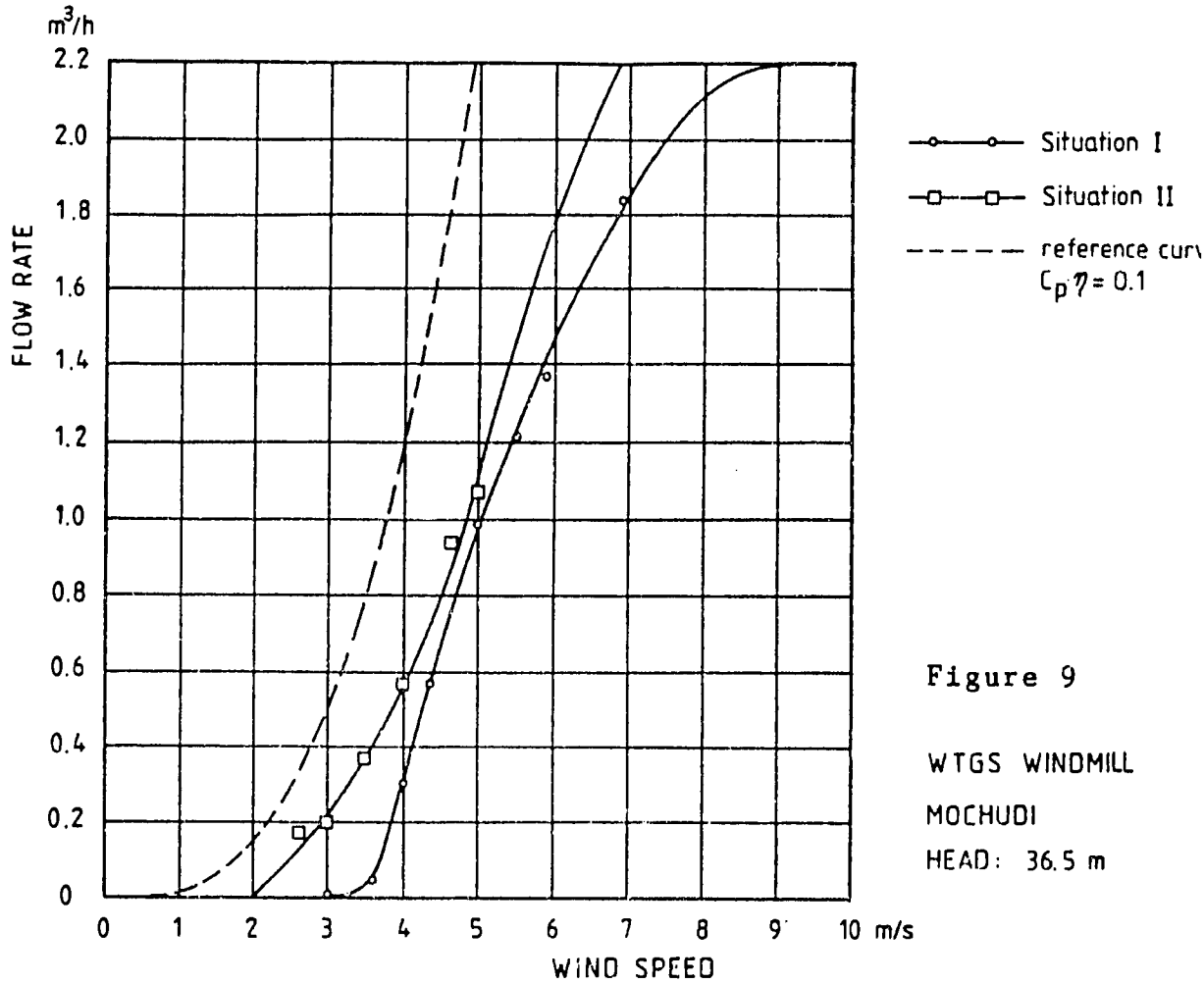



Figure 9

WTGS WINDMILL

MOCHUDI

HEAD: 36.5 m

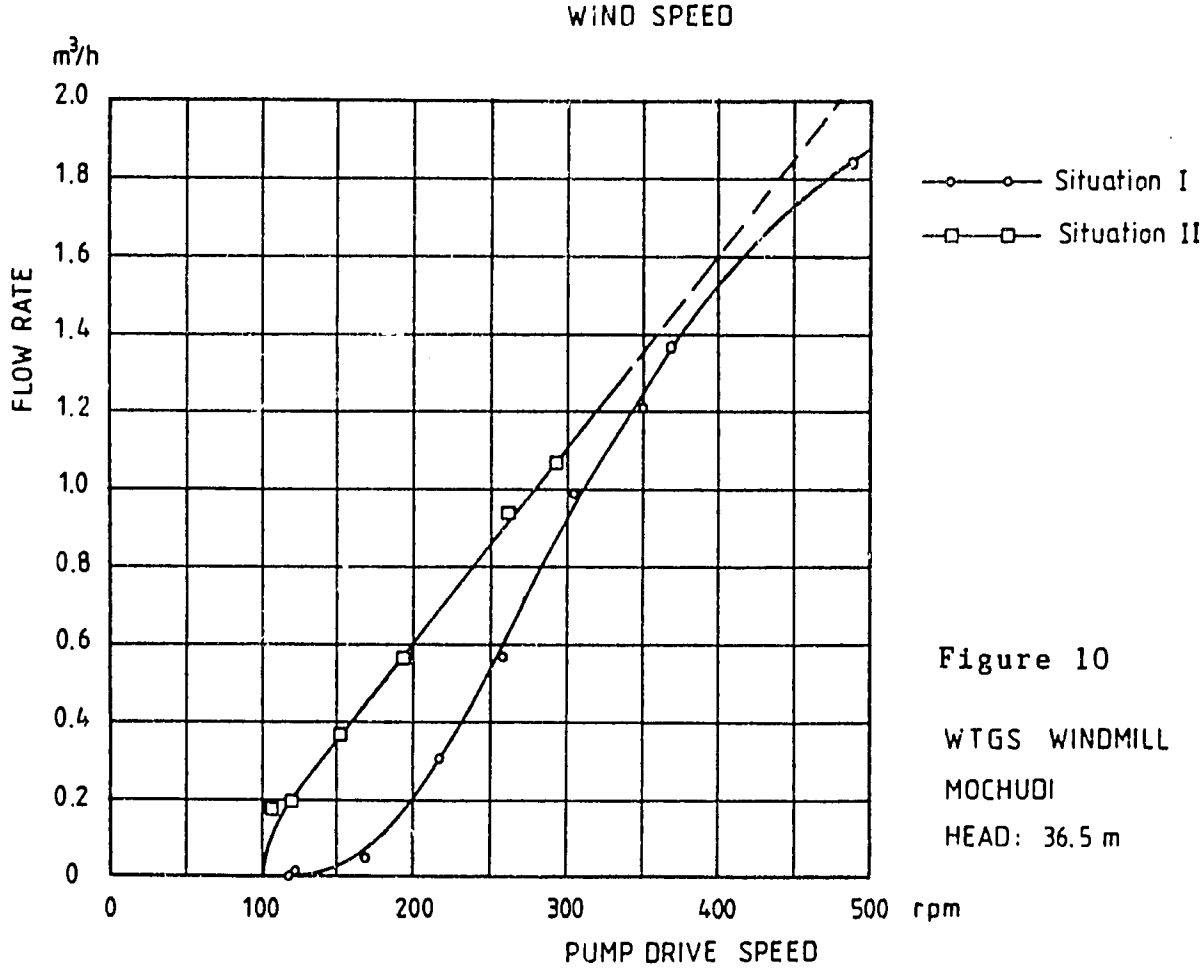



Figure 10

WTGS WINDMILL

MOCHUDI

HEAD: 36.5 m

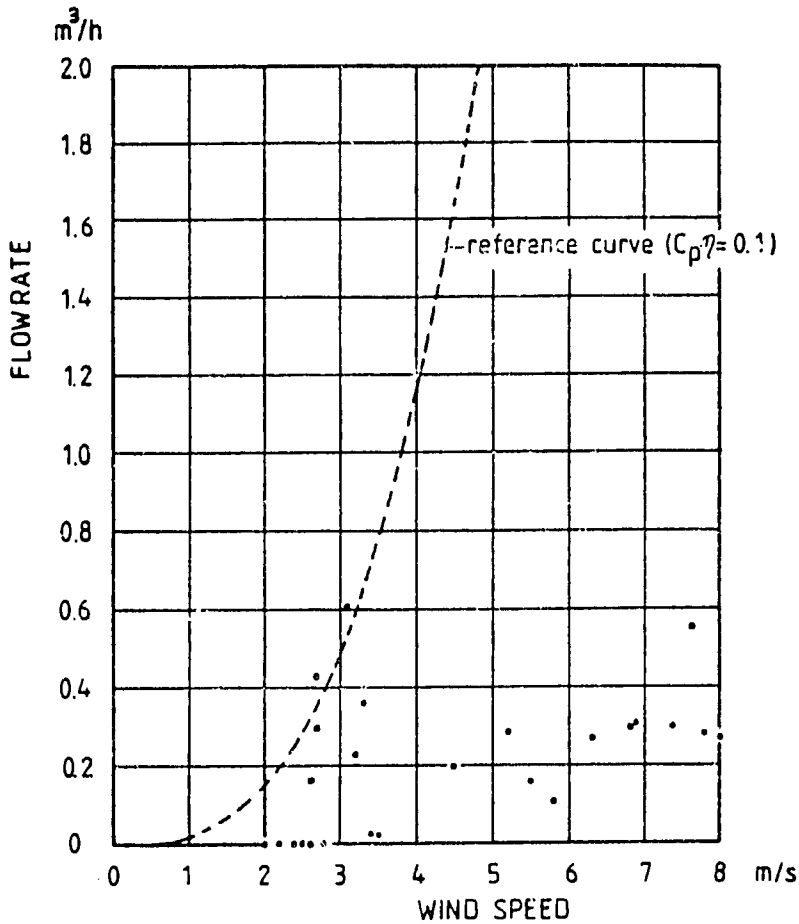



Figure : 11

WTGS WINDMILL

SHOSHONG

HEAD = 33.4 m

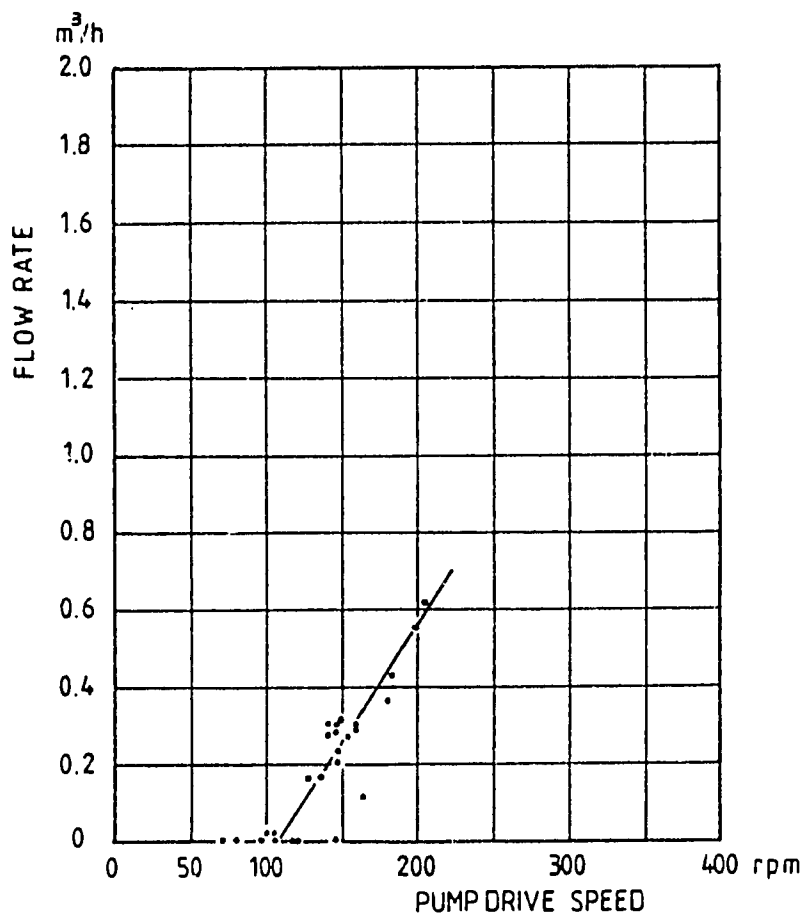



Figure : 12

WTGS WINDMILL

SHOSHONG

HEAD = 33.4 m

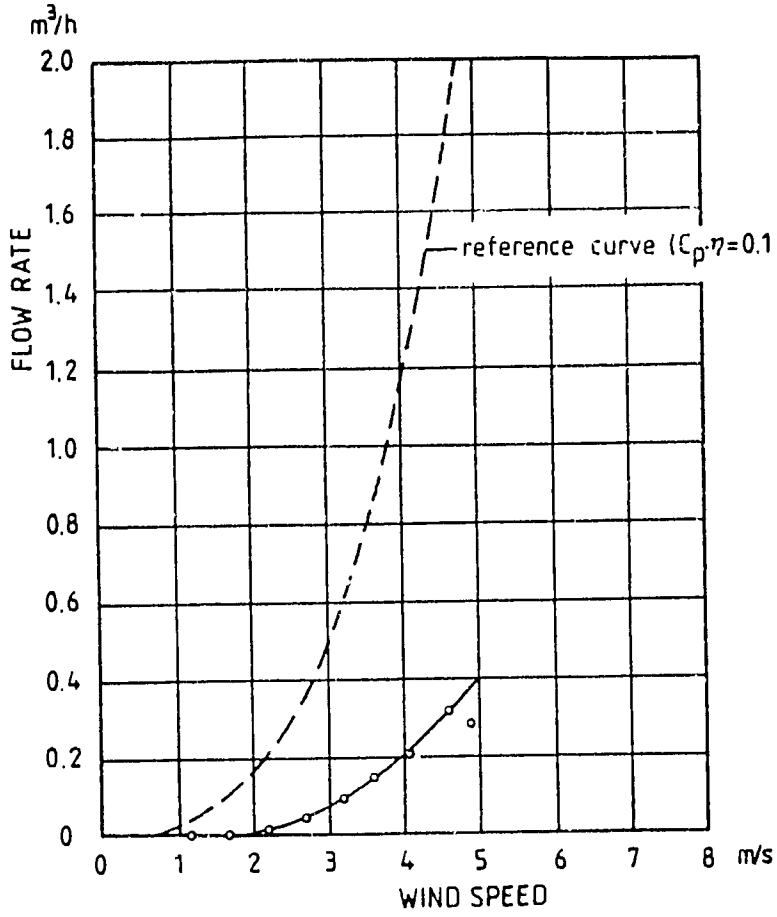



Figure : 13

RIIC WINDMILL
MOCHUDI
HEAD: 36.5 m

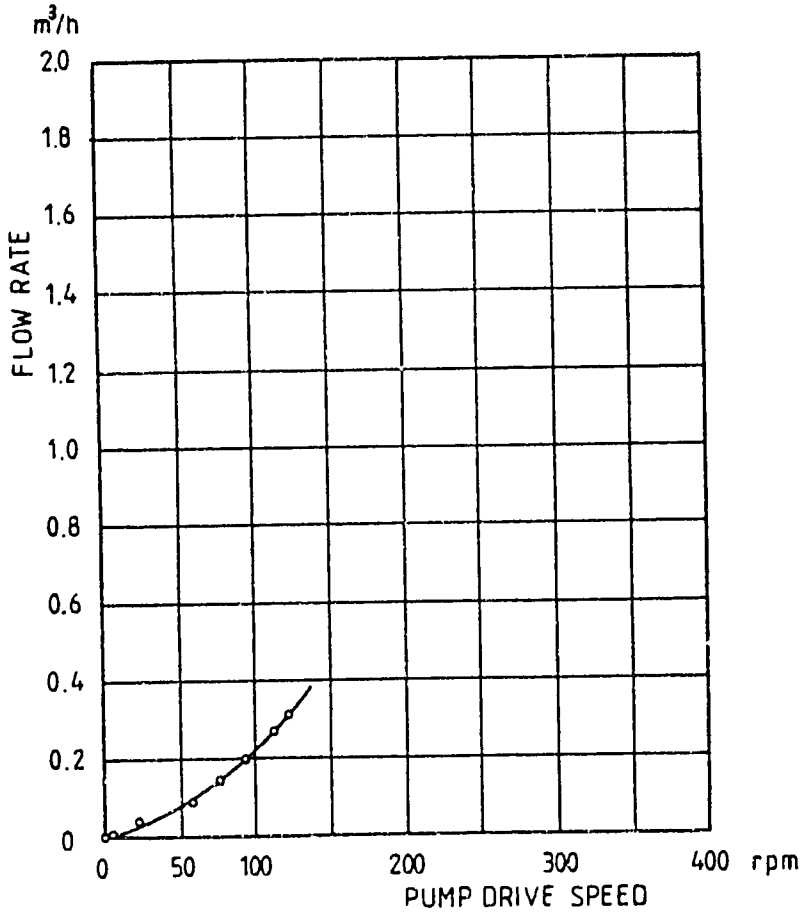



Figure 14

RIIC WINDMILL
MOCHUDI
HEAD: 36.5 m

## 5 MONTHLY PUMPING OUTPUT

In order to get an impression about the long term performance of the windmill, the monthly pumping output and the pumping availability have been established.
This is done by synthesizing the pump curve (as shown in Figure 9) with the Weibull distribution of wind speeds.
For this purpose the output of the WTGS windmill in Mochudi has been normalized for situation I and II. For each 1 m/s wind speed increment the corresponding output has been listed in Table 4 for both situations.

| wind speed m/s | output I m3/h | output II m3/h |
|---|---|---|
| 0.5 | 0 | 0 |
| 1.5 | 0 | 0 |
| 2.5 | 0 | 0.10 |
| 3.5 | 0.08 | 0.37 |
| 4.5 | 0.66 | 0.78 |
| 5.5 | 1.24 | 1.48 |
| 6.5 | 1.67 | 2.04 |
| 7.5 | 2.01 | > 2.20 |
| 8.5 | 2.17 | > 2.20 |
| 9.5 | - | > 2.20 |

Table 4 : Normalized output WTGS windmill Mochudi

The Weibull wind speed distribution has been calculated with the probability density function for a Weibull distribution:

$$f(v) = \frac{k}{v} \left(\frac{v}{\bar{v}}\right)^k G \, e \left[-G \left(\frac{v}{\bar{v}}\right)^k\right]$$

whereby $G = \Gamma^k(1 + \frac{1}{k}) = 0.568 + 0.434/k$

This is calculated in steps of 1 m/s, so very little error is introduced over exact integration.
First the Weibull distribution has been calculated for the months Jan/Febr, March and April 1985 with the average wind speeds as monitored with the BRET equipment. The shape factor of the distribution (k - value) has been derived with the so called Weibull-paper. The results of these calculations are listed in Table 5.1, Appendix 5 and visualized in Figure 14, whereby the measured freqency distribution from Figure 3 has been converted into m/s intervals.
It is concluded that the calculated Weibull distribution (represented by the curves) gives a good fit with the measured one.

