IT Power

DFID

WINDPUMP DEVELOPMENT: from test bed to technology transfer

R6242

Final Report

DFID

Subsector: **Energy efficiency**

Theme: **E2 Develop the use of renewable sources of energy**

Project title:

WINDPUMP DEVELOPMENT: from test bed to technology transfer

Research Scheme No. **R6242**
IT Power Project No. 95509
Final Report
May 1995 - October 1997

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1. OBJECTIVES OF THE PROJECT

This report, the final report for the project, has been prepared by IT Power for the Engineering Division of the DFID, under Research Scheme R6242, ‘Windpump Development: from test-bed to technology transfer’.

Figure 1.1 Stage II prototype, developed as part of this project, under test in the UK

1.1 Background to the work

During the 1980s IT Power developed, with DFID (then ODA) support, a successful range of water pumping windpumps which are still being successfully manufactured in Zimbabwe, Pakistan and Kenya. These were direct-drive crank machines aimed at providing reliable water supply to rural communities in developing countries. Although they performed this task their market was restricted mainly to institutional end-users by their large size and hence relatively high cost.

Assessment of existing small windpump designs revealed that none were appropriate for manufacture and use in the developing world: Small crank driven machines run too fast and as a result tend to be unreliable; while geared machines are complex, more costly to manufacture and require increased maintenance (gears usually run in an oil-bath). IT Power has therefore aimed to provide a suitable design for a small windpump which can be effectively manufactured and maintained in developing countries.

In 1990 IT Power received support through the European Commission (EC) JOULE Programme to investigate innovative features for the new design. This culminated in the design and manufacture of a Stage I prototype. A test and development programme was then funded by DFID (then ODA), Research Scheme R5674B. This involved installation, commissioning and testing of the Stage I prototype which was found to perform well. The central feature of the new design being an innovative, but simple to manufacture gearing mechanism which proved itself to be efficient and reliable. During this project contact was established with potential manufacturers in developing countries and their representatives were invited to a demonstration seminar (also funded by ODA/DFID) to see the windpump and to discuss design and manufacturing issues. This seminar, together with a Small Windpump Market Study, which served to emphasise the demand for the product and justify continued development, helped to formulate the details of the design development needs.

1.2 Project objectives

This research project (R6242) began in May 1995 and was completed in October 1997. Its aim has been to carry the IT Power small windpump development forward from the Stage I prototype, effectively a test-bed machine, to a Stage II or pre-production prototype stage.

The windpump development has been carried forward to a Stage II prototype with a 2.0m rotor diameter (in accordance with the wishes of the overseas partners and the findings of the market study), taking into account lessons from the test programme on the Stage I prototype. The Stage II prototype has been manufactured and tested in the UK, and a design package has been formulated in liaison with the overseas partners. Stage II prototypes have been built in partners countries, with technical support and engineering assistance from IT Power. This project has therefore taken the windpump design from the test-bed to the point of technology transfer, with completed prototypes in the partner countries, namely China, India, South Africa and Zimbabwe.

2. WORK CARRIED OUT IN THIS PERIOD

The objectives of the project have been achieved in three phases designated by the following activities:

1. Stage I prototype - continued testing;
2. Stage II prototype design and development
    a. Development of the Stage II design, in liaison with overseas partners;
    b. Manufacture and testing of the Stage II prototype in the UK, including design modifications and production of design package;
3. Technology transfer through liaison with partners in four developing countries to allow Stage II prototype manufacture in developing countries with technical support and engineering assistance from IT Power.

This section describes the work carried out under each of these activities over the duration of the project.

2.1 Stage I prototype - continued testing

Continued testing allowed further performance data to be obtained from the Stage I prototype (under test at Silsoe Campus, Cranfield University) and also gave opportunity for previously unknown design faults/problems to become apparent. Specifically the aims of this extended testing were as follows:

- To identify any mechanical problems arising from extended use and to use this information in the Stage II prototype design;
- To assess critical components for signs of wear, and hence consider any design implications;
- To make an accurate assessment of the performance by collection of long term data.

Testing was continued from the start of this project until December 1996. Minor problems were encountered, but largely in components obsolete to the Stage II prototype design. One minor failure, but which illustrated an important problem, that this continued testing highlighted at an early stage was that the gearbox drive train mechanism had some weaknesses that were prone to failure.

2.2 Stage II prototype development:
Development of Stage II design, in liaison with overseas partners

This activity included scaling down the design of the Stage I prototype (a 3.0m rotor diameter machine) and incorporating lessons learnt from the testing of that prototype.

Important aspects of the overall design were first addressed, such as rotor layout and performance, based on rotor diameter, number of blades and blade details (angle of attack, etc.). This then allowed for the development of the separate sections of the machine; rotor, gearbox, tower, head, tail/furling mechanism, A-frame and foundations.

In addition a special programme investigated improvements to the gearbox and specifically the gearbox drive train (identified as a weak link in the Stage I prototype design). Alternative designs were investigated and the optimum option identified. This new drive train linkage was tested during the next phase of the project to ensure that the weaknesses had been overcome.

2.3 Stage II prototype development:
Manufacture and testing of Stage II prototype in the UK, including design modifications and production of design package

This activity included not only the manufacture and testing of the Stage II prototype (based in the UK) but also the development of the full design package. The design package has been developed from the Stage II prototype design to incorporate modifications as identified during the testing phase, these are discussed in more detail in Sections **Error! Reference source not found.**.

In addition a special programme tested improvements to the gearbox drive train on a purpose built test rig before manufacture of these components for the Stage II prototype.

2.4 Technology transfer to allow Stage II prototype manufacture in developing countries with technical support and engineering assistance.

During the previous project (Research Scheme R6242B) six potential partners from developing countries who were interested in manufacturing the new windpump had been identified. Their representatives attended a demonstration seminar to see the windpump and to discuss design and manufacturing issues. This activity in the current project allowed for the relationships with the potential partners to be developed and for four partners to be chosen to manufacture the Stage II prototypes in their own countries (the countries concerned being China, India, South Africa and Zimbabwe. Two visits were made to each partner, the first to discuss the requirements of the manufacturing process and to pass them the design package, and the second to review their progress, discuss problems which had arisen, etc. Four Stage II prototypes, manufactured by the partners in their own countries, have now been, or are almost, completed.

Further details of the choice of partners and the status of their development work are discussed in Sections 3.2.9 and 3.4.

3. RESULTS OF FINDINGS OBTAINED BY THE PROJECT

Headings in this section refer to activities largely as described in the original proposal but where changes in the programme were made (as agreed with DFID) i.e. early gearbox testing then this is reflected in the report presentation.

3.1 Stage I prototype - continued testing

The stage I prototype windpump (3m rotor diameter) was under continuous unattended testing at the Silsoe Campus test site of Cranfield University from March 1995 to December 1996 (see Figure 3.1**Error! Reference source not found.**). Since unattended running began the machine has completed in the order of four million pump strokes. The mechanical condition of the windpump was checked once a week and data was downloaded every fortnight. The machine was regularly lowered to the ground and examined more thoroughly for signs of wear or damage.

Figure 3.1: The Stage I prototype during testing at the Silsoe site

The performance of the Stage I prototype is illustrated in Figure 3.2 and Figure 3.3. Each point represents a 10-minute average with the pumping head set at 20m. The lower threshold running wind speed of the prototype has been further improved following some minor design changes. Pumping now begins at wind speeds as low as 2m/s.

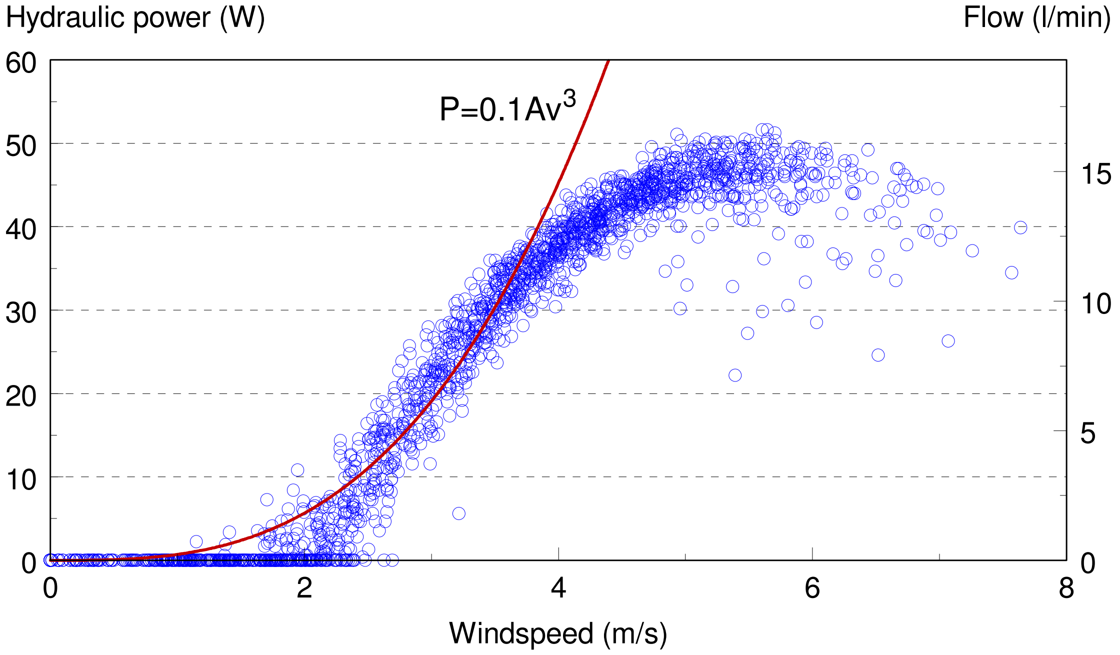


Figure 3.2 : Hydraulic power and flow as a function of wind speed (20m pumping head)