If these Weibull distributions are sythesized with the normalized windmill output, the following values are found for monthly output and availability (Table 5).
In the same table also the real measured output and the calculated output whereby the normalized windmill output is synthesized with the monitored wind speed distribution are presented.
It is concluded that the output prediction model whereby the normalized windmill output is synthesized with the Weibull frequency distribution, represents a very good fit.

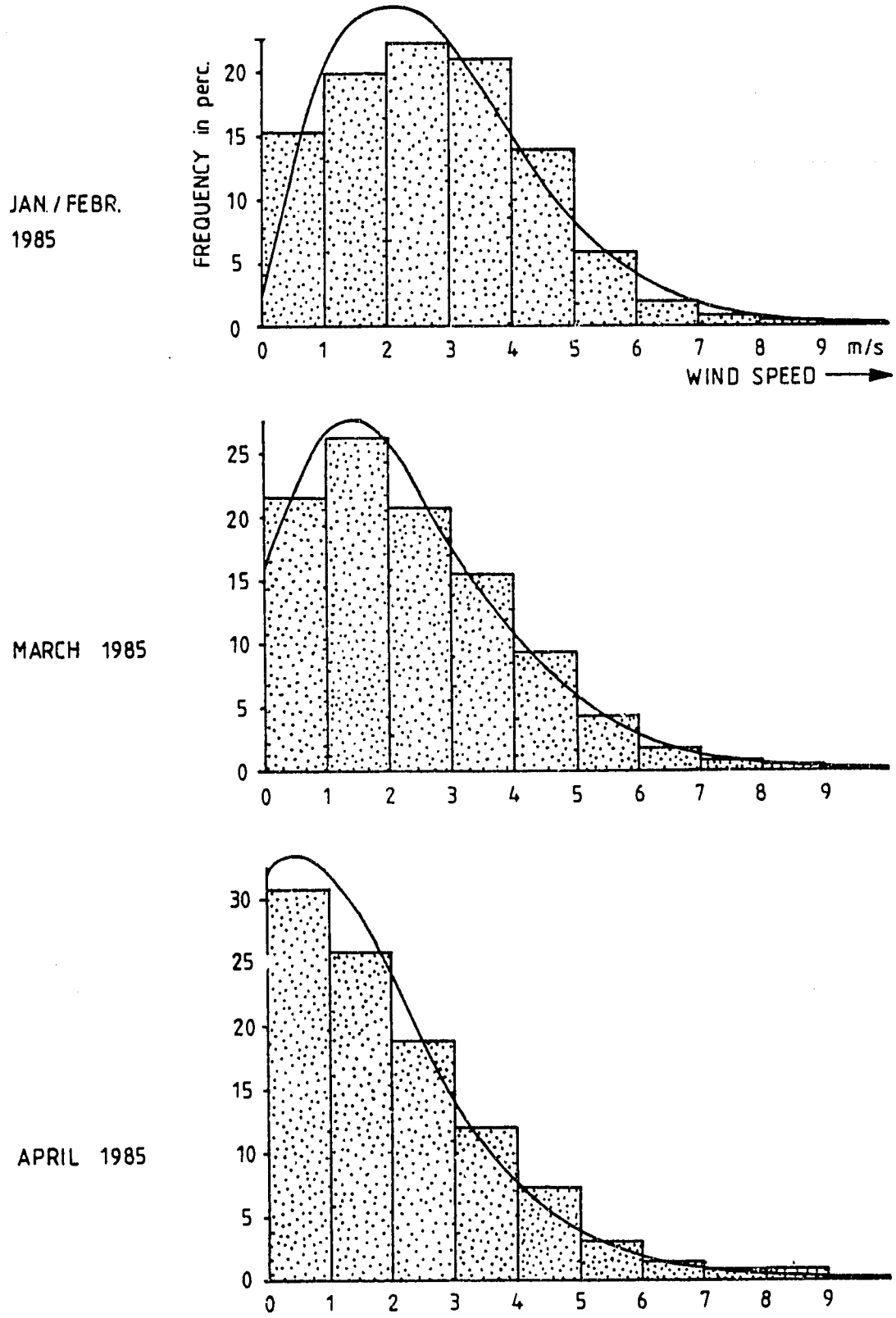



Figure 14 : Histogram of wind speed distribution at the WTGS windmill site in Mochudi with the calculated Weibull frequency distribution curve (Histogram converted into 1 m/s bins)

| Period | calc. output I with Weib.distr. m3 | measured output m3 | calc. output with real freq. distr. m3 |
|---|---|---|---|
| Jan/Febr. | 284 | 290 | 276 |
| March | 131 | 132 | 138 |
| April | 76 | 76 | 92 |

Table 5 : Comparison of output calculations with real outputs

The measured outputs were obtained from the BRET monitoring equipment and corrected for over-estimation by the BRET equipment.
This over-estimation is caused by the sensor system used for measuring the flow. The sensor also generates pulses if the water flows back in the borehole which happens if the pump stands still. Then the water in the delivery pipe from the flow meter to the storage tank flows slowly back into the borehole because the mono pump is not equiped with a footvalve. Besides, very small vibrations of the dial of the flow meter also results in generating pulses. These vibrations occur very frequently around the start speed of the clutch. All these faulty generated pulses are, of course, added to the total displayed by the monitoring equipment leading to a over-estimation of the output.
The rate of over-estimation is erratic. In this case the ratio of over-estimation has been assessed by simultaneously readings of the BRET monitoring display and the direct readings from the flow meter at the beginning of a period and at the end. The over-estimation was 11.7% , 2.1% and 2.7% for the periods of Jan/Febr, March and April respectively.

Three more Weibull wind speed distributions are calculated for the following monthly average wind speeds and k-values:

| v | k |
|---|---|
| 3.2 | 1.9 |
| 3.6 | 2.0 |
| 4.0 | 2.0 |

In this case, however, the real k-values are not known because no wind speed distribution data were available at higher average wind speed months. Nevertheless it is expected that the assumed k-values represent rather accurate the real distribution.
If these Weibull distributions are synthesized with the normalized windmill output I and II , than the following monthly outputs and pumping availabilities may be expected, see Table 6.

| v m/s | k - | Output I m3 | Availa bility % | Output II m3 | Availa bility % | Increment in output % |
|---|---|---|---|---|---|---|
| 2.0 | 1.3 | 86 | 21 | 139 | 40 | 62 |
| 2.4 | 1.5 | 124 | 30 | 193 | 52 | 56 |
| 2.8 | 1.8 | 169 | 40 | 257 | 64 | 52 |
| 3.2 | 1.9 | 243 | 49 | 346 | 72 | 42 |
| 3.6 | 2.0 | 325 | 57 | 445 | 79 | 37 |
| 4.0 | 2.0 | 404 | 62 | 539 | 82 | 33 |

Head: 36.5 m

Table 6 : Monthly output at different montly average wind speeds

It may be observed that the outputs given in the first three rows of this table seem to be contradictionary with the outputs given in Table 5. This is not so. The difference is the time span over which the output is calculated. In Table 6 an average month consisting out of 730 hours has been taken, where as the time span in Table 5 is 1222, 769 and 646 hours respectively in accordance with the hours the readings were taken, to facilitate comparison.
Table 6 is visualized in Figure 15.

The conclusion is clear, that in situation II the windmill pumps more, ranging from 33% to 62%, depending on the average windspeed and that the water availability also has improved considerably. And this at the same investment costs.
However, in order to realize situation II, the clutch needs to be redesigned and the functioning of the furling mechanisme needs to be improved. The testing results show clearly that it is certainly worthwhile to invest in these needed modifications.

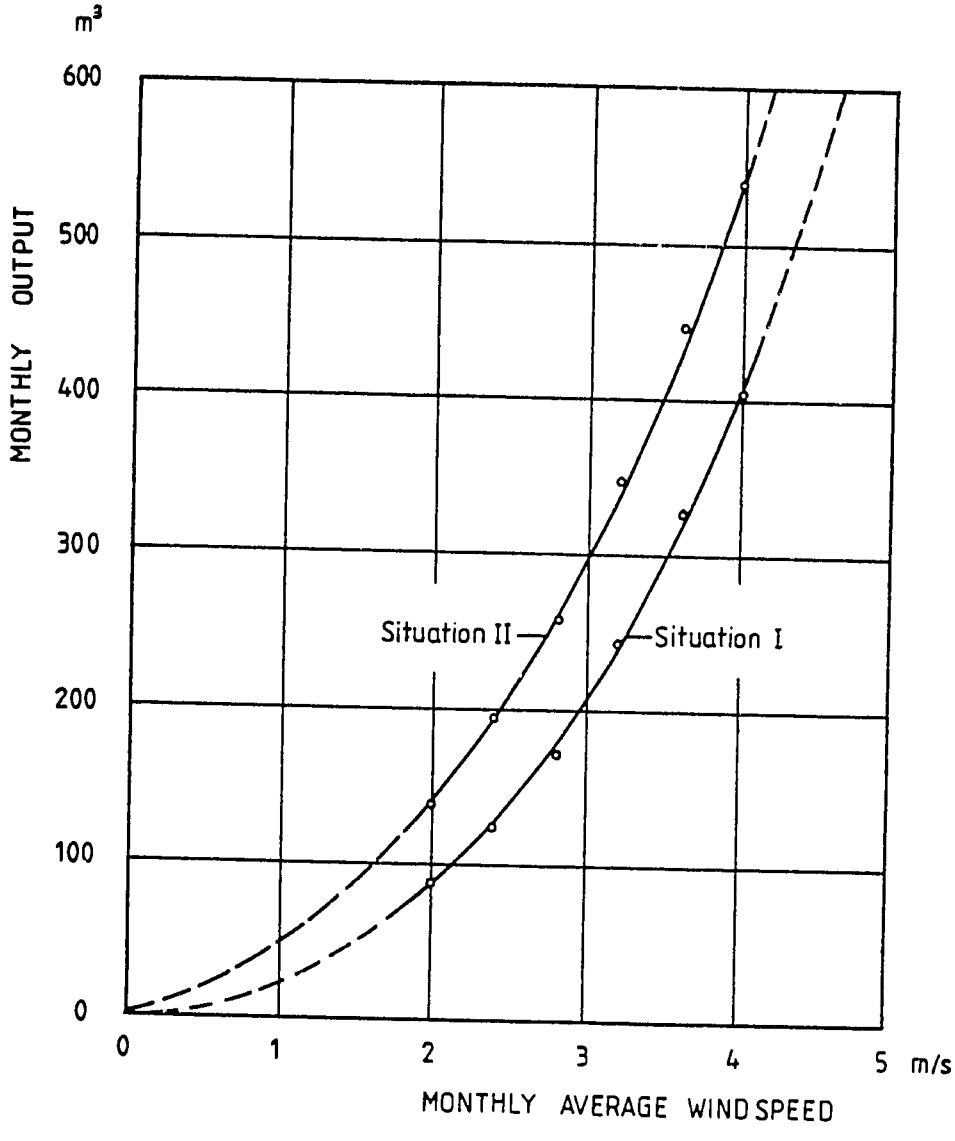



Figure 15 : Monthly output in m3 versus monthly average wind speed. For different monthly average wind speeds, different k-values are taken. See Table 6

## 5.2 Scope for the WTGS windmill

The scope for the WTGS windmill in Botswana may in fact only be assessed after sufficient data has been collected on the prevailing wind speeds in Botswana.
Once BRET has analysed their wind speed data and assessed the monthly average wind speeds and Weibull shape factors for the various stations in Botswana, the expected output of the WTGS windmill at a particular site may easily be calculated with the normalized WTGS II windmill output presented in this report.

With the quantity of water lifted by the windmill at specific sites in Botswana and the costprice of the complete windmill-pump system, a cost-benefit analyses may be carried out. By comparing the windmill with other water lifting devices, such as diesel pump, solar energy pump, biogas pump or animal driven pump, not only the economic aspects should be considered, but also the environmental impact, job creation, foreign currency, safety, benefits, spinn-offs, operating skills needed, reliability, maintenance etc. should be taken in to account.
As soon as sufficient reliable wind speed data are available, it is recommended to carry out such an analyses in order to get an impression about the potential market for the WTGS windmill in Botswana.

As far as the manufacturing of the windmill is concerned, Momoso seems able to produce limited number of WTGS windmills yearly, presupposed that a proper set of drawings along with a building manual are made availeble to them.

However, as long as the clutch and the furling mechanism have not been improved, it is advised to limit the production of the WTGS windmill and no active selling policy should be taken up.

# 6 DISCUSSION OF THE TESTING RESULTS

## 6.1 WTGS windmill in Mochudi

The extrapolation of the output curve I above 7 m/s is arbitrary and is merely based on the visual observations of the functioning of the furling mechanisme. It was observed that the furling mechanisme acted instable and at momentaneous wind speeds of arround 8 m/s it very often was already in furled position affecting the output in a negative sense. The strong diversion of the curve at wind speeds above 7 m/s is fully due to this too early acting furling mechanism. This assumption is also proved by the pump drive speed versus flow rate curve (Figure 10). At higher flow rates, the curve diverses, indicating that during an increasing portion of the 10 minutes measuring intervals the pump stands still, caused by the complete furled position of the windmill, whereby the pump drive speed decreases so much that the clutch disengages. All these considerations and observations have lead to the presented pump curve extrapolation which is expected to correspond rather well with the real pump curve.

The extrapolation of the output curve II above 5 m/s is even more arbitrary. It is merely based on the assumption of an improved acting furling mechanisme. The improved furling mechanisme should work less instable and start furling only at higher wind speeds. This modification is thought to be possible. Because of the uncertainty of the real course of the curve, the expected outputs at 7.5, 8.5 and 9.5 m/s are only indicated in a conservative way as "more than" 2.2 m3/h. However, the results of the output calculation model are thougth to be realistic and certainly not too optimistic. Moreover, by far the largest part of the gain between situation II and I is caused by the improved functioning of the clutch. And that part of the curve is based on the measured results.

The improved behaviour of the clutch could only be maintained during one day, just sufficient to perform the measurements. The improvement was not structural but temporarily achieved by using a "trick". It, however, clearly indicated and represented the behaviour of the clutch once it would have been redesigned and modified.

## 6.2 Characteristics of the windmill

The generated power of the windmill is described by:

$$P_w = \tfrac{1}{2}\rho v^3 \pi R^2 C_p \eta_m \qquad (6.1)$$

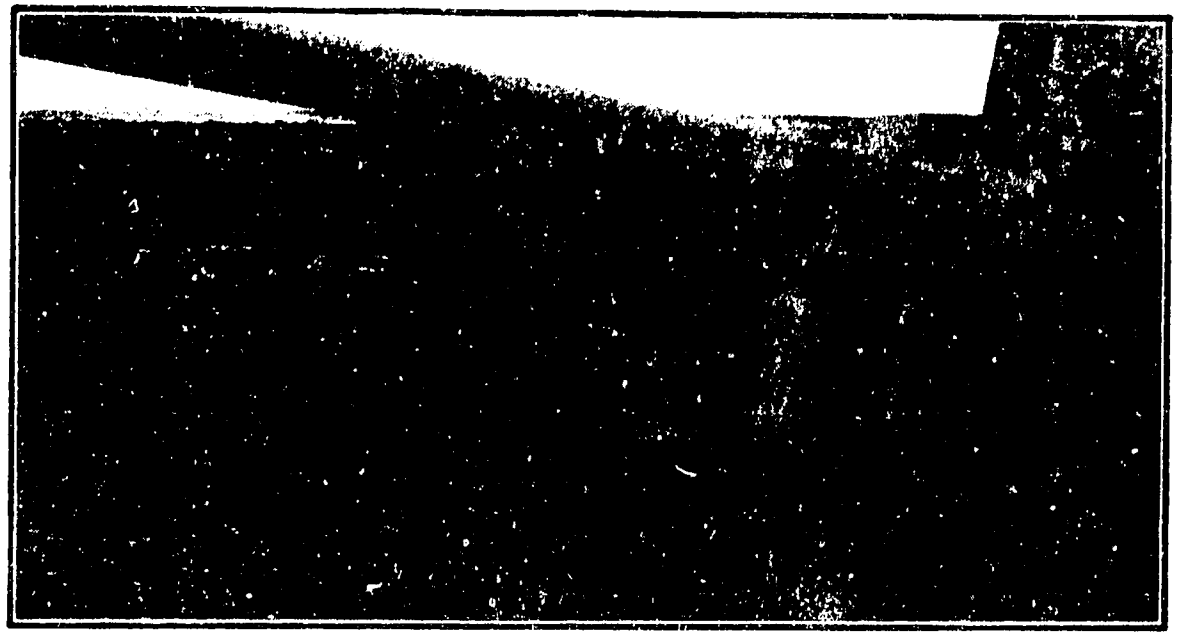
and the power required to lift the water by:

$$P_w = \frac{\rho_w g\ h\ q}{3600\ \eta_{m_2}} \qquad (6.2)$$

If these two Power expressions are combined, the total system efficiency can be described by:

$$C_p\eta = \frac{\rho_w\ g\ h\ q}{\tfrac{1}{2}\rho v^3 \pi R^2\ 3600} \qquad (6.3)$$

where $\eta_{m_1}\eta_{m_2}$ are combined to $\eta$ representing the total mechanical efficiency and



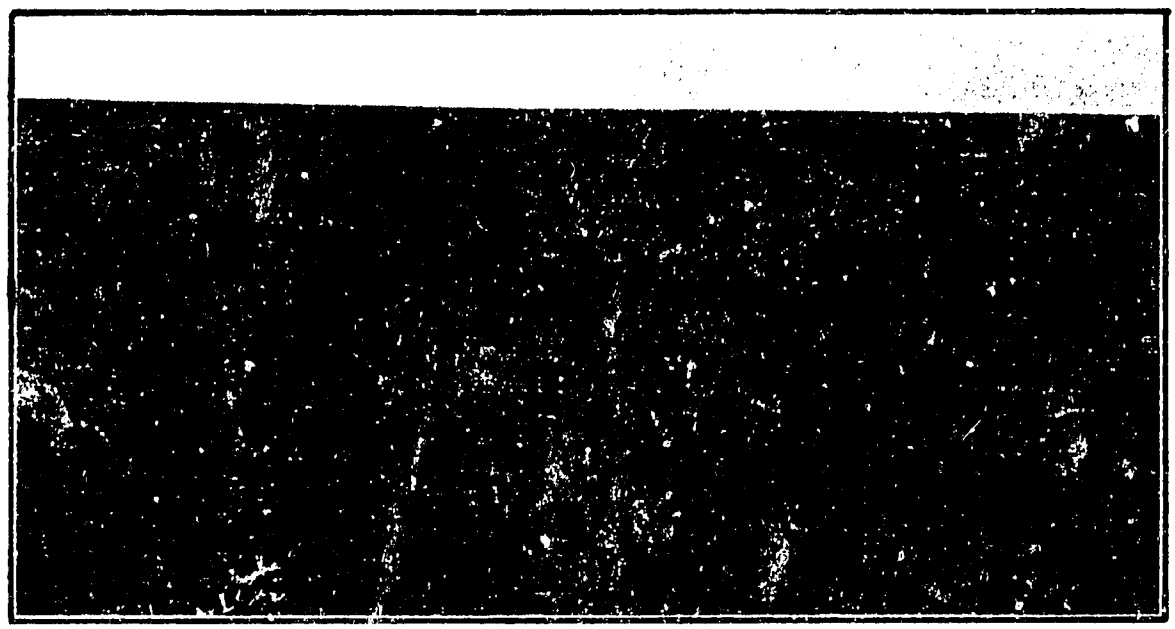


Photo 7, 8 and 9 - Impression of the surrounding of the WTGS windmill in Mochudi (Photo's taken from top of the windmill)

$C_p$ = rotor efficiency,
$\rho_w$ = density of water = 1000 kg/m$^3$,
g = acceleration of gravity = 9.8 m/s$^2$,
h = total head over which the water is lifted in m,
q = water flow in m$^3$/h,
$\rho$ = air density in kg/m$^3$,
v = wind speed in m/s,
R = rotor diameter in m.

For the WTGS windmill in Mochudi with a rotor diameter of 6.2 m a total head of 33.5 + 3.0 = 36.5 m and an air density of 1.048 kg/m$^3$ (see appendix 6) the formula can be reduced to:

$$C_p\eta = 6.281\ q/v^3. \qquad (6.4)$$

If the normalized output values of Table 4 are used with the corresponding wind speeds the following system efficiencies are calculated (Table 7).

| v m/s | qI m$^3$/h | qII m$^3$/h | $C_p\eta$ I % | $C_p\eta$ II % |
|---|---|---|---|---|
| 2.5 | - | 0.10 | - | 4.0 |
| 3.0 | - | 0.22 | - | 5.1 |
| 3.5 | 0.04 | 0.37 | 0.6 | 5.4 |
| 4.0 | 0.31 | 0.57 | 3.0 | 5.6 |
| 4.5 | 0.66 | 0.84 | 4.5 | 5.8 |
| 5.0 | 0.97 | | 4.9 | |
| 5.5 | 1.24 | 1.48 | 4.7 | 5.6 |
| 6.0 | 1.47 | | 4.3 | |
| 6.5 | 1.67 | 2.04 | 3.8 | 4.7 |
| 7.0 | 1.85 | | 3.4 | |
| 7.5 | 2.01 | > 2.20 | 3.0 | > 3.3 |
| 8.0 | 2.12 | | 2.6 | |
| 8.5 | 2.17 | > 2.20 | 2.2 | > 2.2 |
| 9.0 | 2.20 | | 1.9 | |
| 9.5 | | > 2.20 | | > 1.6 |

Table 7 : System efficiencies of the WTGS windmill (situation I and II)

The system efficiencies are displayed in Figure 16.

The reference curve as displayed in Figures 9, 11, and 13 is calculated with formula 6.4 whereby a constant efficiency of 10 % has been taken. The purpose of this curve is just as a reference; it gives an quick impression how far the pump curve lags behind this reference curve.
The calculation is as follows:

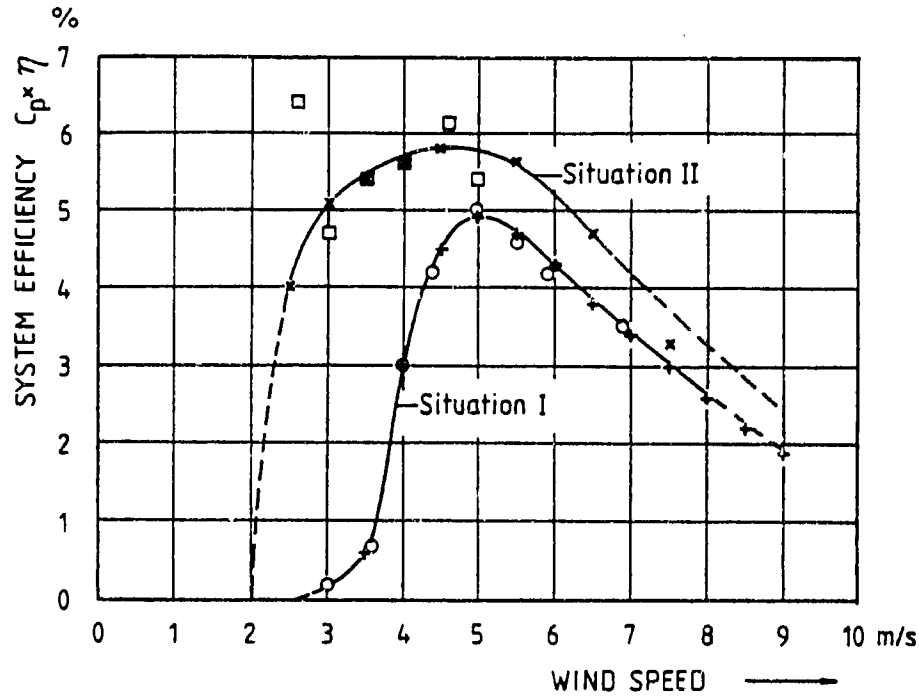
$$C_p\eta = 6.281\ q/v^3$$

for $C_p\eta = 0.1$ the expression can be rewritten as:

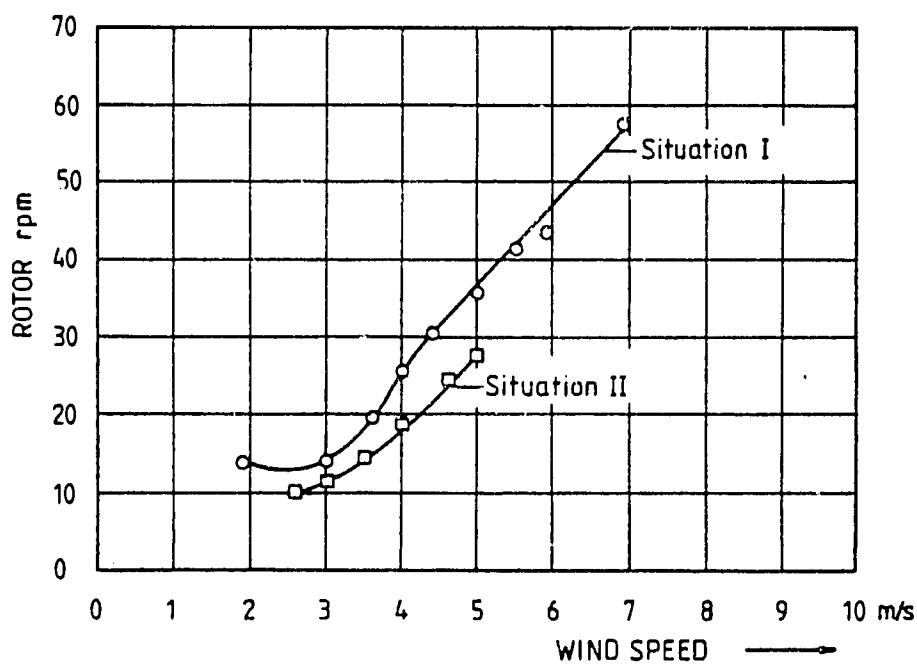
$$q = 0.0159\ v^3$$

for subsequent v's the output is computed; see Table 8.

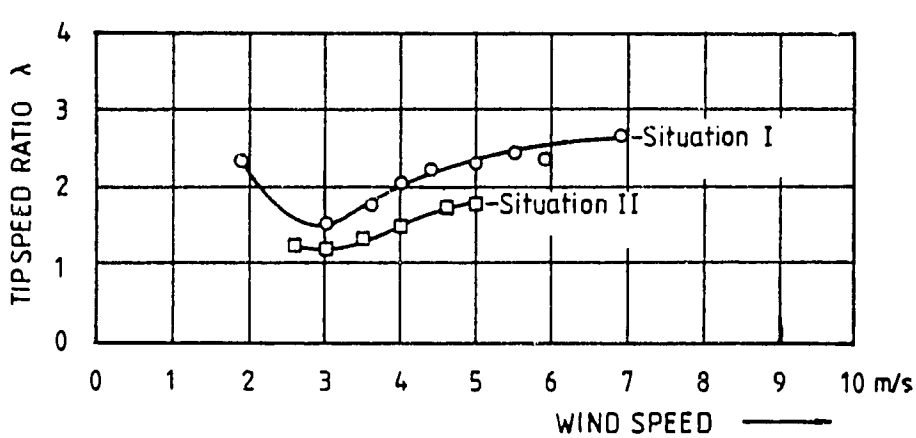
SYSTEM EFFICIENCY
VERSUS
WIND SPEED




ROTOR rpm
VERSUS
WIND SPEED




TIP SPEED RATIO
VERSUS
WIND SPEED




Figures 16, 17 and 18 : Windmill characteristics of the WTGS windmill in Mochudi.

| v m/s | q $m^3/h$ |
|---|---|
| 1 | 0.016 |
| 2 | 0.13 |
| 3 | 0.43 |
| 4 | 1.02 |
| 5 | 1.99 |

Table 8 : Reference curve

The rotor speed versus wind speed is displayed in Figure 17.

The tip speed ratio is calculated by using the following formula:

$$\lambda = \frac{2\pi nR}{v\ 60}$$

or with a rotor radius of R = 3.1 m, it reduces to:

$$\lambda = 0.325\ n/v$$

with n = rotor speed in rpm
and v = wind speed in m/s.

The result of this calculation with the subsequent wind speeds and corresponding rotor speeds are listed in Table 6.1, Appendix 6 and visualised in Figure 18.

## 6.3 Blade design

As mentioned already in Chapter 1.5, the rotor was designed with the following parameters:

| | |
|---|---|
| Rotor radius | :3.1 m |
| Number of blades | :8 |
| tip speed ratio | :2.5 |
| Type of blades | :arched steel plates with tube on concave side and a curvature of 7% |

For this blades the Cd/Cl ratio is 0.05, the angle of attack 5° and the lift coefficient Cl=0.9.

Calculating the blades according to litt.1 yields the following values for chords and blade setting angles; whereby the blades have been linearized at 0.5 R and 0.9 R, for chords and blade setting angles:

| | | | |
|---|---|---|---|
| chord at the tip | : 0.33 m | setting angle | : 8° |
| chord at the foot | : 0.62 m | setting angle | : 26° |

However, the blades have been made with a curveture of 10 %, for which other values for the lift coefficient and angle of attack have to be taken; 4° and Cl=1.1 respectively.

The corresponding chords and setting angles would than be:

| | | | |
|---|---|---|---|
| chord at the tip | : 0.27 m | setting angle | : 9° |
| chord at the foot | : 0.51 m | setting angle | : 27° |

With the used blades, with a foot chord of 0.60 m and a tip chord of 0.35 m, the tip speed ratio is calculated as $\lambda = 2.2$. The blade setting angles should be at the tip 11° and at the foot of the blade 30°.
This corresponds (by accident?) quite well with the observed blade setting angles of 12° and 30° at the tip and the foot of the blade respectively.

The rotor efficiency is with these blades reduced from 0.36 to 0.35 and the torque coefficient is increased from 0.14 to 0.16. The starting torque has increased from 0.08 to 0.11.

Although the original design parameter for a tip speed ratio of 2.5 is not met with these blades, it is reccomended to keep on using these blades. The positive gain in torque coefficient and starting torque is considered to be more important than the very small loss in rotor efficiency.
The smaller rotor speed is easy to compensate by a slightly increased transmission ratio.

## 6.4 Transmission ratio

The transmission ratio of the WTGS windmill in Mochudi is 8.5.
The starting torque of the mono pump was measured as about 30 Nm (after it has been standing still for one hour or more).
With a starting torque coefficient of the windmill of 0.11, this would result in a start wind speed of 7 m/s if the windmill would have been directly connected to the mono pump. This clearly indicates that a device to overcome the very high starting torque of the mono pump is a absolute necessity.

The power required by the pump to lift a minimal flow of 0.1 m3/h is 10 Watt. This amount of power is generated by the windmill at a wind speed of 2.4 m/s (at a total system efficiency of 0.045; see Figure 16, which includes the pump efficiency).
The pump delivers this flow at about 100 rpm, whereas the rotor speed at a wind speed of 2.4 m/s is about 9 rpm.
The transmission ratio would than have to be 100/9= 10.8
and the clutch should engage at a pump drive speed of 100 rpm.
The torque developed by the windmill at this wind speed is 4.2 Nm, whereas the torque required by the pump, once it rotates, is about 2 Nm. So the system is stable.
The condition is, however, that the clutch engages at once when the pump drive speed is reached. If not, i.e if the clutch starts slipping, than the stored energy in all the rotating parts of the windmill will be dissipated by the clutch. This will slow the windmill down till a equilibrium is reached between the power developed by the windmill and the power dissipated by the clutch. If the wind speed increases, the clutch simply dissipates more energy, because the speed increases, resulting in a increased force of the brake shoes against the brake drum. Only if this force has reached a value high enough to develop sufficient friction, the brake out torque of the pump is reached. This will only be the case at very high (momentaneous) wind speeds.

It is observed that if the clutch engages at once, the momentum of the windmill at the start speed of 2.4 m/s is sufficient to overcome the brake

out torque of the pump.

**This implies also that with a proper working clutch the windmill pump system is not sensitive to individual deviating mono pumps with lower or higher starting torques.**
It also implies that a lower starting torque of a individual mono pump does not lead to a higher output. On the contrary, in general, a lower starting torque implies a more loose fit of the mono pump rotor in the stator, resulting in a lower volumetric efficiency of the pump. This would affect the output in a negative sense.
For practical reasons, the engagement speed of the clutch should be set at 100 rpm. A much lower speed is not possible because the space needed for the fly weights on the brake shoes is limited. A much higher speed would result in a output loss. At a pump speed of 100 rpm the flow rate is about 0.1 m3/h. Lower flow rates do not really contribute to the water output. Because the flow rate of a mono pump at a particular pump speed is hardly affected by the total head, the engagement speed of the clutch may be taken the same for all heads.

The transmission ratios to be used for various heads have been listed in Table 9.

| head m | transmission ratio | start speed m/s |
|---|---|---|
| 20 | 13.0 | 2.0 |
| 30 | 11.2 | 2.3 |
| 40 | 10.4 | 2.5 |
| 50 | 9.6 | 2.7 |
| 60 | 9.3 | 2.8 |
| 70 | 8.6 | 3.0 |
| 80 | 8.3 | 3.1 |
| 90 | 7.9 | 3.3 |
| 100 | 7.6 | 3.4 |

Table 9 : Transmission ratios for different heads

The output at other heads than the WTGS windmill in Mochudi may easily be calculated by multiplying the normalized output with the difference in transmission ratio and taking into account the different starting speed. For example, if one wants to know the output at a head of 80 m, multiply the normalized output at 36.5 m with 8.3/10.8= 0.77 and synthesize these with the frequency distribution of wind speeds for those wind speeds higher than the start wind speed concerned.
Note that, although the head is more than doubled in this example, the output is more than halve, depending on the specific distribution of wind speeds.

## 6.5 Mono pump

The mono pump used for the windmill installation is a ES-15 with a maximum flow rate of approximately 6 m3/h at a maximum speed of 1500 rpm. See for the typical average pump capacity Appendix 6, Figure 6.1.
According to manufacturerer's specifications, the efficiency at a head of 36.5 m is about 70 %, however, other sources mention efficiencies of 40 %. The flow rate is a lineair function of the speed; at low speeds however,

the relation is strongly depending on the specific fit of the rotor in the stator.
In figure 19, the relation between flow rate and speed has been displayed.