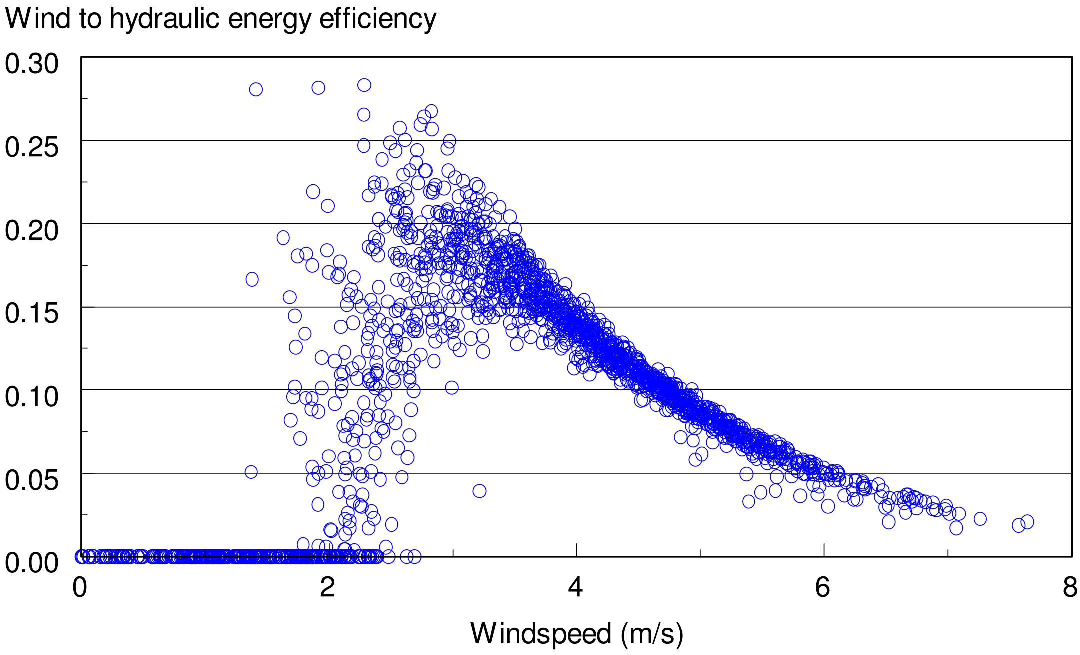


Figure 3.3 : Wind to hydraulic energy efficiency as a function of wind speed (20m pumping head)

The Stage I prototype achieved and maintained its efficiency target during the test period. On Figure 3.2 the $0.1Av^3$ curve has been added, which is taken as a rule of thumb for a ‘good’ windpump at its design wind speed (A is rotor area, v is wind speed). It is most important for a windpump to be efficient at lower wind speeds where less power is available. Figure 3.2 shows that the windpump performs at around the target efficiency level in the critical (i.e. most commonly occurring) windspeed range, from 2.5 to 3.5 m/s. Figure 3.3 shows system efficiency. The efficiency peaks at around 25-30%, whilst averaging at around 20%. Note that at higher heads the peak efficiency and the starting wind speed will be a little higher.

The windpump mechanical reliability has been excellent. One failure occurred at the junction of the pump rod/swivel joint (part of the drive train connecting the pump to the gearbox). Modified on-site for the Stage I prototype, the design of this component for the Stage II prototype was the subject of detailed investigation and testing.

The main results can be summarised as:

- Design improvements lowered the threshold for operation to a mean of 2m/s (at 20m head). This is an excellent result as most windpumps require at least 3m/s to start;
- The prototype achieved and maintained its efficiency target during the test period. The mean performance exceeded the ‘rule of thumb’ measure of 17% (wind to hydraulic power) at design windspeed. Efficiency peaked at 25-30% and averaged around 20%;
- The swing-tail furling proved effective. The machine furled completely by windspeeds of 10m/s and even in very high winds rotor speed was limited to about 20-30 rpm;
- Mechanical reliability was excellent. A few minor failures occurred - lessons learnt from these were fed back into the Stage II prototype design. Wear on the gear teeth has been minimal.

3.2 Stage II prototype development:
Development of Stage II design, in liaison with overseas partners

3.2.1 Gearbox design

The gearbox design is central to the performance of the new IT Power windpump. On the Stage I prototype the gearbox functioned well. For the Stage II prototype there were three main areas of change addressed:

- Scaling down in size to suit a smaller rotor diameter;

The reduction in size from a 3m to a smaller (2.0m) diameter rotor has two consequences, an increase in rotor speed by a factor of about 1.7 (speed is inversely proportional to rotor diameter) and a reduction in torque (torque is proportional to rotor diameter cubed). The gearbox redesign requirements, therefore, although utilising the same concept, were extensive. Neale and Associates, tribology specialists, were sub-contracted to review the redesigned gearbox and to make recommendations on tooth sizing, etc., since this is a specialised requirement if adequate durability without over-design was to be achieved.

- Off-setting of the gearbox;

This avoids using a side arm to induce furling in gusts or storms (this is also linked to the design of the gearbox drive train). The use of an offset rotor with hinged tail to achieve storm protection (which is the conventional method for windpumps) requires the rotor centre line to be offset by approximately 50 to 100 mm off the yaw axis of the head mechanism and hence off the pump-rod centre line. The previous arrangement was not offset. Figure 3.4 indicates how it is relatively straightforward to attach the flexible pump rod connector to the side of the gearbox casing to achieve the necessary offset. Further information on this investigation is detailed in Section 3.2.2.

- Simplification and redesign to suit manufacturing requirements;

A key requirement is to produce a design which lends itself to replication in a commercial manufacturing environment. Simplicity (i.e. as few components as possible) is the primary requirement followed by the need to use conventional and widely used processes and materials. There is also a particular need to build in a range of dimensional tolerances that will permit good reliability without imposing excessive demands and costs on the manufacturer.

Preliminary development work to determine the size and likely gear ratio for the new gear box was completed by IT Power after which a specialised engineering design consultancy (Neale Consulting Engineers), under subcontract to IT Power, carried out a detailed analysis to review the geometry and loads and hence determine the requirements for the gear material and tooth size, the track roller contact material, and the shaft sizes. Other important features which the analysis reviewed were the relative merits of the tooth positioning, i.e. internal or external teeth for the gearbox racks, construction methods and overall dimensions and probable construction costs. A copy of the Consultant Engineers ‘report is included in Annex III.

The most important conclusion from the gearbox analysis was that the gearbox design is entirely feasible for gear ratios of between 4:1 and 6:1 (specified preferred limits). Plastic gear teeth (nylon or acetal) were highlighted as being appropriate for the marginal lubrication conditions expected. The shaft sizes were confirmed as acceptable, based on the required layout. It is of particular importance to note that the analysis concluded that either an external or internal configuration could be used for the tooth layout but the externally toothed rack has advantages in terms of size, weight and cost.

The design for the gearbox was finalised by IT Power. The gearbox design was chosen to incorporate an externally toothed rack, with plastic gear teeth and a cast iron casing. It incorporates a speed reduction ratio of 4.9:1. This non-integer ratio has been chosen to ensure that the same gear teeth, on the pinion and the rack section, do not contact each revolution. This will help to contribute to reduced teeth wear.

The gearbox details include:

- A stainless steel pinion running on plastic rack teeth (acetal for the straight rack portions and nylon ends). Nylon is a stronger material (stresses are higher at the ends) but it has a high coefficient of thermal expansion and is also prone to absorb moisture and expand which could cause problems over the rack length;
- A gearbox incorporating external teeth, hence the tendency is for the gear teeth to over mesh at top dead centre of the pump stroke. For this reason hardened inserts have been incorporated which allow the cam follower bearings to take the load off the plastic teeth at this point.

Various important changes and improvements have been made to the gearbox, the design for which has now been completed (including the detail drawings).

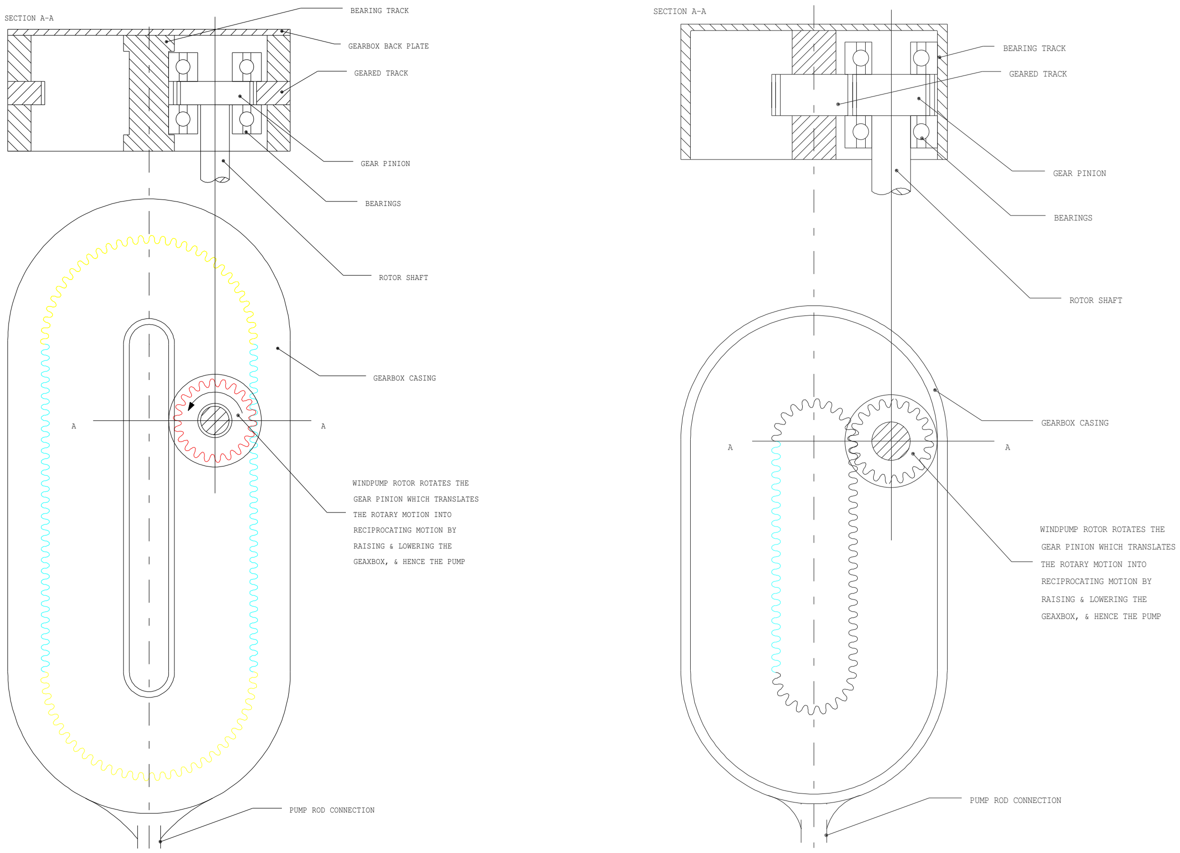


Figure 3.4a Internally toothed gearbox

Figure 3.4b Externally toothed gearbox

Figure 3.4 : Illustration of alternative rack tooth configurations

3.2.2 Gearbox drive train design

The gearbox drive train was shown to be a weak point on the Stage I prototype so this was an important area to be addressed. Investigation was required to assess the means to limit the freedom of movement of the gearbox. The dynamics of the gearbox at the top of each stroke tended to produce vibration problems at high running speeds.

A number of possible arrangements for constraining the gearbox, based on modifications to the original design, were considered and layouts developed. Figure 3.5 illustrates one concept that was reviewed and tested.

The gearbox restraining system, illustrated in Figure 3.5, and other possible arrangements were assessed using the gearbox test rig constructed for extended testing of the Stage I prototype gearbox. Further information on the testing process can be found in Section 3.3.1.

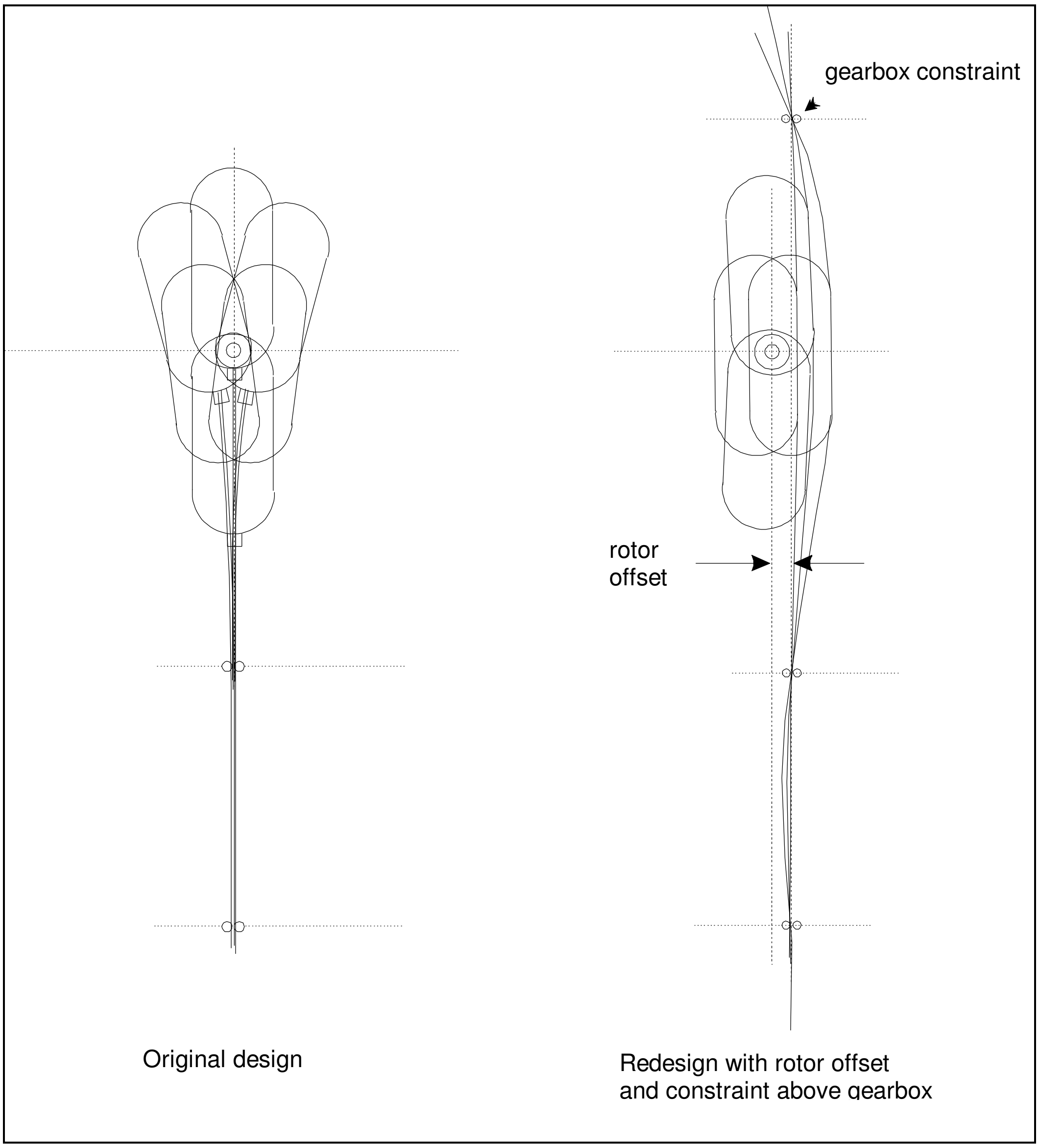


Figure 3.5: Option for gearbox/pump rod arrangement

Of these modifications to the original design none was found to be satisfactory and it was concluded that the design of the gearbox drive train must be completely reviewed. Entirely new layouts were considered and three viable options were selected for further analysis. These options were:

- Solid linkage running between rollers (schematic – Figure 3.6a);
- Solid linkage attached to radius arm (schematic - Figure 3.6b);
- Solid linkage using cross head guide (schematic - Figure 3.6c).

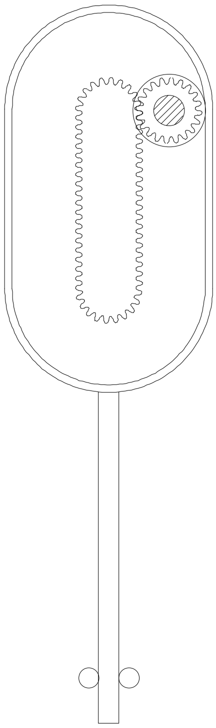


Figure 3.6a : Linkage & rollers

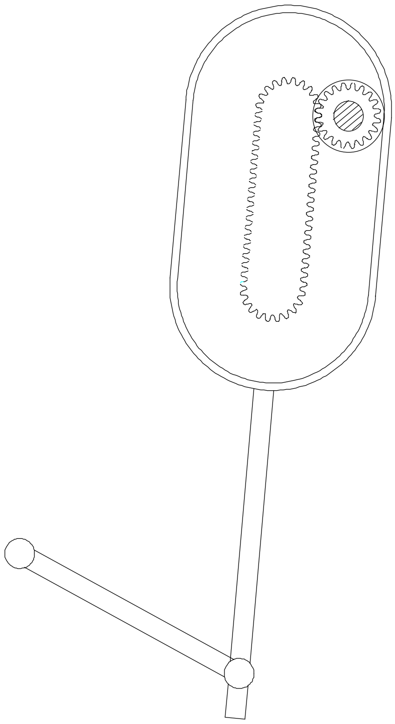


Figure 3.6b : Linkage & radius arm

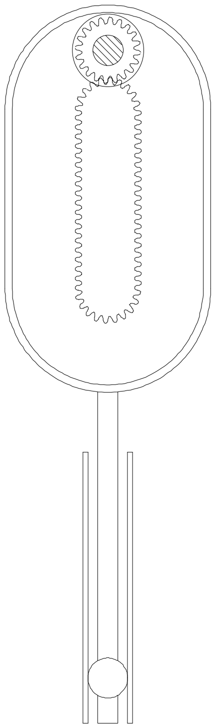


Figure 3.6c : Linkage & cross-head

These options were analysed in detail by the Consultant Engineers as part of their work on the gearbox design. The results of the analysis are summarised in Table 3.1 (the full report is included in Annex IV). It is clear that for almost all of the design criteria the solid linkage with cross-head guide has the best results. This option was therefore chosen for further testing on the gearbox test rig.

The results of the test work are presented in Section 3.3.1.