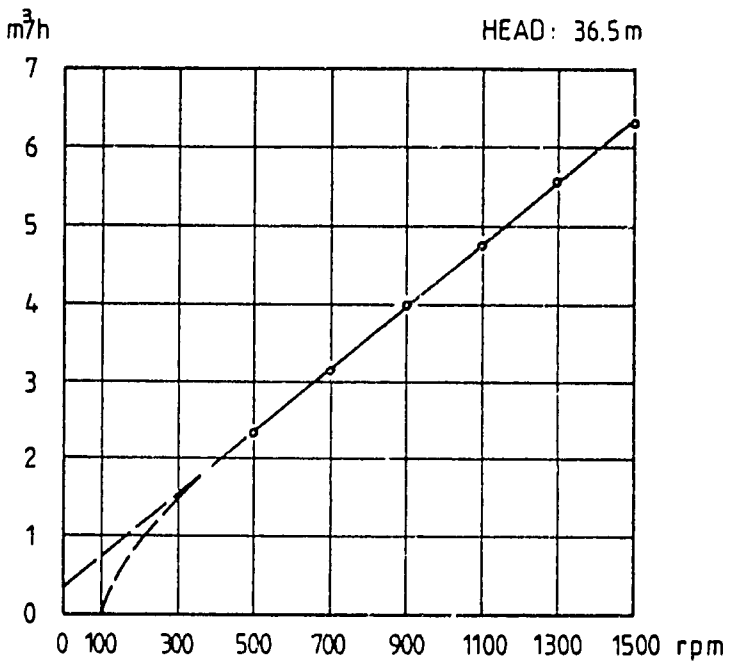



Figure 19 : Flow rate versus speed of the Mono pump

This curve has been derived from the the first graph in Appendix 6 for a head of 36.5 m. It may be concluded that the manufactures specifications are slightly optimistic; the straight extrapolated part of the curve, which represents a perfect leakfree fit of the rotor, indicates still an output of 0.4 m3/h at a speed of zero! Because there will be always some leakage between the rotor and stator of the pump, the real curve will lie more or less under the displayed one, depending on the fit of the rotor. The real position of the curve may only be assessed by measuring the flow rates at different constant speeds and will vary from pump to pump. This means also that as long as the specific pump curve is not known, comparing two windmill installations, although driving the same type of pump and with the same head, becomes a tricky affair. A second complication is the starting torque of the pump, which is different for each individual pump. There is however a relation between the starting torque of the pump and the pumpcurve (at low speeds). The more loose fit of the rotor, the less the starting torque and the higher the minimum speed required before the pump delivers any water. The fit of the rotor is not only a matter of a individual pump but also changes by the running hours the pump makes.

Because, for a specific application, an individual pump may be selected on the type of fit of the rotor, it is important to know which fit gives the best overall results. This depends on the type of drive used for the pump. For the WTGS windmill with the automatic clutch to overcome the starting torque a rather good fit seems to be the best option. This will guarantee a good discharge at low speeds.

For the RIIC windmill with the permanent variomatic windmill-pump coupling a more loose fit might be a better option. This will help the windmill to start easier.

Another characteristic of the Mono pump is that the starting torque is not constant. The starting torque depends on the time elapsed since the pump stopped. From zero to one hour this relation is about exponential. Due to the nature of the stator material the water film between rotor and stator is being pressed away when the pump stands still. This results in a material to material contact creating a sort of sticky holding of the rotor. This behaviour is responsible for the very high starting torques of the pump after it has been standing still for an hour or more.

Recently, Monopump S.A. has developed a new material for the stator of the Mono pump. An all nitrile rubber stator replaces the 90% natural 10% nitrile rubber used in the standard Mono pumps. This material would have two characteristics which makes it more suitable than the old material being used. The new material does not absorb water and this makes the starting torque more controllable and constant over time. Secondly, it does not have a "memory" and therefore it maintains its original starting torque.
The reduction in starting torque was predicted considerably.
It is however not expected that a WTGS windmill with a proper working clutch will have a better performance with this new pump type. With a not proper working clutch, the performance will of course be improved. Also with this new pump type, a proper working clutch is a neccesity.

# 7 COSTPRICE WINDMILLS

In this chapter the costs of the WTGS windmill-pump system are calculated. Details are given in Appendix 7. These costs are based on the actual costs which were made for the construction of the second and third windmill. The prices are based on the April 1985 market situation in Botswana. For most windmill materials the prices are given in Appendix 7. All prices and costs are given in the local currency Pula. In April 1985 the exchange ratio was about: 1 Pula = US $ 0.58 or 1 Pula = Dfl 2.13.

Also the cost of the RIIC windmill is presented in this Chapter and the total investment costs for both systems are compared.

## 7.1 Costprice WTGS windmill

| | | | |
|---|---|---|---|
| Material | | | |
| Tower | P 634 | | |
| Chassis | P 1478 | | |
| Tail | P 123 | | |
| Rotor | P 229 | | |
| Rotor shaft assembly | P 270 | | |
| Transmission | P 712 | | |
| Belt tensioner | P 59 | | |
| Clutch | P 265 | | |
| Paint | P 52 | | |
| Subtotal | | P 3822 | |
| Labour | | P 1529 | |
| Installation costs | | P 383 | |
| Profit 10% | | P 573 | |
| Total | | | P 6307 |

Additional costs
(depending on distance to site)

| | | |
|---|---|---|
| Transport costs (10 tons truck for windmill parts - 1 trip) | 80 thebe/km | |
| Travel costs (2 trips) | 40 thebe/km | |
| | | P 1,60/km |

Remark: The additional costs are based on 1 trip with a 10 tons truck whereby all the windmill parts are brought to the site as well as all other materials needed for building the foundation, help devices for errection of the windmill, etc. The 2 trips for travel costs are based on 1 trip for building the foundation and all other preparatory works, and after curing

the concrete foundations (say 5 days), 1 trip for the actual errection of the windmill. The costs of the materials and labour required for the installation are already included in the "Installation costs", as these are not depending on the distance to the site.

## 7.2 Costprice RIIC windmill

According to RIIC the costprice of the 6.2 m diameter RIIC windmill is about P 8700. This includes labour and profit. Labour required for building one machine was specified as P 4400 (about 1000 hours); material costs for one machine were specified at P 4300.
It was expected that, once the machine would be built in bigger series the costprice would go down.
The costprice includes the installation of the windmill.

## 7.3 Comparing investment costs of RIIC and WTGS windmill

The RIIC and WTGS windmill in Mochudi were both sold to BRET.
The total costs for both machines are listed below.

| | RIIC windmill Pula | WTGS windmill Pula |
|---|---|---|
| windmill | 8500 | 9500 |
| installation costs windmill | incl. | 1200 |
| monopump, rods, pipe, head | 1900 | 1700 |
| tank | 450 | 450 |
| plumbing to tank | 500 | 500 |
| labour for installing tank and plumbing etc. (about 2 days) | 500 | 500 |
| labour for installing mono pump (about 1 day) | 250 | 250 |
| TOTAL | 12100 | 14100 |

In case the WTGS windmill costs and installation costs are calculated according the costprice analyses presented in this Chapter, the windmill would cost P 6307 and the transport and travel costs would be (distance Mochudi- Kanye = 175 km): 2 x 175 km x P 1.60/km = P 560.
This brings the total investment costs to P 10267.

The main difference in costprice of the two windmills is caused by the difference in the number of labour hours to built the windmills:

| | RIIC windmill | WTGS windmill |
|---|---|---|
| material costs | P 4300 | P 3822 |
| installation costs | - | P 383 |
| labour hours | 1000 h | 457 h |
| hours valued at (incl.profit) | P 4.40/h | P 4.50/h |
| total labour costs | P 4400 | P 2057 |
| transport and travel | - | P 560 |
| minus mono head pulley | - | 200 (-) |
| Total | P 8700 | P 6622 |

However, as stated by the RIIC staff it may be possible to bring down the number of hours required to built one RIIC windmill.
On the other hand the number of hours for building one WTGS windmill (traced from the Job-cards of MOMOSO) might be well on the low side, caused by inaccurate accounting for the indirect hours related to building the machine.
If the indicated costprice reduction (chapter 7.4) would be applied, the price of the WTGS windmill would decrease by about (181+10+10%) P 210.

It may be concluded that the WTGS windmill will be most probably around 20 % cheaper than the RIIC windmill.

## 7.4 Costprice reduction of the WTGS windmill

The costprice of the present WTGS windmill tower could easily be reduced by using a smaller size angle iron for the top section and all cross bracings, without affecting the strength of the tower.
This is possible because the buckling lengths towards the top of the tower become gradually smaller.
It is suggested to change all angle irons 50x50x5 into 40x40x4 exept for the towerlegs of the bottom section and to change all cross bracings from 30x30x5 into 30x30x4.

The costprice of the tower would than become:

| material | | length mm | weight kg | cost P |
|---|---|---|---|---|
| angle iron | 50x50x5 | 18000 | 68 | P 68 |
| | 40x40x4 | 103854 | 251 | P 251 |
| | 30x30x4 | 41280 | 73 | P 73 |
| misc. (10%) | | | 39 | P 39 |
| | | | 431 | P 431 |
| waste (5%) | | | | P 22 |
| TOTAL | | | | P 453 |

This is a costprice reduction of P 181 and a weight reduction of 173 kg (=29%).

By complete redesigning the tower, even a higher weight- and costprice reduction would be possible.

On other components of the windmill also some small weight and costprice reductions are possible. For example the distance between rotor and tower could safely be reduced with 100 mm resulting in a 100 mm shorter chassis and rotor shaft. This would also contribute to a better functioning of the furling mechanism.
The savings on materials for the chassis and rotor shaft would be about P 10 only.

## 8. TESTING RESULTS OF THE CENTRIFUGAL CLUTCH

### 8.1 Introduction

On request of the WTGS the clutch was tested in a labatory situation at the Twente university of technology in the Netherlands in september 1984.
The purpose was to get more insight in the mechanism of the clutch and to establish the relation between the preload of the spring, the mass of the flyweights and the cut-in speed and cut-out speed and torque transmitted by the clutch.
The results of these measurements are described in this Chapter.
Also a theoretical model has been developed to describe the relation between the different parameters. With this model the behaviour of the clutch is described fairly well, so that on forehand the spring tension and flyweights may be determined in order to get a specific engagement speed.
The (by the WTGS reported) hysteresis was not found. This is explained by the interaction of windmill, clutch and monopump, whereby it seems that the disengagement speed is lower than engagement speed. This is, however, fully due to the characteristic of the monopump, which has a starting torque, much higher than its normal working torque, once it is moving. Because the hysteresis of the clutch is a very essential neccessity for a proper and efficient working of the clutch, suggestions have been made to achieve this feature.

Photo 10 - Centrifugal clutch

### 8.2 Test procedure

Using drawings and information available from the WTGS, the clutch was manufactured in the same way as in Botswana (Photo 10). In order to simulate the windmill a variable speed electric drive is used. The mono pump is simulated by an adjustable belt brake system. The brake torque and the speed of the drive are measured (Photo 11). By setting up increasing loads the driving speed at which the clutch is able to transmit the load has been determined. In this way the speed-torque characteristic of the clutch is established. This is carried out for several combinations of spring pre-load and flyweight masses, so that the influences of spring pre-load and mass of the flyweights on the speed-torque characteristic are established.

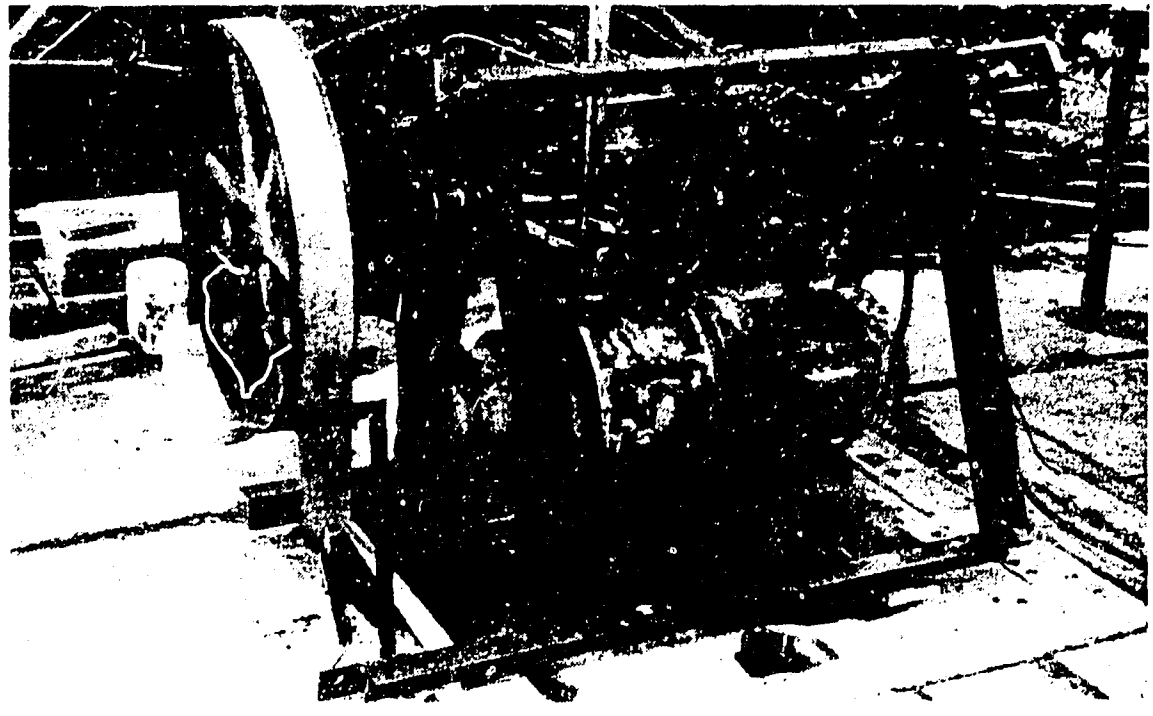


Photo 11 - Test arrangment with v riable speed drive and belt brake system

## 8.3 Measuring results

The measuring results are listed in Table 8.1, Appendix 8, and visualized in Figure 20.
Four tests have been performed with three different flyweights and 2 different spring tensions, with the following specifications:

Test A: flyweights: 0.308 kg each, spring tension 60 N and 78 N
Test B: flyweights: 0.463 kg each, spring tension 60 N and 78 N
Test C: flyweights: 0.771 kg each, spring tension 60 N and 78 N
Test D: flyweights: 0.771 kg each, spring tension 157 N and 170 N.

By drawing the curves through the measured points, the deflection of the points at higher torques have been deliberately ignored. These points do not represent correct values because due to the system of measurement "fading" occured at this part. The load applied on the brake drum was choosen such, that the clutch just could brake out. In this way the maximum friction force between brake shoe and drum could be established, at different drive speeds. The consequence of this system of measurement is that all the energy brought into the system is dissipated by friction between brakeshoes and drum and consequently converted into heat. This heat results in an increase in temperature of the friction material and affects the friction coefficient badly. This effect, known as fading, occurs in this test at an energy dissipation of approximately 1000 W.
In a normal windmill installation this level of energy dissipation i.e slipping of the clutch will not be reached.

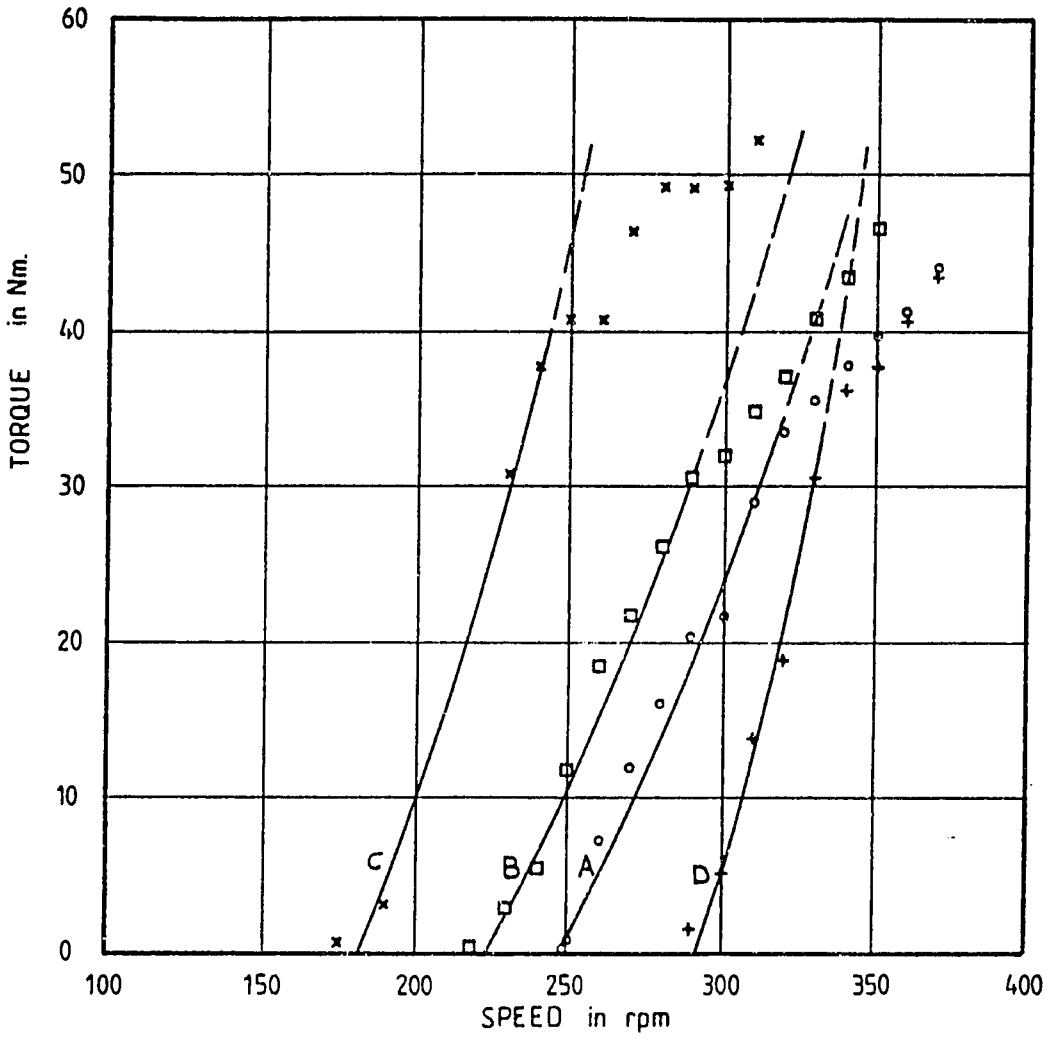



Figure 20 : Measured torque-speed curves of the clutch

## 8.4 Theoretical model of the clutch

It is possible to develop a mathematical expression of the characteristic of the clutch.
For this purpose first all the forces acting on the system have been analysed (see Figure 21) and the configuration of the different elements of the clutch have been determined. In order to calculate the friction forces exerted by the brake shoes on the brake drum as a result of the generated centrifugal forces, the centrifugal forces and their line of application are calculated first.

From the equation of equilibrium follows:

$$F1 \times a1 + F2 \times a2 + F3 \times a3 + F4 \times a4 = F5 \times a5 \qquad (8.1)$$

and

$$F5 = F1 + F2 + F3 + F4 \qquad (8.2)$$

whereby

F4 is the mass of the brake shoe without the mass of the pivoting bush and amounts 0.802 kg.