CRITERION	**Side spring**	**Linkage & rollers**	**Linkage & radius arm**	**Linkage & cross-head**
No. of bearings, rollers or pivots	6	3	3	2
Leaf spring	Yes	No	No	No
Control of motion	Moderate	Good	Good	Good
Lateral accelerations **a) at TDC** **b) at BDC**	 Moderate Moderate	 Moderate Moderate	 Moderate Moderate	 Moderate + Moderate -
Casing height	Moderate	Moderate	Large	Moderate
Casing width	Moderate	Moderate	Large	Moderate +
Pump rod lateral movement	Zero	Moderate	Moderate	Zero
Diameter of column	Moderate (rollers in column)	Moderate (rollers in column)	Small	Small (single roller in column)

Table 3.1 : Analysis of gearbox drive train options

3.2.3 Rotor design

The first step in the design of the rotor for the Stage II prototype was to determine the geometry of the rotor. This included a study to determine the performance characteristics of different designs and a consideration of the physical layouts that these implied.

The Stage I prototype had a 3m diameter rotor made up from sixteen blades. Changes were obviously required in the move from a 3.0m to a 2.0m or similar rotor diameter machine to ensure that adequate performance was retained whilst complying with limitations due to a decrease in size. In addition it was intended to incorporate changes based on lessons learnt during the testing of the Stage I prototype.

A computer programme, used previously, to predict the blade requirements for a smaller machine and hence to predict the likely performance using different rotor configurations, was further developed to predict the performance of the new machine. This programme is based on documented aerodynamic theory specifically developed for wind machine design.

The graphs which follow illustrate the results for a number of different rotor configurations. Table 3.2 describes the relevant parameters used in the graphs.

Designation	Description
B	No. of blades on the windpump rotor
C	Blade chord length - measured as a straight line distance across the width of a curved blade
TSR	Tip speed ratio - a measure of the ratio of the blade tip tangential velocity over the free wind speed
Cp	Coefficient of power - a dimensionless measure of the proportion of the available wind power that can be converted into useful power by the rotor
Cq	Coefficient of torque - a dimensionless measure of the torque available from the rotor
Ct	Coefficient of thrust - a measure of the thrust developed by the rotor

Table 3.2: Parameters displayed/varied in analysis

Figure 3.7 and Figure 3.8 show the variation in coefficient of power, Cp, and coefficient of torque, Cq, for rotor diameters of 1.8m, design tip speed ratios of 1, at a rated wind speed of 5 m/s, with various blade configurations. The model’s prediction of the existing stage one prototype (3m rotor diameter) is also illustrated.

One of the main requirements for the machine design is to have as high as possible starting torque without unduly compromising the efficiency. In addition the tip speed ratio at maximum power coefficient is best kept relatively low, so that rotor speeds at any given wind speeds will be lower, an advantage for the reliability of the pump, etc. Hence the combination of 10 blades with a chord length of 0.25 m was chosen as the most promising.

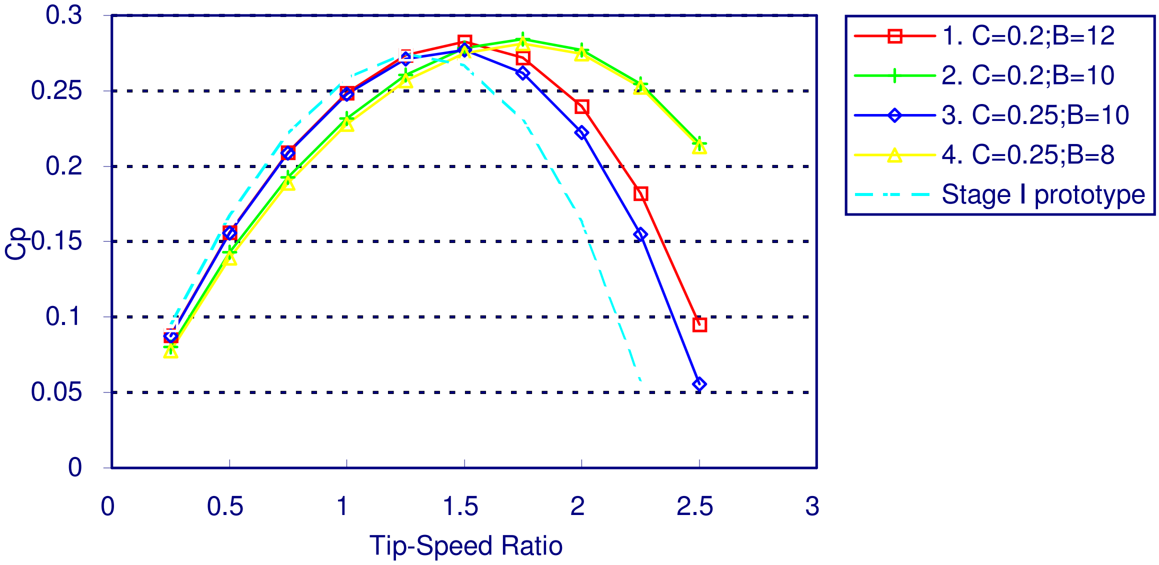


Figure 3.7: Coefficient of power, Cp v. tip speed ratio, TSR
Rated wind speed = 5m/s, design TSR = 1

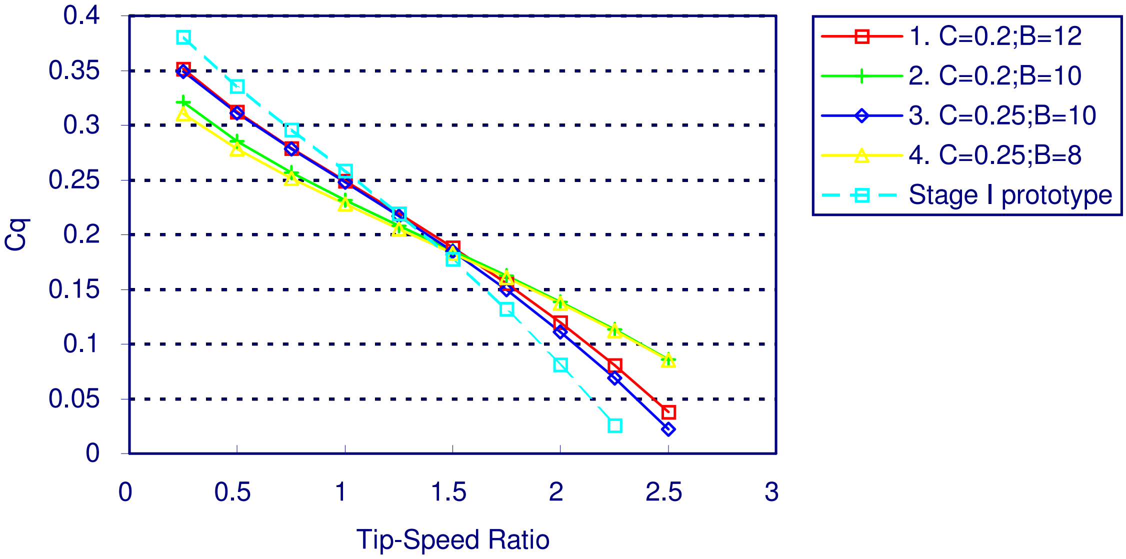


Figure 3.8: Coefficient of torque, Cq, v. tip speed ratio, TSR
Rated wind speed = 5m/s, design TSR = 1

Figure 3.9 illustrates this configuration (B=10, C=0.25m). The ideal values are from the theoretical model. Corrected values represent losses due to wake rotation and tip losses.

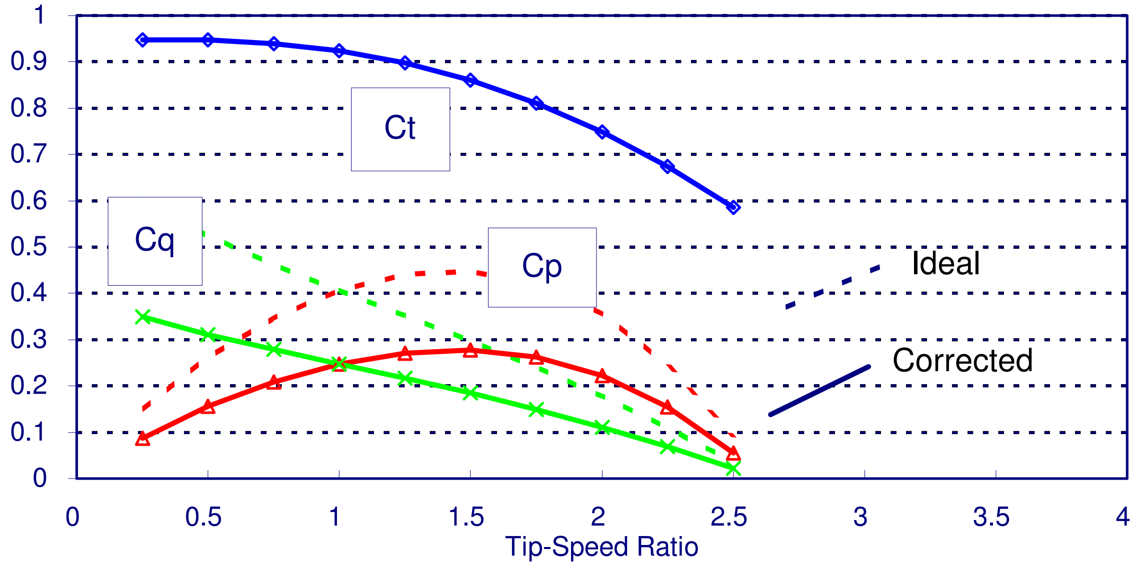


Figure 3.9: Coefficients of power, torque & thrust, Cp, Cq & Ct, v. tip speed ratio, TSR
B = 10, C = 0.25, rated wind speed = 5m/s, design TSR = 1

Based on this choice further work was carried out to determine the most suitable rotor diameter, tip speed ratio and blade angle settings. Figure 3.10 and Figure 3.11 illustrate the results of this work. It should be noted that although the coefficients of power and torque are lower for a rotor diameter of 2.0m than for 1.8m decreasing the rotor diameter would represent a decrease in power of 23% (power is proportional to diameter squared) and a decrease in torque of 37% (torque is proportional to diameter cubed), all other variables being constant.

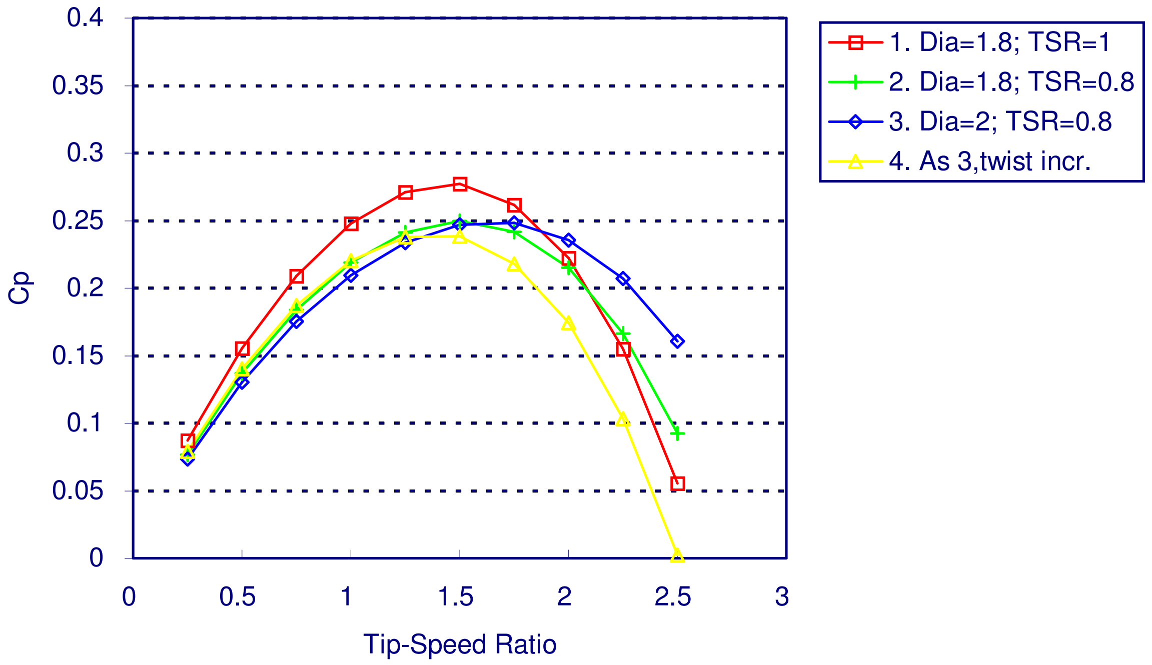


Figure 3.10: Coefficient of power, Cp v. tip speed ratio, TSR
B = 10, C = 0.25, rated wind speed = 5m/s, design TSR = 1

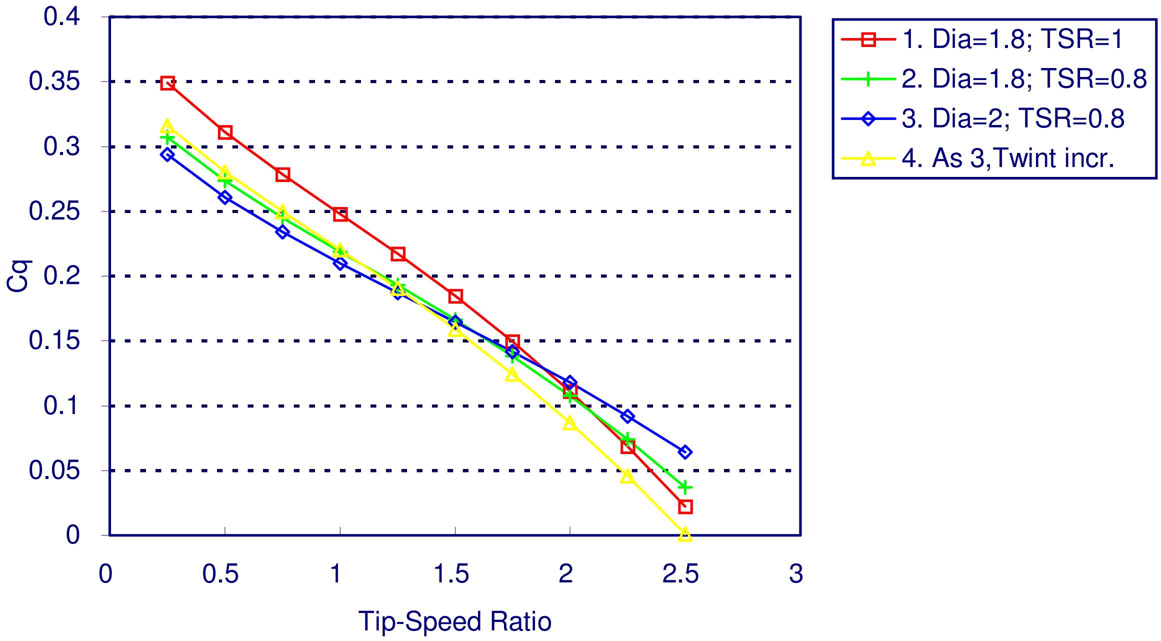


Figure 3.11: Coefficient of torque, Cq, v. tip speed ratio, TSR
B = 10, C = 0.25, rated wind speed = 5m/s, design TSR = 1

This programme is designed to develop a blade shape such that the layout will develop its maximum efficiency. In addition the blade setting angles can be varied, this can be observed in Figure 3.10 and Figure 3.11, option 4. For this option the coefficient of power is reduced but the coefficient of torque is increased. This implies that the starting torque will be improved, if the machine starts in lower wind speeds it will run for more of the time so that even though the average power output is reduced the overall water output should increase.

It should also be noted that a decrease in tip speed ratio will produce an improved starting torque (not directly illustrated on these graphs since the model is only valid for a machine in motion). For these reasons the final choice for the rotor configuration has been chosen:

Rotor diameter	2.0m
No of blades	10
Blade chord length	0.25m
Design tip speed ratio	0.8
Blade twist increased from ideal	

After determining the geometry of the rotor design the details of the design layout were completed. Options were developed to determine the detailed design of the rotor head, i.e. the mounting of the ten blades to the blade spars, and blade spars to the blade hub, to form the rotor. The aim has been to keep the layout as simple as possible whilst still allowing flexibility, i.e. the blades should be easily removable from the hub for replacement and transportation. A feature of the design is to avoid any welds at highly stressed places.

The final layout incorporates the blades fitted to tubular blade spars which are themselves welded to unequal angle channel. The angle is them bolted to the hub with two bolts per blade. Engineering drawings (assemblies only) of the Stage II prototype are presented in Annex I.

3.2.4 Head design

Preliminary strategies for the machine head/rotor drive were explored and designs finalised. Options were developed to consider different layout and to determine the optimum design of the rotor head. Considerable redesign was required from the Stage I prototype which had incorporated a blade furling mechanism which proved to be over complicated and costly and which was therefore abandoned.. In addition this process included other developments from the Stage I prototype, incorporating changes where issues were raised during the testing of this prototype. The aim has been to keep the layout as simple as possible to help keep material and machining costs low.

Figure 3.12 illustrates some of the options considered for the rotor hub and rotor drive. As previously mentioned, based on the Stage I prototype some redesign was required because the furling mechanism on the Stage I prototype encroached on the rotor drive layout. In the event, a design based on the third layout illustrated in Figure 3.12 was used.

Engineering drawings (assemblies only) of the Stage II prototype are presented in Annex I.

3.2.5 Tower design

The three legged tower design, as used on the Stage I prototype was proven to be effective, and offered a saving in steel compared to a four corner tower. Consequently the basic design remains the same, however improvements were made to simplify manufacture and construction of the tower.

Engineering drawings (assemblies only) of the Stage II prototype are presented in Annex I.

3.2.6 Tail / furling mechanism design

By offsetting the rotor (using the newly designed gearbox drive train system) no drag plate was required, as used on the modified version of the Stage I prototype. The tail furling system was therefore simplified. It was concluded however that the prototype should allow scope for adjustment of the tail angle according to the local prevailing conditions in the different countries. The design will need to be developed and finalised according to the requirements of the different partners.