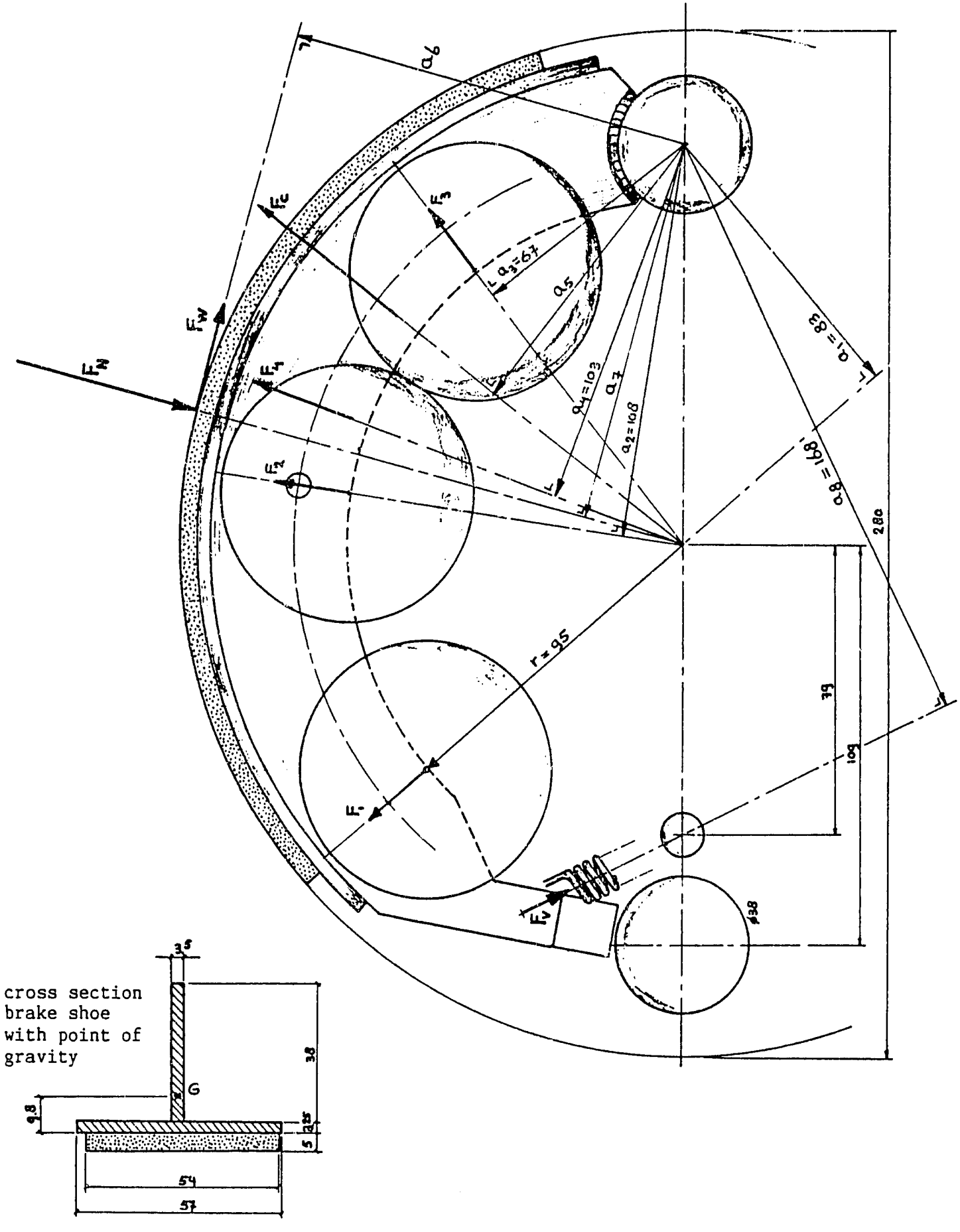



Figure 21 : Configuration of the brake shoe

F1 , F2 and F3 are equal and are the masses of the flyweights. For the test two different weights have been used:
for test A : 0.308 kg
for test B : 0.463 kg
for test C and D : both the weights = 0.771 kg.
a1 = 0.083 m
a2 = 0.108 m
a3 = 0.067 m
a4 = 0.103 m

Substituting the given values and equation (8.2) in (8.1) yields

for test A : a5 = 0.094 m
for test B : a5 = 0.092 m
for test C an D : a5 = 0.090 m.

This means that the total mass of flyweights and brake shoe may be thought concentrated at distances of 94, 92 and 90 mm respectively to the centre of the pivot of the brake shoe.

If the base plate with the brake shoes on it is rotating anti clock wise, the following equations are valid:

The equation of equilibrium with regard to the centre of the pivoting point is:

$$Fc \times a5 + Fw \times a6 - Fn \times a7 - Fv \times a8 = 0 \qquad (8.3)$$

whereby: $$Fw = Fn \times f \qquad (8.4)$$

and $$Fc = m\,\omega^2\,r \qquad (8.5)$$

whereby: Fc = centrifugal force excerted by the rotating mass of the brake shoe and flyweights on the brake shoe (N)
Fw = friction force excerted bij de brake drum on the brake shoe (tangentially directed) (N)
Fn = normal force excerted by the brake drum on the brake shoe (radially directed) (N)
Fv = force of the spring at the moment of engaging (N)
a5 = 0.092 m (the average of 90,92 and 94 mm has been taken)
a6 = see Figure 21 (m)
a7 = see Figure 21 (m)
a8 = 0.168 m
f = friction coefficient of the brake shoe friction material
m = total mass of brake shoe and applied fly weights (kg)
ω = speed of rotation of the base plate (rad/s)
r = radius of point of application for the centrifugal force (m)

Substituting (8.5) en (8.4) in to (8.3) yields

$$Fw = \frac{Fv \times a8 - m\,\omega^2\,r \times a5}{-(a7/f - a6)} \qquad (8.6)$$

This equation describes the friction force excerted by one brake shoe on the brake drum.

The term (a7/f - a6) is defined as a machine constant because it is not possible to predict at which point on the circumference of the brake shoe the resulting normal force and friction force will act. It is also not possible to calculate this (theoretical) point of application, because there are infinite combinations possible for one and the same value of the term.
We may however, indicate the ranges, which are possible for a7 , a6 and f, in order to see the possible range this defined machine constant could have.

| position on brake shoe: | near tip | middle | near foot |
|---|---|---|---|
| The range for a7 is: | 0.08 m | 0.109 m | 0.04 m |
| The range for al is: | 0.25 m | 0.14 m | 0.04 m |

the range for f is between 0.2 and 0.6

For these three positions and an average friction coefficient of 0.4 the machine constant would be:

| | |
|---|---|
| near tip : | - 0.05 m |
| middle : | 0.13 m |
| near foot : | 0.06 m |

After synthesizing the theoretical model with the measured curves a value of (a7/f-a6) = 0.0635 m has been found.

What actually is needed is a "self engaging" system. This self engaging effect would occur if the machine constant would be negative.
This is theoretically possible; it is within the range of possible values the machine constant may have.
Therefore it may be worthwile to remove all the friction material from the brake shoe exept for, say, 5 cm at the tip.
If the clutch is self engaging, slip will not occur anymore and the strong reduced area of friction material will not cause problems. The area of the friction material normally is determined by the amount of heat generated when the brake slips. If no slip occurs no energy will be dissipated and no heat generated.

The characteristics of the used springs are shown in Figure 22. For test A, B and C the spring extension was adjusted at 2.5 mm, resulting in a spring tension of 6.1 kg (60 N) and 8.0 kg (78 N) for spring A and spring B respectively. For test D the spring extension was adjusted at 11.5 mm, resulting in a spring tension of 16.0 kg (157 N) and 17.3 kg (170 N) for spring A and B respectively.
The indicated spring tension is achieved if the brake shoes are in contact with de brake drum. In rest position of the brake shoes the tension of the spring is less and depends on the free play which has been allowed.
Wear of the friction material of the brake shoes will consequently result in an increased spring tension and an increased speed of engagement.

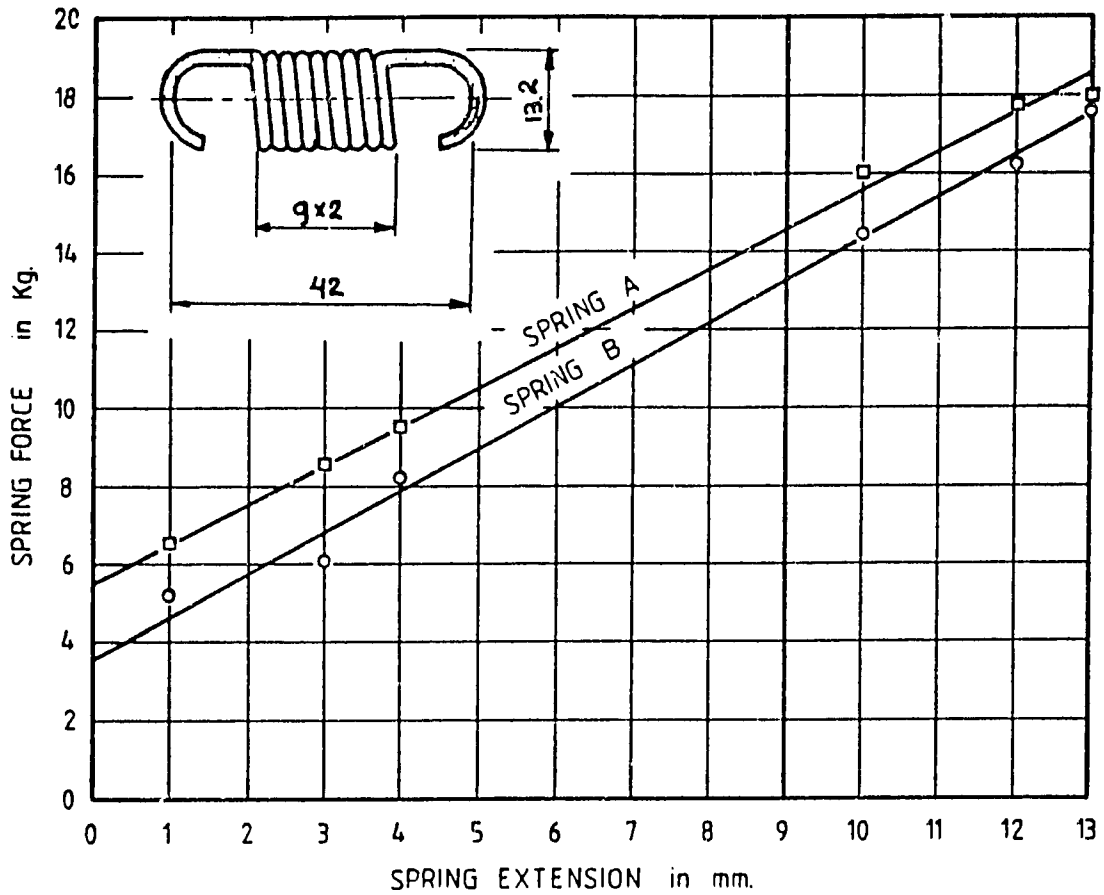



Figure 22 : Characteristics of the used springs

The torque transmitted by the two brake shoes may now be described by:

$$T = (Fw1 + Fw2) \times R \tag{8.7}$$

whereby
- T = torque transmitted by the clutch (Nm)
- Fw1 = friction force on one brake shoe (N)
- Fw2 = friction force on other brake shoe (N)
- R = internal radius of brake drum (m)

Substitution of (8.6) into (8.7) yields:

$$T = R \times \frac{(Fv1 + Fv2)\ a8 - 2\ m\ \omega^2\ r \times a5}{-\ (a7/f - a6)} \tag{8.8}$$

substituting the values for the 4 tests yields:

Test A : $T = 0.076\ \omega^2 - 51$
Test B : $T = 0.094\ \omega^2 - 51$
Test C : $T = 0.130\ \omega^2 - 51$
Test D : $T = 0.130\ \omega^2 - 121$

These equations have been graphically presented in Figure 23 and we may conclude that they fit nicely with the measured results of the tests.

This means that this theoretical model describes the characteristics of the clutch in a representative manner and that this model may be used for the calculation of a specific engaging speed of the clutch.

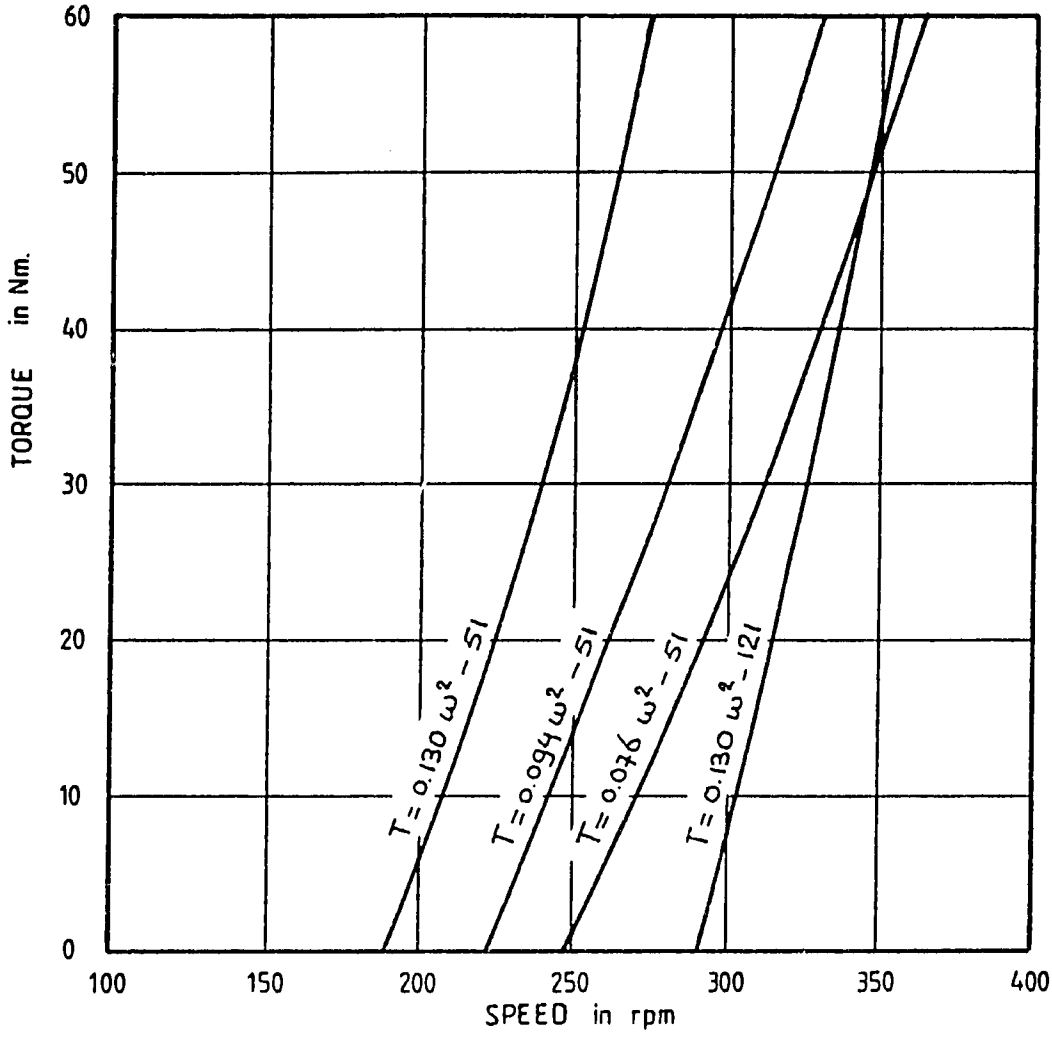



Figure 23 : Calculated Torque-speed curves of the clutch

This model also shows very clearly that the total mass applied for the fly weights should be as high as practically possible (limited by the space inside the brake drum), as this results in a (wanted) steap curve of torque-speed characteristic. The engaging speed is easy to adjust by the pre-load of the springs. One should take care that the pre-load of the two springs is exactly equal.

For a certain engagement speed the required spring tension may now easily be calculated with the above described model.
Suppose an engagement speed of 100 rpm is wanted, then the spring tension is calculated as follows:

$$T = 0.130\ \omega^2 - C \qquad (8.9)$$

with

$$C = R \times \frac{(Fv1 + Fv2)\ a8}{-\ (a7/f - a6)} \qquad \text{(= second part of (8.8))} \qquad (8.10)$$

At the moment of engagement the transmitted torque is zero or:

$$T = 0 \qquad (8.11)$$

Substitution of (8.11) in (8.9) yields:

$$C = 0.130\ \omega^2$$

For a speed of 100 rpm $\omega = \frac{2\pi n}{60} = 10.47$ rad/s

and

$$C = 0.130 \times 10.47^2 = 14.25$$

Substituting the known values in (8.10) yields

$$Fv_1 + Fv_2 = \frac{14.25 \times 0.0635}{0.14 \times 0.168 \times 9.8} = 3.9 \text{ kg}$$

The spring tension should therefore be 1.95 kg for each in order to achieve an engagement speed of 100 rpm.

# 9 CONCLUSIONS AND RECOMMENDATIONS

## 9.1 Conclusions

- In general the windmill seems of a sound design and rigid construction.

- The centrifugal clutch, which forms an essential component of this windmill does not function optimal. With a sound working clutch the output of the windmill could be increased with more than 50 % at the lower wind speeds.

- The furling mechanism is rather instable and acts at too low wind speeds already causing an unnecessarary reduction in output.

- At a monthly average wind speed of 3 m/s, the windmill will pump an average of 210 m3 per month with a pumping availability of 44 %. If the clutch and furling mechanism are modified, the figures would be 300 m3 at an availability of 67 % (over a head of 37 m).

- Especially the tower of the windmill is over-dimensioned. Redesigning the tower would result in a small costprice reduction of the windmill.

- If the windmill is properly built, maintenance is limited to lubricating the bearings occasionally.

- If proper drawings with a building manual would exist, Momoso should be able to built the windmill properly, without much or any guidance from the WTGS group.

- Momoso is not thought to be able to carry out drastic redesigning on the windmill; the theoretical knowledge about the working principle of the windmill and the interaction with the clutch and the pump is not adequately for this purpose.