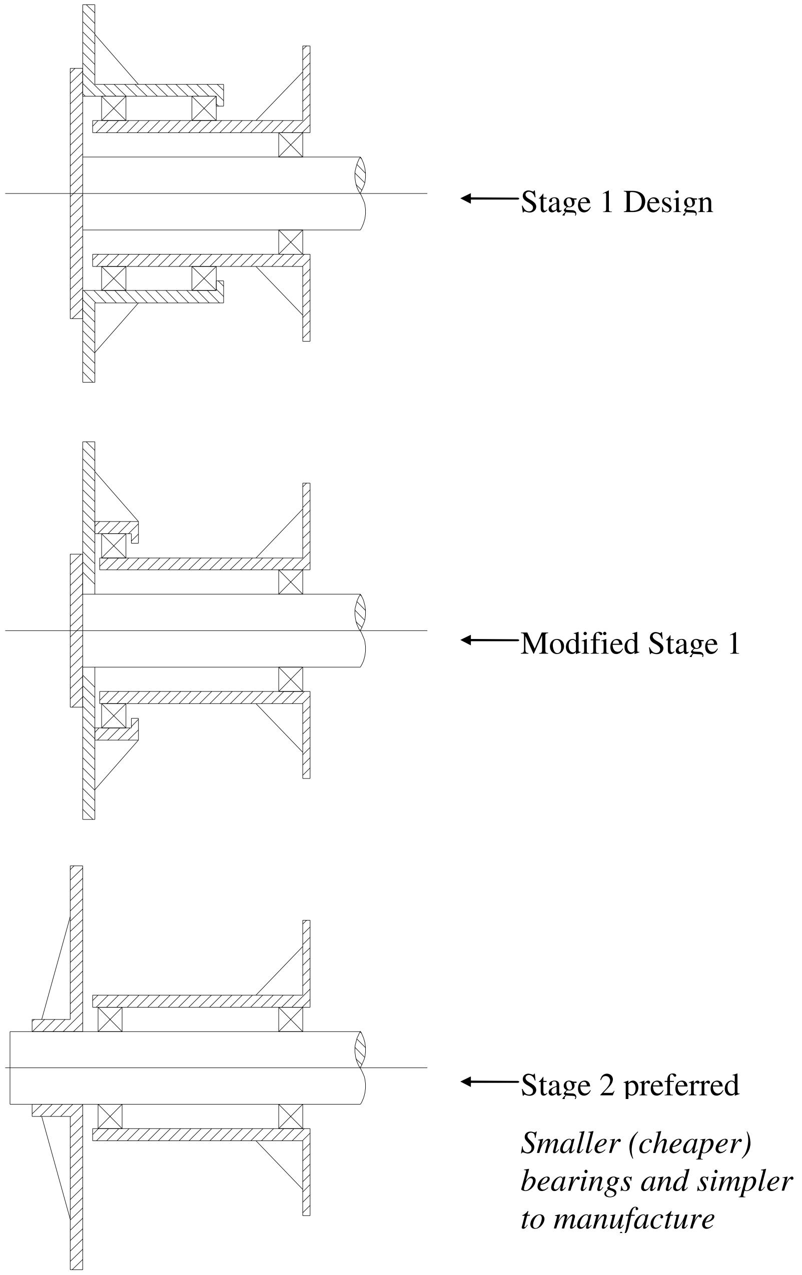
Engineering drawings (assemblies only) of the Stage II prototype are presented in Annex I.

3.2.7 A-frame and foundations design

The Stage II prototype installed in the UK was able to make use of the same foundations, the same A-frame[1] (although with minor modifications), and the same winch point, etc. as the previous machine minimising manufacturing and installation time. The installation process and equipment had been proven effective for the Stage I prototype so the designs were based on those for that machine but were modified slightly as required.

Engineering drawings (assemblies only) of the Stage II prototype are presented in Annex I.

[1] The A-frame provides an elevated fulcrum for the winch cable when the tower is in the lowered position. This is essential for lifting, rather than dragging the tower when the winch is applied.



Smaller (cheaper) bearings and simpler to manufacture

Figure 3.12 : Preliminary rotor hub and drive train options considered

3.2.8 System overview

The software package used to produce final designs facilitated preliminary analysis of the peak loads on key highly stressed components. Once the design layout was finalised, a detailed check was performed to analyse the stresses within the critical components, to ensure their mechanical integrity. Fatigue life was a key design consideration. Ease of assembly and material usage (to keep costs to a minimum) aspects were also considered.

A final check was made on each drawing to eliminate drawing errors so that a minimum number of problems will be encountered during the manufacturing process. The drawings were checked both in house and by independent consultants.

Engineering drawings (assemblies only) of the Stage II prototype are presented in Annex I.

3.2.9 Liaison with partners

A seminar, to demonstrate the New IT Power Windpump, was held in July 1994. This seminar formed part of the ODA funded project R5674A. The attendees and their organisations are listed in Table 3.3. These collaborators were contacted at the beginning of the project to review their interest in continuing with the programme to develop the IT Power windpump. Information regarding the plans and schedule of this project and the progress of the work to date were sent to the participants.

Country	**Company**	**Name**	**Activities**
Botswana	Rural Industries Innovation Centre (RIIC)	Mr D Disele	NGO. Experience with R&D on rotary drive version of the earlier IT Windpump in early 1980s.
India	NEPC (Natural Energy Processing Company)	Mr V Vasudevan	Windpump and (grid-connected) wind-generator manufacturer.
India	WindFab	Mr S Gurumoorthy	Windpump manufacturing company
Indonesia	Yayasan Bethel Cabang	Mr W J Gucker	NGO involved in agricultural development through local workshops. Has experimented with windpumps.
Mongolia	Monmar Engineering Co. Ltd	Mr B Chadraagyn	Joint venture manufacturer of small wind generators
Zimbabwe	Stewarts and Lloyds	Mr D Carroll	Manufacturer of the original IT Windpump & general water supply equipment

Table 3.3 : Attendees at the New IT Power windpump demonstration seminar

Of these six original partners, who attended the IT Power Windpump Demonstration Seminar, one responded to enquiries concerning the further development during this project. This was Stewart & Lloyds of Zimbabwe who expressed themselves as keen to continue to collaborate with IT Power on this venture. Contacts were maintained with the other partners, but their positions were reassessed during the project and it was considered that two companies were in the position to continue the partnership and build a Stage II prototype machine, Stewart & Lloyds, Zimbabwe and WindFab, India. The details are described in Table 3.4 .

In the early stages of the project a package including a paper (presented at the ISES World Solar Energy Congress, Harare, Zimbabwe and later published in the Solar Energy Journal) and information on IT Power's windpump activities was produced (Annex VI). This was sent to any enquirers. There was also further interest in the project though articles published in the DFID Energy Efficiency newsletters. In response to this interest a status sheet was added to the package to show the current activities.

A number of new potential manufacturers (who could be involved as partners in this project or as licensees to the final design) were identified (IT Power received a large number of enquiries relating to this work). Three groups (from India, China and South Africa) visited IT Power to discuss possible collaboration on the new IT Power windpump.

Since this programme aimed to commence the manufacture with four partners, two new collaborators were selected who seem to have the capabilities required. They were Avin Energy Systems Limited, India and Joffe Sheet Metal Products (Pty) Ltd, South Africa, also detailed in Table 3.4. The Chinese delegation were interested in using the machine for both irrigation and water supply. IT Power agreed to work with them and the group identified suitable manufacturers in their region.

Company	Country	Status	Attended 1994 seminar	Comments
WindFab	India	Commercial company involved in windpumping systems	Yes	Has the ability to manufacture and to market goods
Stewart and Lloyds	Zimbabwe	Commercial company involved in windpumping systems	Yes	Has the ability to manufacture and to market goods
NEPC - Micon	India	Commercial company involved in large-scale wind electric systems	Yes	As a group also involved in other activities. Market growth has limited their interest in new activities
RIIC	Botswana	Renewable energy R&D	Yes	Interested in developing the windpump but they have not come forward with a suitable manufacturing partner
Yayasan Bethal Cabang	Indonesia	NGO	Yes	Interest in the windpump was led by the personnel involved, who no longer work for the NGO
Monmar Engineering Co. Ltd	Mongolia	Commercial company involved in small-scale wind electric systems	Yes	Appeared interested at seminar but no longer responding to letters.
Avin Energy Systems Ltd	India	Commercial company involved in renewable energy systems	No	Has the ability to manufacture and to market goods. Keen to diversify, visited IT Power at own expense to discuss the windpump project.
Joffe Sheet Metal (Pty) Ltd	South Africa	Commercial company involved in sheet metal products for agricultural industry	No	Has the ability to manufacture and to market goods. Keen to diversify, visited IT Power at own expense to discuss the windpump project.
Delegation from Hebei Province	China	Two agricultural machinery manufacturers identified as potential manufacturers	No	Delegation visited IT Power at own expense to discuss the windpump project. Two agricultural machinery manufacturers identified as potential manufacturers.

Table 3.4 : Potential windpump collaborators

Once the potential partners had been identified visits were made to discuss the project, view the manufacturing facilities, provide partners with the engineering drawings. This work is discussed in Section 3.4.

3.3 Stage II prototype development: Manufacture and testing of Stage II prototype in the UK, including design modifications and production of design package

3.3.1 Gearbox drive train test and modification

The gearbox testing was rescheduled, to be carried out before the manufacture of the gearbox for the Stage II prototype, when it became clear that there was a potential problem with vibrational effects due to the design of the gearbox drive train, hence this aspect of the work is reported on before the manufacture of the gearbox.

The gearbox test-rig based at IT Power's offices in Eversley was modified so that quantitative measurements of gearbox movement envelopes are possible using video recording equipment. A board marked with graduation lines was placed behind the gearbox and a video camera mounted on a 6m scaffold tripod centred in front of the gearbox.

The test rig was used to look at several possible gearbox drive train configurations, as discussed in Section 3.2.2. Results were video recorded and the motion at different speeds analysed in terms of movement envelope and vibration. This provided an important input to the design work for the Stage II prototype gearbox drive train.

The first tests carried out looked at options for attachment of the spring pump-rod to the side of the gearbox, basically modifications to the existing design.

In theory, side attachment offers several advantages - (i) ease and robustness of attachment compared to a centre fixing (ii) the pump rod (and hence the yaw bearing) can be offset from the rotor centre therefore dispensing with the need for a side vane to produce a furling moment to yaw the rotor head (iii) the pump rod is more closely in-line with the rack on which the pinion teeth are acting, thereby reducing the turning moment on the gearbox (and hence the bending on the spring) on the lift stroke.

However, in practice significant problems emerged when this configuration was tested on the rig. The momentum of the gearbox as it comes over the top of the stroke causes a resonance to be set up with the spring (unloaded on the down-stroke) causing severe vibration in the drive train at some speeds. It was concluded that using a spring for the top pump rod section does not give the necessary motion control and vibration suppression at all speeds.

Based on these tests and discussions with the subcontractor, Neale Consulting Engineers, (see Section 3.2.2) several new gearbox linkage options were developed which offer significant advantages.