- A careful conclusion is that the WTGS windmill is competitive with the RIIC windmill. The WTGS windmill pumps more water at lower investment costs.

- The problem of the high starting torque of a Mono pump can be easily overcome by the automatic centrifugal clutch once it has been redesigned. The system is not critical to deviations in starting torques of individual Mono pumps.

## 9.2 Recommendations

- A complete set of drawings with a small building manual should be made, not only in order to enable Mcmoso to built a sound windmill, but also to enable other interested parties outside Botswana to built this windmill. WTGS has no objections against using their design by other parties outside Botswana, provided that the redesigning of the clutch and improving the furling mechanism has been carried out.

- The clutch should be redesigned.

- The functioning of the furling mechanisme should be improved.

- The tower should be redesigned in order to reduce the costprice and weight of the present tower.

- The manual furling system needs modification in order to make it possible for one person to operate. With the present system two persons are required.

APPENDIX 1

# TERMS OF REFERENCE

# FOR A MISSION TO BOTSWANA

Executor : The TOOL Foundation (Technical Development with Developing Countries)

Under commission of: The Wild Geese Foundation

1. Testing the WTGS/Momoso windmill-monopump combination by means of:

   a) measurement of the input-output relation and determining the overall efficiency of the system;
   b) determining influence of the blade angles on the starting behaviour and overall efficiency of the system;
   c) determining optimal gear ratio;
   d) behaviour of centrifugal starting device.

2. To advice about technical improvements, costreduction and efficient manufacturing.

3. To discuss the possibilities for WTGS/Momoso to construct, install, maintain and marketing the windmill.

4. To assess the conditions under which the windmill system can be attractive. Taking account of the time constraint, possible locations for installing windmills for the benefit of target groups like schools, hospitals and other social institutes, will be identified, taking in consideration technical and social-economical viability.

5. To report about the findings and give recommendations about the follow-up if required.

   a) a provisional report will be made during the mission in Botswana and discussed with the WTGS/Momoso;
   b) a concept of the final report will be made after completion concluding desk study in the Netherlands and sent to TOOL;
   c) with the inclusion of WTGS and TOOL's comments, the report is finalized.

6. The mission is under commission of the Wild Geese Foundation and to assist WTGS/Momoso on their request. TOOL is responsible for executing the mission and reporting to Wild Geese Foundation.

APPENDIX 2

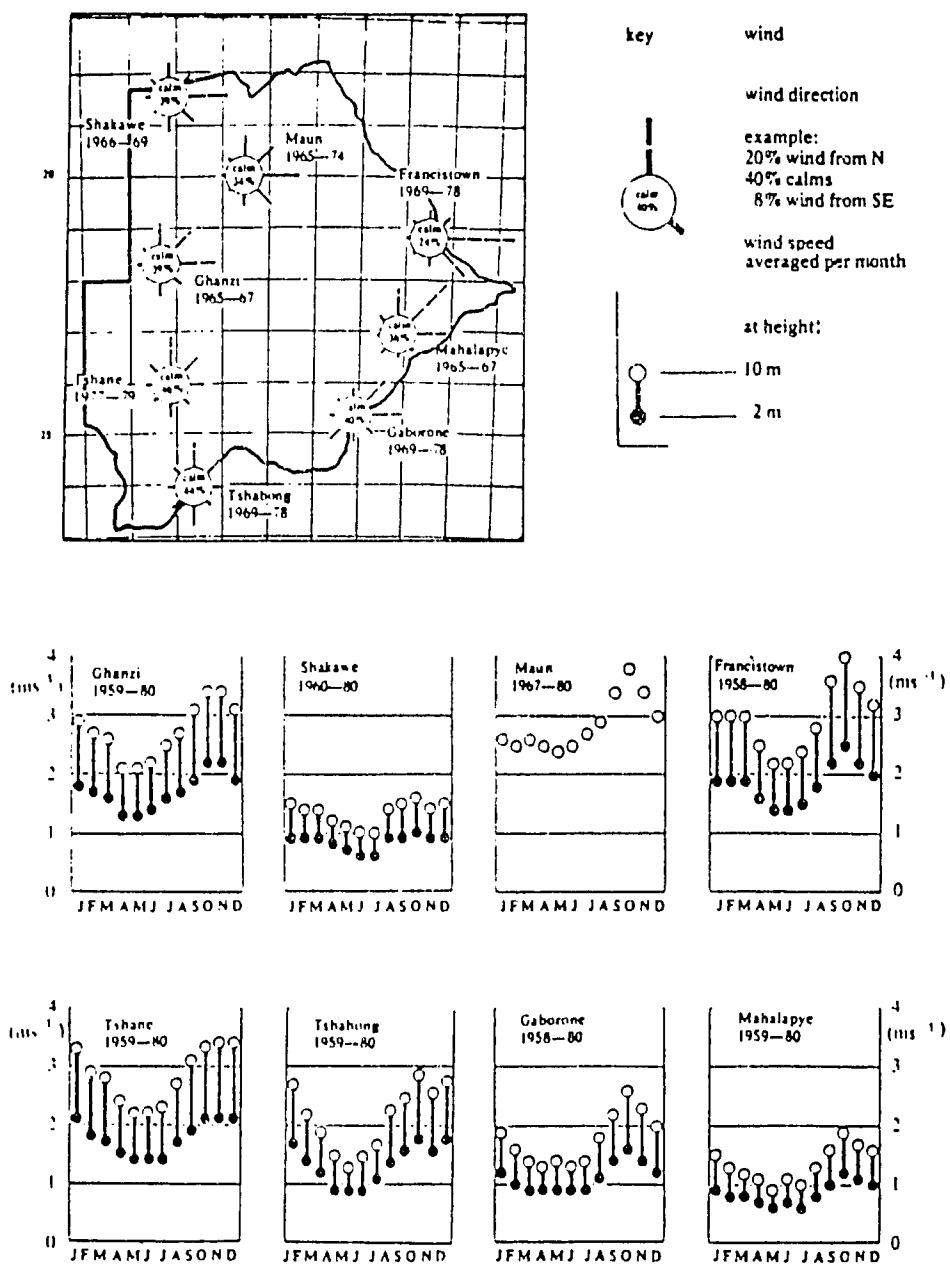



Figure 2.1 : Wind speed averages per month for selected stations in Botswana. (v10 is extrapolated from v2 : v10 = 1.6 v2). Source: The climate of Botswana in Histograms, Botswana Notes and Records, Volume 16, by J. Andringa.

APPENDIX 2 (continued)

Wind speed distribution at the WTGS windmill site in Mochudi monitored by the BRET monitoring equipment (1985).

| wind speed bin km/h | Jan/Febr 9/1-14.17h 1/3-12.00h in perc. | March 1/3 2/4 in perc. | April 2/4 29/4 in perc. |
|---|---|---|---|
| < 2 | 8.6 | 12.5 | 19.1 |
| 2 - 4 | 8.1 | 11.1 | 14.5 |
| 4 - 6 | 11.2 | 15.8 | 15.1 |
| 6 - 8 | 11.8 | 13.4 | 13.2 |
| 8 -10 | 12.3 | 11.4 | 10.4 |
| 10 -12 | 12.7 | 9.7 | 8.0 |
| 12 -14 | 11.5 | 8.4 | 6.2 |
| 14 -16 | 9.1 | 6.1 | 4.8 |
| 16 -18 | 6.3 | 4.3 | 3.4 |
| 18 -20 | 3.9 | 2.9 | 2.0 |
| 20 -22 | 2.1 | 1.7 | 1.2 |
| 22 -24 | 1.1 | 1.0 | 0.8 |
| 24 -26 | 0.6 | 0.6 | 0.4 |
| 26 -28 | 0.3 | 0.4 | 0.3 |
| 28 -30 | 0.2 | 0.2 | 0.3 |
| >30 | 0.2 | 0.4 | 0.5 |

Table 2.1 : Wind speed distribution at the WTGS windmill site in Mochudi.

Wind speed distribution at the WTGS windmill site in Mochudi converted in to m/s bins.

| wind speed bin m/s | Jan/Febr. % | March % | April % |
|---|---|---|---|
| 0 - 1 | 15.1 | 21.4 | 30.7 |
| 1 - 2 | 19.9 | 26.1 | 25.9 |
| 2 - 3 | 22.1 | 20.6 | 18.9 |
| 3 - 4 | 20.9 | 15.4 | 12.0 |
| 4 - 5 | 13.6 | 9.2 | 7.2 |
| 5 - 6 | 5.6 | 4.3 | 3.0 |
| 6 - 7 | 1.9 | 1.7 | 1.3 |
| 7 - 8 | 0.6 | 0.7 | 0.6 |
| > 8 | 0.3 | 0.5 | 0.7 |

Table 2.2 : Wind speed distribution at the WTGS windmill site in Mochudi in m/s.

APPENDIX 3

CALIBRATION OF ÆOLIEN KINETICS A 010649 / 5 ANEMOMETER

31 AUG 1984

SOURCE: H. SCHOTTE W.E.G. T.H.E. R - 697 - S JAN. 1985

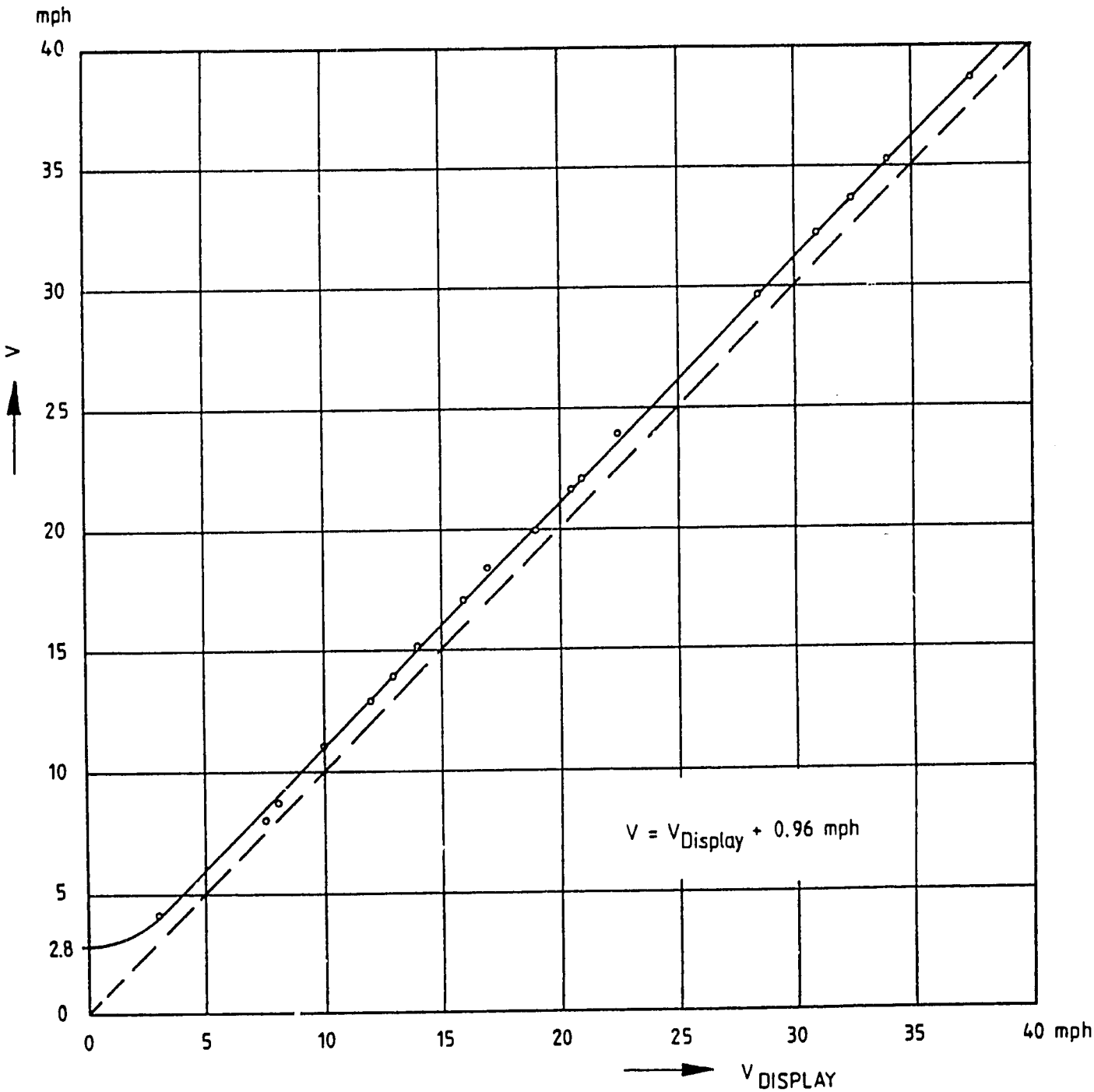



Figure 3.1 : Calibration curve of "TOOL" anemometer assessed by CWD at the university of Technology in Eindhoven, August 1984.

APPENDIX 3 (continued)

Weekly average wind speeds monitored by the BRET monitoring equipment at the RIIC windmill site and the WTGS windmill site both in Mochudi.

| week no. | v RIIC m/s | v WTGS m/s |
|---|---|---|
| 2 | 2.22 | 2.81 |
| 3 | 1.89 | 2.56 |
| 4 | 2.27 | 2.99 |
| 5 | 2.26 | 3.05 |
| 6 | 1.61 | 2.39 |
| 7 | 1.70 | 2.43 |
| 8 | 1.58 | 2.41 |

Table 3.1 : Weekly average wind speeds at RIIC and WTGS windmill site.

| WTGS vb m/s | Mochudi vt m/s | RIIC vb m/s | Mochudi vt m/s | WTGS vb m/s | Shoshong vt m/s |
|---|---|---|---|---|---|
| 2.37 | 2.11 | 1.27 | 1.76 | 0.78 | 0.92 |
| 3.55 | 3.24 | 3.69 | 4.00 | 2.32 | 2.47 |
| 1.61 | 1.34 | 3.89 | 4.20 | 2.63 | 2.77 |
| 4.09 | 3.80 | 3.28 | 3.61 | 1.85 | 1.73 |
| 2.16 | 1.87 | 2.14 | 2.48 | 1.35 | 1.54 |
| 2.87 | 2.64 | 2.89 | 3.20 | 4.44 | 4.53 |
| 2.00 | 1.70 | 2.83 | 3.22 | 7.02 | 7.07 |
| 1.78 | 1.07 | 1.57 | 1.99 | 5.30 | 5.31 |
| 2.94 | 2.78 | 1.34 | 1.77 | 3.61 | 3.68 |
| 2.54 | 2.42 | 1.31 | 1.68 | 1.56 | 1.30 |
| 2.93 | 2.77 | | | 1.13 | 0.85 |
| 2.54 | 2.37 | | | 4.40 | 4.32 |
| 2.53 | 2.31 | | | 7.36 | 7.29 |
| 2.64 | 2.65 | | | 6.99 | 6.94 |
| | | | | 6.33 | 6.37 |

Table 3.2 : Comparison of the BRET anemometers with the TOOL anemometer (uncorrected values).

**Koninklijk Nederlands Meteorologisch Instituut**

Voor de revisie.

**IJkbewijs**

No.9379/k

Soort instrument: Wind prospector

Schaalverdeling: in Mph

Fabrikant: Rhode Island

Nummer: A 010649

Schaalbereik van 0 tot 100 mph

De volgende correcties gelden:

| | mph. | corr. in mph |
|---|---|---|
| bij | 40 | - 0.4 |
| bij | 35 | + 0.2 |
| bij | 30 | + 0.3 |
| bij | 25 | + 0.5 |
| bij | 20 | + 0.4 |
| bij | 15 | + 0.7 |
| bij | 10 | + 0.7 |
| bij | 5 | + 0.6 |
| bij | 2 | + 1.5 |

Bijzonderheden:

De ijknauwkeurigheid bedraagt 0.1 m/sec

Aanloopsnelheid = 2.8 mph.

Geldigheidsduur ijking 2 jaar

DE BILT, mei, 19 85

Het Hoofd van de Instrumentele Afdeling van het Kon. Ned. Meteor. Instituut,

(Ir. L.H.C.C. van den Enden)

Het K.N.M.I. aanvaardt geen geldelijke aansprakelijkheid terzake van de eventuele gevolgen van verrichte ijkingen. Dit ijkbewijs bevat geen garantie in voor de deugdelijkheid en de goede werking van het instrument.

Table 3.3 : Calibration certificate of the "TOOL" anemometer assessed by KNMI De Bilt, May 1985.

APPENDIX 4

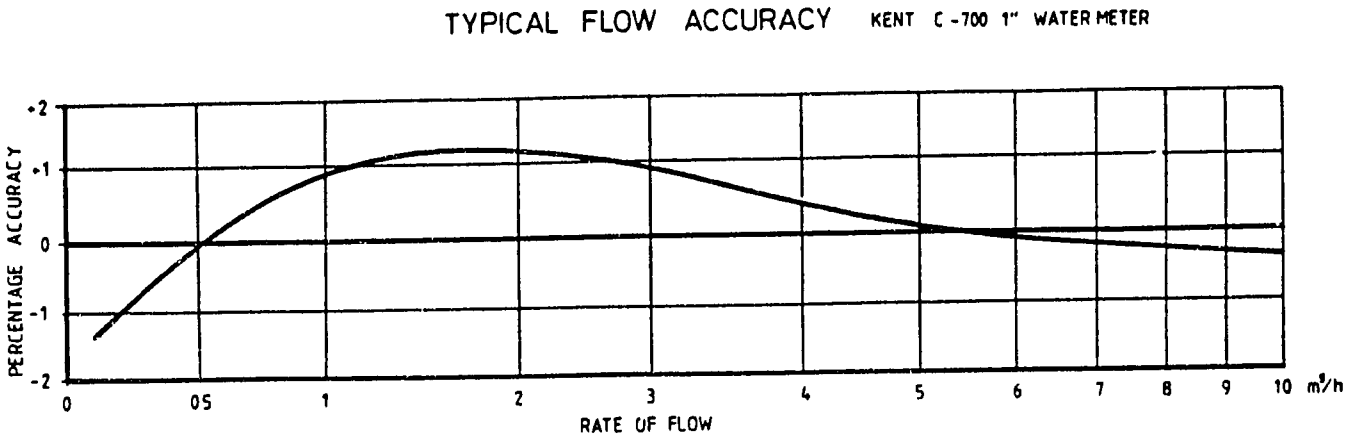



Figure 4.1 : Typical flow rate accuracy of watermeter

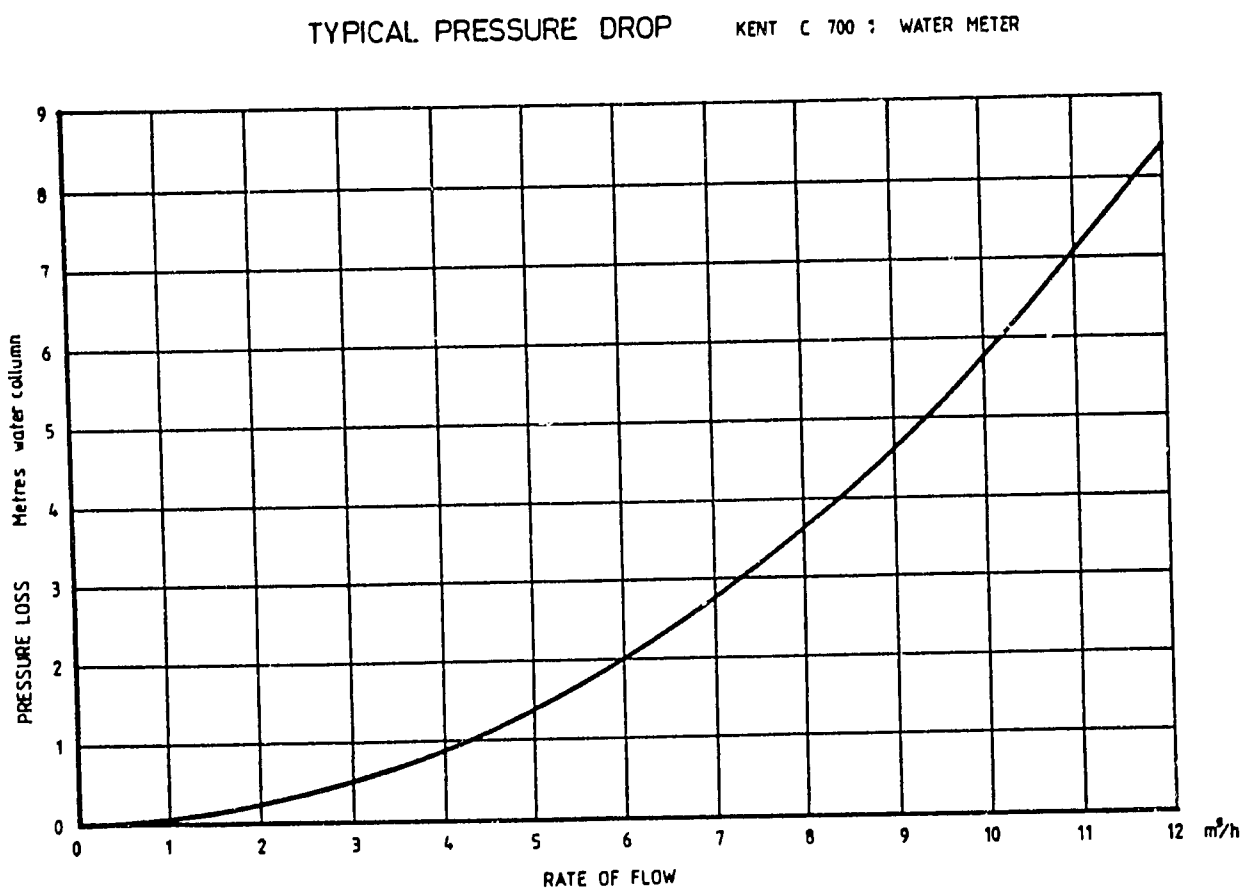



Figure 4.2 : Typical pressure drop of watermeter.

APPENDIX 4 (continued)

Measuring data on the WTGS windmill in Shoshong.

Windmill : WTGS 1 st protocype
Pump : Mono pump ES 15
Total head : 33.4 m

| Date 1985 | Wind speed m/s | Time interval s | Number of shaft rev. - | Pump drive speed rpm | Output m3/h |
|---|---|---|---|---|---|
| 24/4 | 2.6 | 600 | 311 | 98 | 0 |
| - | 2.0 | 600 | 255 | 80 | 0 |
| - | 2.7 | 600 | 464 | 146 | 0.30 |
| - | 2.5 | 600 | 337 | 106 | 0 |
| - | 2.4 | 600 | 375 | 118 | 0 |
| - | 3.2 | 600 | 474 | 149 | 0.23 |
| - | 2.7 | 600 | 568 | 179 | 0.43 |
| - | 3.3 | 600 | 571 | 180 | 0.36 |
| - | 3.1 | 600 | 650 | 205 | 0.61 |
| - | 2.5 | 600 | 384 | 121 | 0 |
| - | 2.6 | 600 | 436 | 137 | 0.16 |
| - | 2.2 | 600 | 226 | 71 | 0 |
| - | 2.8 | 600 | 374 | 118 | 0 |
| 25/4 | 7.6 | 600 | 633 | 199 | 0.55 |
| - | 8.0 | 600 | 447 | 141 | 0.27 |
| - | 7.4 | 600 | 447 | 141 | 0.30 |
| - | 7.8 | 1260 | 979 | 147 | 0.28 |
| - | 6.8 | 540 | 458 | 160 | 0.30 |
| - | 6.9 | 1200 | 949 | 149 | 0.31 |
| - | 6.3 | 600 | 489 | 154 | 0.27 |
| - | 5.5 | 2520 | 1687 | 127 | 0.16 |
| - | 5.8 | 480 | 419 | 165 | 0.11 |
| - | 5.2 | 900 | 764 | 160 | 0.29 |
| - | 4.5 | 600 | 462 | 146 | 0.20 |
| - | 3.5 | 600 | 314 | 99 | 0.02 |
| - | 3.4 | 900 | 495 | 104 | 0.02 |
| - | 2.5 | 600 | 264 | 83 | 0 |

Table 4.1 : Measuring data on the WTGS windmill in Shoshong.

APPENDIX 4 (continued)

Measuring data on the RIIC windmill in Mochudi.

Windmill : RIIC 5.2 m diameter
Pump : Mono pump ES 15
Total head : 36.5 m
Sampling time : 600 seconds

| Number of samples | Wind speed m/s | Shaft speed rpm | Output m3/h |
|---|---|---|---|
| 5 | 1.2 | 1 | 0 |
| 12 | 1.7 | 1 | 0 |
| 17 | 2.2 | 5 | 0.01 |
| 6 | 2.7 | 21 | 0.04 |
| 8 | 3.2 | 56 | 0.09 |
| 19 | 3.6 | 78 | 0.15 |
| 21 | 4.1 | 95 | 0.20 |
| 12 | 4.6 | 121 | 0.32 |
| 5 | 4.9 | 111 | 0.28 |

Table 4.2 : Measuring data on the RIIC windmill in Mochudi.

APPENDIX 5

Frequency distribution of wind speeds synthesized with normalized windmill output.

| Wind Speed v m/s | Spec. Output Q m³/h | Jan./Febr. | | March | | April | |
|---|---|---|---|---|---|---|---|
| | | Freq. | F x Q | Freq. | F x Q | Freq. | F x Q |
| 0.5 | | 0.151 | | 0.214 | | 0.307 | |
| 1.5 | | 0.199 | | 0.261 | | 0.259 | |
| 2.5 | | 0.221 | | 0.206 | | 0.189 | |
| 3.5 | 0.08 | 0.209 | 0.0167 | 0.154 | 0.0123 | 0.120 | 0.0096 |
| 4.5 | 0.66 | 0.136 | 0.0898 | 0.092 | 0.0607 | 0.072 | 0.0475 |
| 5.5 | 1.24 | 0.056 | 0.0694 | 0.043 | 0.0533 | 0.030 | 0.0372 |
| 6.5 | 1.67 | 0.019 | 0.0317 | 0.017 | 0.0284 | 0.013 | 0.0217 |
| 7.5 | 2.01 | 0.006 | 0.0121 | 0.007 | 0.0141 | 0.006 | 0.0121 |
| 8.5 | 2.17 | 0.003 | 0.0065 | 0.005 | 0.0109 | 0.007 | 0.0152 |
| Mean Pumping Output : m³/h | | | 0.226 | | 0.180 | | 0.143 |
| Monthly Pumping Output : m³ | | | 276 | | 138 | | 92 |
| Pumping Availability : | | 43 % | | 32 % | | 25 % | |

Table 5.1 : "Monthly" pumping output and pumping availability resulting from synthesizing the measured frequency distribution of wind speeds with the normalized windmill output I.

| Wind Speed v m/s | Spec. Output Q m³/h | Jan/Febr. | | March | | April | |
|---|---|---|---|---|---|---|---|
| | | Freq. | F x Q | Freq. | F x Q | Freq. | F x Q |
| 0.5 | 0 | 0.126 | | 0.225 | | 0.333 | |
| 1.5 | 0 | 0.243 | | 0.227 | | 0.289 | |
| 2.5 | 0 | 0.246 | | 0.220 | | 0.188 | |
| 3.5 | 0.08 | 0.186 | 0.0149 | 0.143 | 0.0114 | 0.107 | 0.0086 |
| 4.5 | 0.66 | 0.114 | 0.0752 | 0.081 | 0.0535 | 0.056 | 0.0374 |
| 5.5 | 1.24 | 0.058 | 0.0719 | 0.041 | 0.0508 | 0.028 | 0.0347 |
| 6.5 | 1.67 | 0.026 | 0.0434 | 0.019 | 0.0317 | 0.013 | 0.0217 |
| 7.5 | 2.01 | 0.010 | 0.0201 | 0.008 | 0.0161 | 0.006 | 0.0121 |
| 8.5 | 2.17 | 0.003 | 0.0065 | 0.003 | 0.0065 | 0.002 | 0.0043 |
| 9.5 | | 0.001 | | 0.001 | | 0.001 | |
| Mean Pumping Output : m³/h | | | 0.232 | | 0.170 | | 0.118 |
| Monthly Pumping Output : m³ | | | 284 | | 131 | | 76 |
| Pumping Availability : | | 40 % | | 30 % | | 21 % | |

Table 5.2 : "Monthly" pumping output and pumping availability resulting from the matched Weibull distributions synthesized with the normalized windmill output I. The time span has been taken the same as the time span during which the real frequency distributions were recorded as well as the real outputs.

APPENDIX 5 (continued)

| Wind Speed v m/s | Spec. Output Q m³/h | $\bar{v}$ = 2.0 m/s k = 1.3 | | $\bar{v}$ = 2.4 m/s k = 1.5 | | $\bar{v}$ = 2.8 m/s k = 1.8 | |
|---|---|---|---|---|---|---|---|
| | | Freq. | F x Q | Freq. | F x Q | Freq. | F x Q |
| 0.5 | | 0.333 | | 0.225 | | 0.126 | |
| 1.5 | | 0.289 | | 0.227 | | 0.243 | |
| 2.5 | | 0.188 | | 0.220 | | 0.246 | |
| 3.5 | 0.08 | 0.107 | 0.0086 | 0.143 | 0.0114 | 0.186 | 0.0149 |
| 4.5 | 0.66 | 0.056 | 0.0370 | 0.081 | 0.0535 | 0.114 | 0.0752 |
| 5.5 | 1.24 | 0.028 | 0.0347 | 0.041 | 0.0508 | 0.058 | 0.0719 |
| 6.5 | 1.67 | 0.013 | 0.0217 | 0.019 | 0.0317 | 0.026 | 0.0434 |
| 7.5 | 2.01 | 0.006 | 0.0121 | 0.008 | 0.0161 | 0.010 | 0.0201 |
| 8.5 | 2.17 | 0.002 | 0.0043 | 0.003 | 0.0065 | 0.003 | 0.0065 |
| 9.5 | | 0.001 | | 0.001 | | 0.001 | |
| Mean Pumping Output : m³/h | | | 0.118 | | 0.170 | | 0.232 |
| Monthly Pumping Output : m³ | | | 86 | | 124 | | 169 |
| Pumping Availability : | | 21 % | | 30 % | | 40 % | |

Table 5.3 : Monthly pumping output and pumping availability resulting from the matched Weibull distributions synthesized with the normalized windmill output I.
As time span has been taken an average month of 730 hours.

| Wind Speed v m/s | Spec. Output Q m³/h | $\bar{v}$ = 2.0 m/s k = 1.3 | | v = 2.4 m/s k = 1.5 | | $\bar{v}$ = 2.8 m/s k = 1.8 | |
|---|---|---|---|---|---|---|---|
| | | Freq. | F x Q | Freq. | F x Q | Freq. | F x Q |
| 0.5 | | 0.333 | | 0.225 | | 0.126 | |
| 1.5 | | 0.289 | | 0.227 | | 0.243 | |
| 2.5 | 0.10 | 0.188 | 0.0188 | 0.220 | 0.0220 | 0.246 | 0.0246 |
| 3.5 | 0.37 | 0.107 | 0.0396 | 0.143 | 0.0529 | 0.186 | 0.0688 |
| 4.5 | 0.78 | 0.056 | 0.0437 | 0.081 | 0.0632 | 0.114 | 0.0889 |
| 5.5 | 1.48 | 0.028 | 0.0414 | 0.041 | 0.0607 | 0.058 | 0.0858 |
| 6.5 | 1.04 | 0.013 | 0.0265 | 0.019 | 0.0388 | 0.026 | 0.0530 |
| 7.5 | > 2.2 | 0.006 | 0.0132 | 0.008 | 0.0176 | 0.010 | 0.0220 |
| 8.5 | > 2.2 | 0.002 | 0.0044 | 0.003 | 0.0066 | 0.003 | 0.0066 |
| 9.5 | > 2.2 | 0.001 | 0.0022 | 0.001 | 0.0022 | 0.001 | 0.0022 |
| 10.5 | | | | | | | |
| 11.5 | | | | | | | |
| 12.5 | | | | | | | |
| Mean Pumping Output : m³/h | | | 0.190 | | 0.264 | | 0.352 |
| Monthly Pumping Output : m³ | | | 139 | | 193 | | 257 |
| Pumping Availability : | | 40 % | | 52 % | | 64 % | |

Table 5.4 : Monthly pumping output and pumping availability resulting from the matched Weibull distributions synthesized with the normalized windmill output II.
As time span has been taken an average month of 730 hours.

APPENDIX 5 (continued)

| Wind Speed v m/s | Spec. Output Q m³/h | $\bar{v}$ = 3.2 m/s k = 1.9 | | $\bar{v}$ = 3.6 m/s k = 2 | | v = 4 m/s k = 2 | |
|---|---|---|---|---|---|---|---|
| | | Freq. | F x Q | Freq. | F x Q | Freq. | F x Q |
| 0.5 | | 0.087 | | 0.060 | | 0.048 | |
| 1.5 | | 0.198 | | 0.159 | | 0.132 | |
| 2.5 | | 0.230 | | 0.207 | | 0.181 | |
| 3.5 | 0.08 | 0.199 | 0.0159 | 0.202 | 0.0162 | 0.188 | 0.0150 |
| 4.5 | 0.66 | 0.140 | 0.0924 | 0.160 | 0.1056 | 0.163 | 0.1076 |
| 5.5 | 1.24 | 0.083 | 0.1029 | 0.107 | 0.1327 | 0.122 | 0.1513 |
| 6.5 | 1.67 | 0.042 | 0.0701 | 0.061 | 0.1019 | 0.080 | 0.1336 |
| 7.5 | 2.01 | 0.018 | 0.0362 | 0.030 | 0.0603 | 0.047 | 0.0945 |
| 8.5 | 2.17 | 0.007 | 0.0152 | 0.013 | 0.0282 | 0.024 | 0.0521 |
| 9.5 | | 0.002 | | 0.005 | | 0.011 | |
| 10.5 | | 0.001 | | 0.002 | | 0.005 | |
| 11.5 | | | | | | 0.002 | |
| 12.5 | | | | | | 0.001 | |
| | | | | | | | |
| | | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Mean Pumping Output : m³/h | | 0.333 | | 0.445 | | 0.554 |
| Monthly Pumping Output : m³ | | 243 | | 325 | | 404 |
| Pumping Availability : | 49 % | | 57 % | | 62 % | |

Table 5.5 : Monthly pumping output and pumping availability resulting from the assumed Weibull distributions with monthly average wind speeds of 3.2, 3.6 and 4.0 m/s resp. synthesized with the normalized windmill output I.
As time span has been taken an average month of 730 hours.

| Wind Speed v m/s | Spec. Output Q m³/h | $\bar{v}$ = 3.2 m/s k = 1.9 | | $\bar{v}$ = 3.6 m/s k = 2.0 | | $\bar{v}$ = 4.0 m/s k = 2.0 | |
|---|---|---|---|---|---|---|---|
| | | Freq. | F x Q | Freq. | F x Q | Freq. | F x Q |
| 0.5 | | 0.087 | | 0.060 | | 0.048 | |
| 1.5 | | 0.198 | | 0.159 | | 0.132 | |
| 2.5 | 0.10 | 0.230 | 0.023 | 0.207 | 0.0207 | 0.181 | 0.0181 |
| 3.5 | 0.37 | 0.199 | 0.0736 | 0.202 | 0.0747 | 0.188 | 0.0696 |
| 4.5 | 0.78 | 0.140 | 0.1092 | 0.160 | 0.1248 | 0.163 | 0.1271 |
| 5.5 | 1.48 | 0.083 | 0.1228 | 0.107 | 0.1584 | 0.122 | 0.1806 |
| 6.5 | 2.04 | 0.042 | 0.0857 | 0.061 | 0.1244 | 0.080 | 0.1632 |
| 7.5 | 72.2 | 0.018 | 0.0396 | 0.030 | 0.0660 | 0.047 | 0.1034 |
| 8.5 | 72.2 | 0.007 | 0.0154 | 0.013 | 0.0286 | 0.024 | 0.0528 |
| 9.5 | 72.2 | 0.002 | 0.0044 | 0.005 | 0.0110 | 0.011 | 0.0242 |
| 10.5 | | 0.001 | | 0.002 | | 0.005 | |
| 11.5 | | | | | | 0.002 | |
| 12.5 | | | | | | 0.001 | |
| | | | | | | | |
| | | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Mean Pumping Output : m³/h | | 0.474 | | 0.609 | | 0.739 |
| Monthly Pumping Output : m³ | | 346 | | 445 | | 539 |
| Pumping Availability : | 72 % | | 79 % | | 82 % | |

Table 5.6 : Monthly pumping output and pumping availability resulting from the assumed Weibull distributions with monthly average wind speeds of 3.2, 3.6 and 4.0 m/s resp. synthesized with the normalized windmill output II.
As time span has been taken an average month of 730 hours.