The gearbox test rig was modified to allow testing of the chosen gearbox drive train mechanism. The option incorporating solid linkage and cross-head mechanism was tested.

The results from the test rig were excellent. Video monitoring of the gearbox and linkage region confirmed predictions that drive control and alignment would be greatly improved with the new linkage. Problems previously encountered with vibrations under realistic pump-cycle rates but relatively low-heads have now been eliminated. The mechanism operates smoothly even at simulated heads in the range of 40-60m. The spring pump rod concept was therefore superseded by a this side-fixed solid linkage.

The details of the final design layout are illustrated in Figure 3.13.

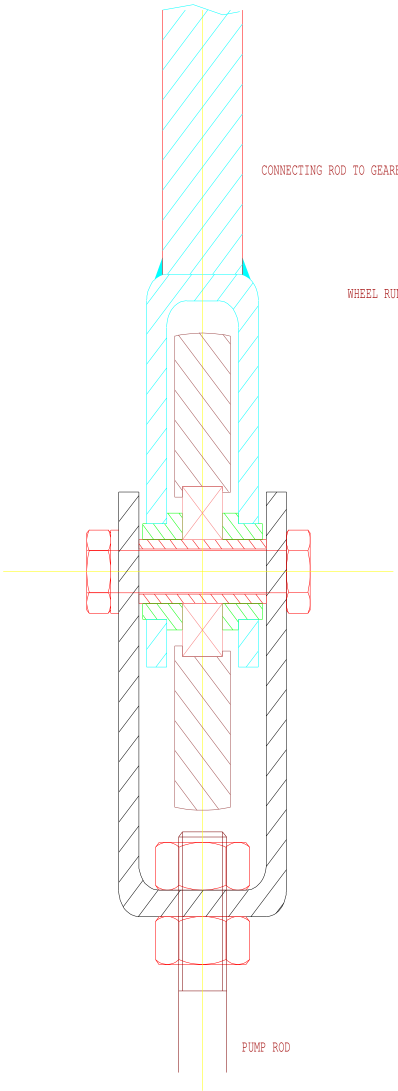


Figure 3.13 : Gearbox linkage mechanism

In total the prototype gearbox test rig completed almost 1.15 million revolutions, including more than 260,000 revolutions testing the modified linkage mechanism.

3.3.2 Gearbox and Windpump build

The manufacture of the stage II prototype in the UK was carried out at an engineering workshop local to IT Power's offices. This ensured that any problems with the drawings/design could be discussed and easily rectified during the manufacturing process.

The stage II prototype was test assembled (see Figure 3.14) at the manufacturing location before being transported to the Test Site at Silsoe, where it was installed.

Figure 3.14 : Test Assembly of the stage II prototype at the UK manufacturing location.

The test assembly of the Stage II prototype at the manufacturing works enabled minor faults/problems to be flagged-up and ensured that these were dealt with before the machine left the manufacturing premises. This procedure of test assembly was recommended for the Stage II prototypes being produced by the developing country manufacturers.

3.3.3 Removal of Stage I prototype and installation of Stage II prototype

Decommissioning and removal of the Stage I prototype from the Silsoe test site (Cranfield University) began once the Stage II prototype was being test assembled at the workshop. The Stage I prototype was taken to IT Power's offices for storage.

After test assembly of the Stage II prototype at the workshop it was transported to the windpump test site, where it was installed (see Figure 3.15). It was installed on the foundations used for the Stage I prototype. Lessons learnt from the installation process were communicated to the overseas partners.

Figure 3.15 : Construction of th e stage II prototype at the Silsoe test site.

3.3.4 Stage II testing programme

After installation of the stage II prototype the testing equipment was installed (see Figure 3.16). The test circuit and equipment is the same as that used for testing of the Stage I prototype although a new flow meter, pressure sensor and power supply unit (on the main monitoring circuit board) were purchased due to a failure of the previous units during the testing programme. These problems resulted in minimal loss of data.

A 50mm bore pump was used for test work, the stroke having changed (as dictated by the new gearbox) from 400mm to 353mm. This size of pump was used so that the test work optimised starting wind speeds. The test work aimed to investigate different heads to assess the optimal starting windspeed and efficieny of the machine. Due to problems encountered with the failiure of instrumentation during the test programme (as noted above) full teesting was not possible at different heads. Results presented here are therefore only for a head of 17.5m.

Data is logged in 10 minute averages calculated from 2 second instantaneous readings. Data has then been *binned* depending on windspeed (in this instance with spreads of 0.5m/s windspeed, i.e. into bins of 0-0.5m/s, 0.5-1.0m/s etc.). Operational averages are then obtained. A selection of other graphs is presented in Annex XI.

Figure 3.17 and Figure 3.18 show the machine rotor speed and operational efficiency (wind input to hydraulic output), using binned data, at 17.5m head, 50mm bore pump.

Figure 3.16 : Installation of the testing equipment

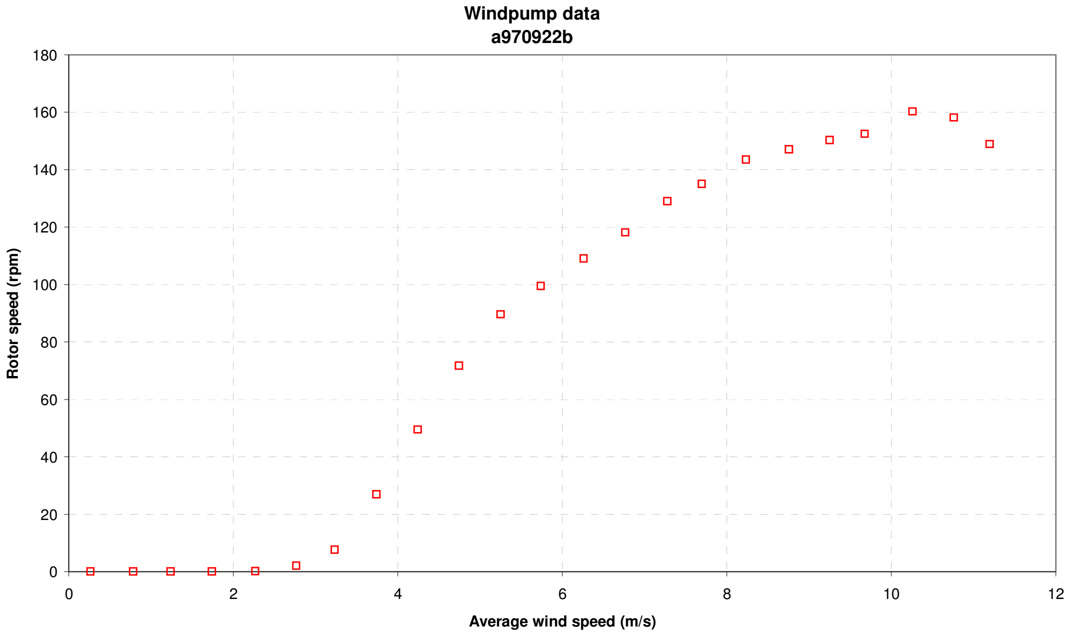


Figure 3.17 : Rotor speed against windspeed (17.5m head, 50mm bore pump)

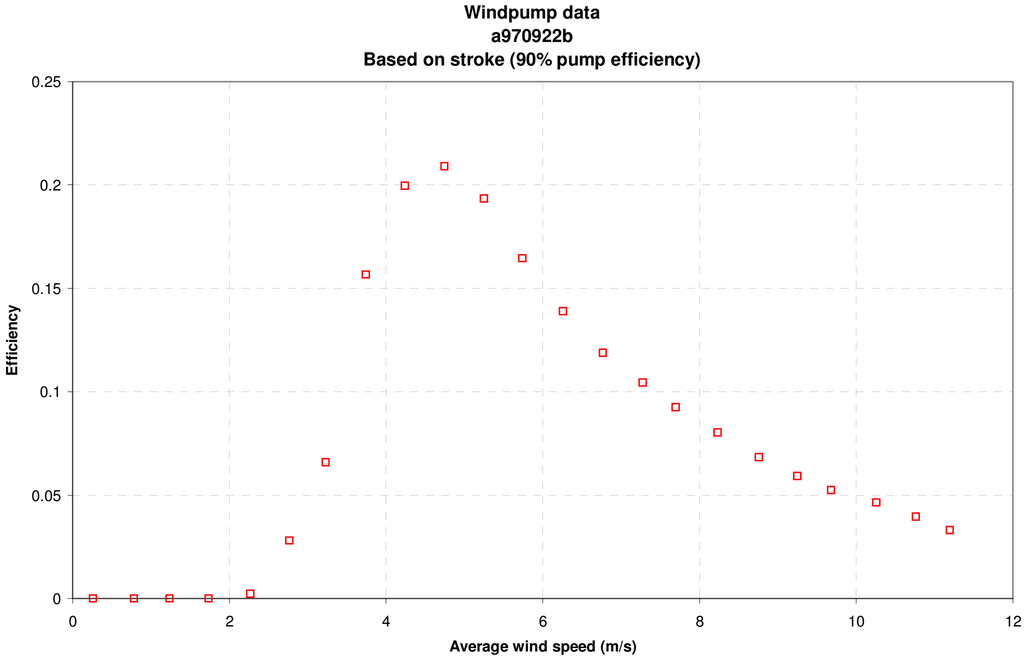


Figure 3.18 : Operational Efficiency (wind input to hydraulic output – 17.5m head, 50mm bore pump)

Important points regarding the performance of the machine which were noted during the test regime are:

- Starting windspeed is around 3.0m/s this is slightly higher than for the previous prototype, but is within the expected performance range;
- Maximum efficiency using the 50mm bore pump at 17.5m head is 21%, a similar average to the stage I prototype. A good machine should have efficiencies above 20%. Further testing is required to fully define the efficiency at different heads;
- That the furling mechanism was functioning reliably and effectively. Furling characteristics are notoriously difficult to predict and problems such as hunting and slamming against the stops are not uncommon. Furling system development requires experimentation and the design was specifically laid out to allow for simple system changes, i.e. variation in tail angle. Further long term testing would be beneficial in order to consider different tail angles for different conditions and to assess the effect of the off-set positioning of the rotor on yawing;

3.3.5 Stage II prototype modifications and production of Stage II design package

The test assembly carried out at the engineering premises where the machine was manufactured ensured that design/assembly problems could be flagged up before the machine was installed.