APPENDIX 6

Correction for air density.

The standard air density at 15°C, 1013 mb, dry air, is 1.225 kg/m3.

Correction for Mochudi conditions:
average temperature. : 25°C
altitude approx. 1000 m
average humidity : 50 %

At an altitude of 1000 m and a temperature of 20°C the air density of dry air is $\rho$ = 1.068 kg/m3

corrected for 25°C this becomes:

$\rho$ = 293/297 x 1.068 = 1.054 kg/m3

correction for an average humidity of 50 % yields:

$\rho$ = 0.944 x 1.054 = 1.048 kg/m3.

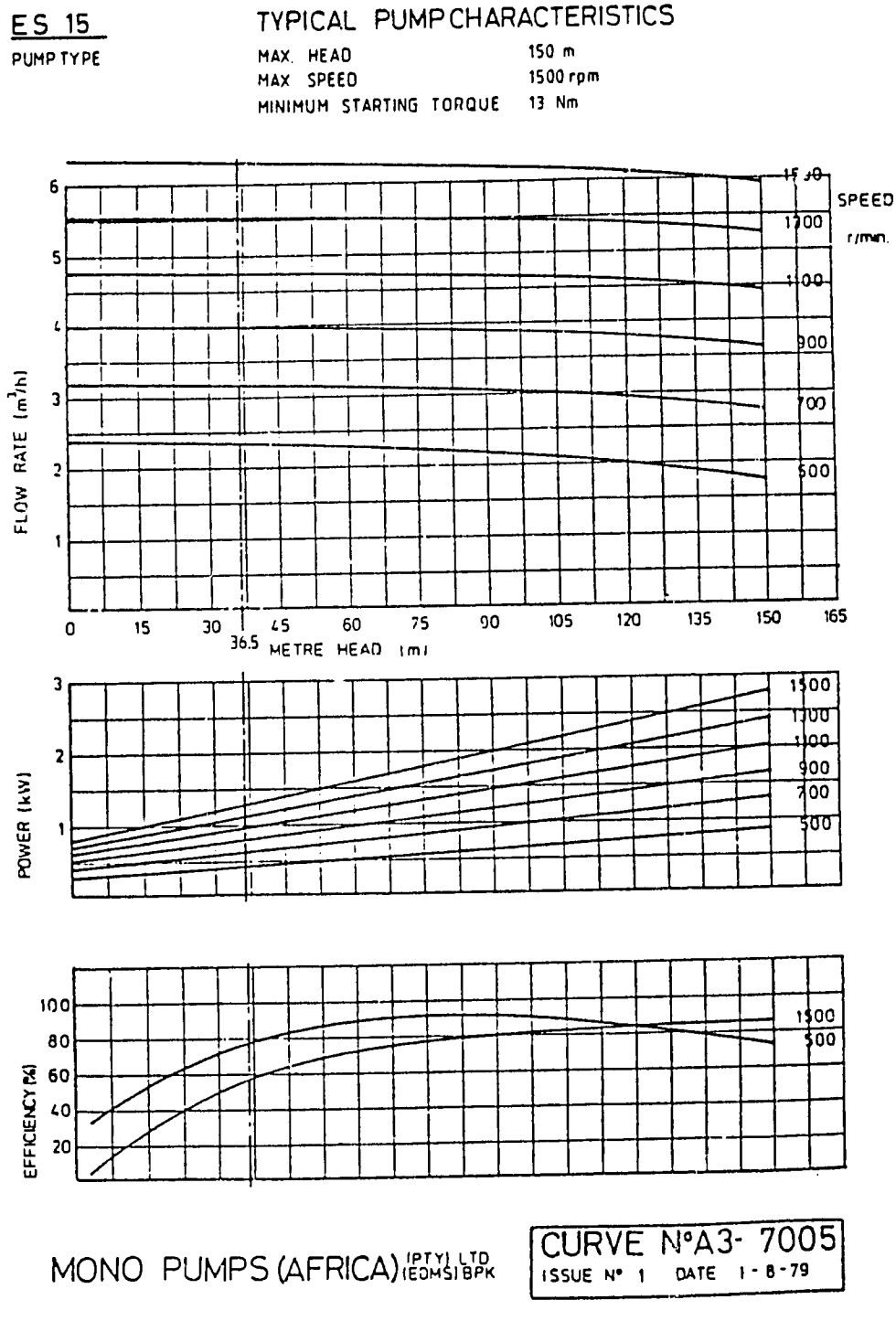



Figure 6.1 : Typical pumpcharacteristics of Mono pump ES 15.

APPENDIX 7

Prices

Prices of "windmill materials" in Botswana, April 1985.
(including 10% transport costs)

| ITEM | | UNIT WEIGHT (kg) | UNIT PRICE (Pula) |
|---|---|---|---|
| angle iron | 50.50.5 mm | 3.77/m | P 3.77/m |
| angle iron | 40.40.5 mm | 2.97/m | P 2.97/m |
| angle iron | 40.40.4 mm | 2.42/m | P 2.42/m |
| angle iron | 30.30.5 mm | 2.18/m | P 2.18/m |
| angle iron | 30.30.4 mm | 1.78/m | P 1.78/m |
| angle iron | 30.30.3 mm | 1.36/m | P 1.36/m |
| angle iron | 25.25.4 mm | 1.46/m | P 1.46/m |
| flat | 30.5 mm | 1.17/m | P 1.17/m |
| square bar | 50.50 mm | 19.50/m | P 35.54/m |
| square tubing | 25.25 mm | 1.50/m | P 2.82/m |
| steelplate | 10 mm | 78.00/$m^2$ | P 85.00/$m^2$ |
| steelplate | 5 mm | 39.00/$m^2$ | P 42.50/$m^2$ |
| galvanized sheet | 0.6 mm | 4.71/$m^2$ | P 8.15/$m^2$ |
| corrugated sheet | 0.6 mm | 7.06/$m^2$ | P 12.23/$m^2$ |
| round bar | 30 mm | 5.51/m | P 9.10/m |
| round bar | 50 mm | 15.32/m | P 25.30/m |
| shaft steel | 75 mm | 34.50/m | P 57.00/m |
| galvanized pipe | 1" (33.5/28.2) | 2.01/m | P 4.00/m |
| | 1.5" (48.1/42.3) | 3.25/m | P 5.89/m |
| | 2" (59.9/54.1) | 4.11/m | P 10.02/m |
| black pipe | 38.0 x 2.0 | 1.79/m | P 4.46/m |
| | 51.0 x 2.3 | 2.78/m | P 4.28/m |
| | 60.3 x 2.3 | 3.31/m | P 5.58/m |
| | 76.1 x 2.6 | 4.75/m | P 5.23/m |
| flexible coupling with taperlocks | | 2.4 each | P 191.00 each |
| gearbox (bevel 1 : 3) | | 28.5 each | P 840.00 each |
| V - belt pulley dia. 315 mm | | 12.0 each | P 97.00 each |
| V - belt type B | 4000 mm | 0.8 each | P 15.50 each |
| bearings compleet | F 65 mm | 5.3 each | P 72.00 each |
| | F 50 mm | 2.6 each | P 70.00 each |
| | F 40 mm | 2.2 each | P 40.00 each |
| | F 30 mm | 1.2 each | P 44.00 each |
| | Y 30 mm | 1.2 each | P 30.00 each |
| | Y 25 mm | 0.8 each | P 16.50 each |
| turntable | 500 L | 15.0 each | P 259.00 each |
| rigid coupling with taperlocks | | 6.0 each | P 100.00 each |

APPENDIX 7 (continued)

Details on construction and installation costs of the WTGS windmill

Material costs

Tower

| material (dim. in mm) | length (mm) | total weight (kg) | cost (P) |
|---|---|---|---|
| angle iron 50.50.5 | 121854 | 459 | 459 |
| 30.30.5 | 41280 | 90 | 90 |
| misc. (10%) | | 55 | 55 |
| | | 604 | 604 |
| waste (5%) | | | 30 |
| TOTAL | | | 634 |

Chassis

| | | | |
|---|---|---|---|
| steelplate 5 mm | 1.40 $m^2$ | 54.6 | 59.50 |
| angle iron 50.50.5 mm | 225 | 0.9 | 0.85 |
| round bar dia. 30 mm | 450 | 2.5 | 4.10 |
| gas pipe 2" | 3650 | 15.0 | 36.57 |
| dampening assembly | | 5.0 | 150.00 |
| turntable 500 L | | 15.0 | 259.00 |
| gearbox 920F (bevel gear 1:3) | | 28.5 | 840.00 |
| flange bearing dia. 30 mm | | 1.2 | 44.00 |
| pillowblock bearing dia. 30 mm | | 1.2 | 30.00 |
| misc. (10 %) | | 12.4 | 24.80 |
| | | 136.3 | 1448.82 |
| waste (2 %) | | | 28.98 |
| TOTAL | | | 1477.80 |

Rotor

| material (dim. in mm) | length (mm) | total weight (kg) | cost (P) |
|---|---|---|---|
| angle iron 40.40.4 | 6624 | 16.0 | 16.03 |
| blackpipe 38 x 2 mm | 8720 | 15.6 | 38.89 |
| steelplate 10 mm dia. 223 mm | | | |
| steelplate 10 mm dia. 138 mm | | 4.2 | 4.58 |
| blackpipe 76.1 x 2.6 mm | 332 | 1.6 | 1.73 |
| blackpipe 51 x 2.3 mm | 24000 | 66.7 | 102.72 |
| galvanized sheet 0.6 mm | 8.25 $m^2$ | 38.9 | 67.24 |
| square bar 50.50 | 1000 mm | 19.5 | 35.54 |
| misc. (10 %) | | 16.3 | 32.50 |
| | | 178.8 | 299.23 |
| waste (10 %) | | | 30.00 |
| TOTAL | | | 229.23 |

Rotorshaft compl.

| | | | |
|---|---|---|---|
| steelplate 10 mm dia 138 mm | | | |
| 10 mm dia 230 mm | | | |
| 10 mm dia 445 mm | | 17.0 | 18.40 |
| 5 mm | | | |
| shaft dia. 75 mm | 960 | 33.1 | 54.72 |
| flange bearing dia. 65 mm | | 5.3 | 72.00 |
| rigid coupling dia. 60/38 mm | | 6.0 | 100.00 |
| misc. (10 %) | | 6.1 | 12.20 |
| | | 67.5 | 257.32 |
| waste (5 %) | | | 12.87 |
| TOTAL | | | 270.19 |

Tail

| | | | |
|---|---|---|---|
| gaspipe 1" | 4000 | 8.0 | 16.00 |
| 1.5" | 4500 | 14.6 | 26.50 |
| 2" | 2000 | 8.2 | 20.04 |
| square tubing 25.25 | 7156 | 10.7 | 20.18 |
| corrugated sheet 0.6 mm | 2.34 $m^2$ | 16.5 | 28.62 |
| misc. (5 %) | | 2.9 | 5.80 |
| | | 60.9 | 117.14 |
| waste (5 %) | | | 5.86 |
| TOTAL | | | 123.00 |

## Transmission

| material (dim. in mm) | length (mm) | total weight (kg) | cost (P) |
|---|---|---|---|
| blackpipe 60.3 x 2.3 mm | 8500 | 28.1 | 47.43 |
| round dia. 50 | 850 | 13.0 | 21.51 |
| flange bearing FY50TB | | 2.6 | 70.00 |
| flange bearing FY40TB | | 2.2 | 40.00 |
| 2 flexible couplings with taperlocks | | 4.8 | 382.00 |
| V - belt pulley dia. 315 | | 12.0 | 97.00 |
| 2 V - belts type B | 4000 | 1.6 | 31.00 |
| misc. (2 %) | | 1.3 | 2.60 |
| | | 65.6 | 691.54 |
| waste (3 %) | | | 20.75 |
| TOTAL | | | 712.29 |

## Belt tensioner

| | |
|---|---|
| tube, shaft, angle iron, rods | 20.00 |
| 2 bearings dia. 25 | 33.00 |
| misc. | 4.00 |
| waste | 2.00 |
| TOTAL | 59.00 |

## Clutch

| | |
|---|---|
| materials | 265.00 |
| TOTAL | 265.00 |

## Paint

| | |
|---|---|
| zinc chromate 1 x 5 l | 22.00 |
| paint 1 x 5 l | 30.00 |
| TOTAL | 52.00 |

## Lathe work

Boarded out lathe work

| | | |
|---|---|---|
| lathe work on main shaft and blade spare adaptors | | 42.18 |

Labour + Lathe machine rent

| | | |
|---|---|---|
| lathe work at BEDU - Gabarone | P 1.75/hour | |
| labour cost for lathe work | P 3.00/hour | |
| mainshaft, flanges shaft, bushes and roller of belt-tensioner blade spar adaptors | 45 hrs. | 213.75 |
| spacing rings for downtube bushes and pivot pins for tower hinge clutch | 21 hrs. | 99.75 |
| assembling clutch | 4 hrs. | 12.00 |
| TOTAL | | 367.68 |

## Labour costs

| | | |
|---|---|---|
| tower chassis tail rotor rotor shaft assembly transmission belt tensioner | 387 hrs. | 1161 |
| lathe work | | 368 |
| TOTAL | | 1529 |

## Installation costs

| | | |
|---|---|---|
| cement 10 bags | | 55 |
| sand, gravel | | 40 |
| reinforment rods, bolts, nuts | | 134 |
| labour for construction of foundations | 2 days | 66 |
| erection of windmill 2 days | | 88 |
| TOTAL | | 383 |

Total weight of the windmill is about 1100 kg

APPENDIX 8

Measuring data on the centrifugal clutch

TEST A:
FLYWEIGHTS 0.308 kg each
SPRING LOAD 7.05 kg average

| speed rpm | ω rad/s | $F_w$ kg | T Nm | P W |
|---|---|---|---|---|
| 247 | 25.9 | 0.1 | 0.3 | 8 |
| 250 | 26.2 | 0.3 | 0.9 | 24 |
| 260 | 27.2 | 2.5 | 7.3 | 199 |
| 270 | 28.3 | 4.1 | 11.9 | 337 |
| 280 | 29.3 | 5.5 | 16.0 | 469 |
| 290 | 30.4 | 7.0 | 20.3 | 617 |
| 300 | 31.4 | 7.5 | 21.8 | 685 |
| 310 | 32.5 | 10.0 | 29.0 | 943 |
| 320 | 33.5 | 11.5 | 33.4 | 1119 |
| 330 | 34.6 | 12.25 | 35.5 | 1228 |
| 340 | 35.6 | 13.0 | 37.7 | 1342 |
| 350 | 36.7 | 13.75 | 39.9 | 1464 |
| 360 | 37.7 | 14.25 | 41.3 | 1557 |
| 370 | 38.7 | 15.0 | 43.5 | 1683 |

TEST B:
FLYWEIGHTS 0.463 kg each
SPRING LOAD 7.05 kg average

| | | | | |
|---|---|---|---|---|
| 218 | 22.8 | 0.125 | 0.4 | 9 |
| 230 | 24.1 | 1.0 | 2.9 | 70 |
| 240 | 25.1 | 1.85 | 5.4 | 136 |
| 250 | 26.2 | 4.1 | 11.9 | 312 |
| 260 | 27.2 | 6.3 | 18.3 | 498 |
| 270 | 28.3 | 7.5 | 21.8 | 617 |
| 280 | 29.3 | 9.0 | 26.1 | 765 |
| 290 | 30.4 | 10.5 | 30.5 | 927 |
| 300 | 31.4 | 11.0 | 31.9 | 1002 |
| 310 | 32.5 | 12.0 | 34.8 | 1131 |
| 320 | 33.5 | 12.75 | 37.0 | 1240 |
| 330 | 34.6 | 14.0 | 40.6 | 1405 |
| 340 | 35.6 | 15.0 | 43.5 | 1549 |
| 350 | 36.7 | 16.0 | 46.4 | 1703 |

APPENDIX 8 (continued)

TEST C:
FLYWEIGHTS 0.771 kg each
SPRING LOAD 7.05 kg average

| speed rpm | ω rad/s | $F_w$ kg | T Nm | P W |
|---|---|---|---|---|
| 175 | 18.3 | 0.2 | 0.6 | 11 |
| 190 | 19.9 | 1.1 | 3.2 | 64 |
| 230 | 24.1 | 11.0 | 31.9 | 769 |
| 240 | 25.1 | 13.0 | 37.7 | 946 |
| 250 | 26.2 | 14.0 | 40.6 | 1064 |
| 260 | 27.2 | 14.0 | 40.6 | 1104 |
| 270 | 28.3 | 16.0 | 46.4 | 1313 |
| 280 | 29.3 | 17.0 | 49.3 | 1444 |
| 290 | 30.4 | 17.0 | 49.3 | 1499 |
| 300 | 31.4 | 17.0 | 49.3 | 1548 |
| 310 | 32.5 | 18.0 | 52.2 | 1697 |

TEST D:
FLYWEIGHTS 0.771 kg each
SPRING LOAD 16.65 kg average

| | | | | |
|---|---|---|---|---|
| 290 | 30.4 | 0.5 | 1.5 | 46 |
| 300 | 31.4 | 1.8 | 5.2 | 163 |
| 310 | 32.5 | 4.8 | 13.9 | 452 |
| 320 | 33.5 | 6.5 | 18.9 | 633 |
| 330 | 34.6 | 10.5 | 30.5 | 1055 |
| 340 | 35.6 | 12.5 | 36.3 | 1292 |
| 350 | 36.7 | 13.0 | 37.7 | 1384 |
| 360 | 37.7 | 14.0 | 40.6 | 1531 |
| 370 | 38.7 | 15.0 | 43.5 | 1683 |

Table 8.1 : Results of measurements on the centrifugal clutch with four combinations of flyweights and spring loads.