During manufacture, test assembly, installation and, in particular, the preliminary test work a number of minor modifications have been made in response to problems encountered/improvements noted during this phase. New drawings in line with these modifications were produced and passed to overseas manufacturers.

During the manufacturing process a number of modifications were made in discussion with the engineering workshop manufacturing the machine. These modifications enabled simpler manufacturing of parts, easier assembly of units and other general improvements.

The test assembly, carried out at the engineering premises where the machine was manufactured, flagged up a number of minor modifications. These included items such as:

- cross bracing for tower (tension bars) - shorten overall length and shorten hook length;
- gearbox casing back cover - fewer screws for fixing;
- gearbox to pump rod - bolts and nut (not simply bolts) to ease assembly;
- pump rod guide mounting system - alignment.

During the installation and the preliminary test work a number of additional modifications have been made in response to problems encountered/improvements noted during this phase. This included items such as:

- tower step redesign - steps proved difficult to use & represent safety problem;
- tower head redesign - machine head did not locate accurately enough on tower top once machine lowered causing damage to the top bearing;
- top and lower tower bearings modified to reduce friction and hence allow easier yawing;
- transmission support column lengthened to reduce thrust on lower bearing.

A full list of changes required, as identified during the manufacture, test assembly, installation and preliminary testing, is included in Annex V. This list was passed to partners overseas, who had already commenced manufacture of the stage II prototype, before modified drawings were completed and sent to them.

A full package of designs incorporating modifications has been produced.

3.4 Technology transfer to allow Stage II prototype manufacture in developing countries with technical support and engineering assistance

3.4.1 Exploratory visits to partners

As discussed in Section 3.2.9 two of the original six interested parties who visited IT Power for the IT Power Windpump Seminar in 1994 have continued as collaborators for the programme, Stewart + Lloyds, Zimbabwe, and WindFab, India. There has also been a considerable number of other parties interested in manufacturing this machine. As noted in Section 3.2.9 the two other companies chosen to collaborate in this programme were Joffe Sheet Metal (Pty) Ltd, South Africa and Avin Energy Systems Ltd, India.

Preliminary visits were made to all of these four partners to assess their workshop capabilities and to hand over drawings to allow them to commence the manufacturing process.

After the visit to Avin Energy Systems it was concluded that this company was not of a suitable nature to be involved in this programme. Their manufacturing facilities had been over stated during their visit to the UK and although it was agreed that external contractors could be used to manufacture the machine the main business of the company was not in manufacturing but in import/export, limiting their experience for such a project. It was concluded that Avin Energy Systems should not be included as a collaborator in this programme.

During this time the Chinese delegation had visited IT Power and were still keen to be involved. Consequently, after a visit by IT Power’s staff to confirm their manufacturing capabilities and to discuss the programme with them, the People’s Government of Cangxian County, Hebei Province (on behalf of Cangxian County Agricultural Machinery Repairing and Manufacturing Factory and NanPi County Machinery Factory) is now a collaborator in this programme. Therefore the partners who are manufacturing the Stage II prototype as a part of this project are:

- People’s Government of Cangxian County, Hebei Province, China.
- WindFab, India;
- Joffe Sheet Metal (Pty) Ltd., South Africa;
- Stewarts+Lloyds, Zimbabwe;

3.4.2 Prototype manufacture in developing countries, including design modifications and visits

At least two visits were made to all of the partners (including one to Avin Energy Systems), see Table 3.5. In the majority of cases follow-up visits were carried out. This was possible within the budget due to links made with other IT Power projects.

Partner	Country	Visit: Type	Visit: Date	Visit: IT Power personnel
Stewarts+Lloyds	Zimbabwe	Preliminary	Last quarter 1996	Peter Fraenkel
Stewarts+Lloyds	Zimbabwe	Follow-up	First quarter 1997	Peter Fraenkel
Stewarts+Lloyds	Zimbabwe	Final	Third quarter 1997	Paul Cowley
WindFab	India	Preliminary	Last quarter 1996	Peter Raftery
WindFab	India	Follow-up	Second quarter 1997	Tory Hart
WindFab	India	Final	Third quarter 1997	Paul Cowley
Joffe Sheet Metal (Pty) Ltd	South Africa	Preliminary	Last quarter 1996	Peter Fraenkel
Joffe Sheet Metal (Pty) Ltd	South Africa	Follow-up	First quarter 1997	Peter Fraenkel
Joffe Sheet Metal (Pty) Ltd	South Africa	Final	Last quarter 1997	Paul Cowley
People’s Government of Cangxian County, Hebei Province	China	Preliminary	First quarter 1997	Frances Crick
People’s Government of Cangxian County, Hebei Province	China	Final	Last quarter 1997	Paul Cowley
Avin Energy Systems	India	Preliminary	Last quarter 1996	Peter Raftery

Table 3.5 : Status of visit made to the project partners

The participating manufacturing partners each received a visit from an IT Power Engineer during September and October 1997. The purpose of these final visits was to ensure that production and plans for installation of the prototype unit were proceeding to schedule, and that component manufacture was to a satisfactory engineering standard. The visits also provided an opportunity for trouble-shooting problems encountered during the manufacturing and installation processes, and for discussing marketing strategies and ideas for further development of the design to improve the suitability of the machine for the specific local markets.

Each of the project partners was at a different stage of production. At the time of visit, only WindFab (India) had completed the on-site installation of their prototype unit (see Figure 3.23). However, it should be noted that WindFab were the last of the manufacturing partners to be visited, and that all of the partners were confident that they would have completed the construction and installation of their respective machines in the near future, subject to location of a suitable test bore-hole. Figures 3.19 to Figure 3.23 show the machines at varying ststes of construction/installation in the developing countries.

The visits highlighted that, in general, the in-country manufacturing partners have adhered closely during the production of their prototype units to the design specified by the UK Consultants. A few of the non-critical modifications to the design drawings, introduced following field testing in the UK (as outlined in section 3.3.5), have not been incorporated in the overseas partners prototype machines, because the components had already been manufactured according to the previous specification, and it was felt that to implement the design changes would be an unnecessary cost burden and would lead to delays in the installation of the machine. The modifications will be incorporated into successive models.

Critical design changes, notably the alterations to the Transmission Support Column and TSC bearing, were highlighted during the visits to the in-country partners. In such cases, the manufacturers had either already implemented the necessary changes, or agreed to change the relevant components on the prototype unit in-line with the new design.

Figure 3.19 : Joffe, South Africa – Early construction work on the Stage II prototype tower

Figure 3.20 : Stewarts & Lloyds, Zimbabwe – Test assembly of the Stage II prototype

Partner	Date of Visit	Manufacturing Status	Installation Status	Target Market	Design Enhancements Required	Other Comments
Joffe SheetMetal, Cape Town, South Africa	10th September 1997	Majority of components manufactured. Some non-critical components manufactured to previous design (should not affect performance and will be corrected for production units)	Borehole identified (water table depth approx 25m), site to be prepared ASAP.	Mainly Private Farmers	Ground furling mechanism; Possible mods to allow easier packing	Some production delay due to essential design drawing modifications; On-site installation expected to be completed by end October 1997.
Stewarts & Lloyds, Bulawayo, Zimbabwe	11-12th September 1997	All components manufactured; Some components to be re-manufactured to latest design; tower to be re-made using correct spec material	Some difficulty locating suitable borehole. Several potential sites identified. Negotiations in-progress (expected depth 50-80m)	NGOs and appropriate government departments (e.g. water, rural development etc.)	Ground / automatic (level-controlled) furling mechanisms; Extractable pump-unit; Bought-in thrust bearing to simplify manufacture of head bearing; User's Manual; Production Manual	Delays due to awaiting gearbox delivery and borehole problems. MoU signed with NUST to monitor field tests. On-site installation expected to be completed by end October 1997.
People's Government of Cangxian County, Hebei Province, China	9-10th October 1997	All components manufactured according to spec. Suitable suction pump under manufacture	Test-site located. (water table depth approx 12m) Borehole to be prepared end of October 1997	Mainly state / local government assisted schemes to small farmers	Ground furling mechanism; Simpler TSC bearing arrangement; User's Manual	Slight delay due to awaiting specification of pump-unit; On-site installation expected to be completed by end October 1997.
WindFab, Coimbatore, India	15-16th October 1997	All components manufactured. TSC bearing arrangement to be re-manufactured according to latest spec.	Machine installed on-site. Water-table depth 35-40m. Engineers spot-checking performance	Mainly private farmers	Ground furling mechanism; Simpler TSC (thrust) bearing arrangement; Users Manual Production Manual	Will continue to monitor performance. Now in least windy period, but pumped water briefly during ITP engineer's visit.

Table 3.6 : Summary of Key Findings resulting from Final Visits to Overseas Manufacturing Partners

Figure 3.21 : People’s Government of Cangxian County, Hebei Province, China – The upper tower section and machine head being test assembled outside the factory

Figure 3.22 : People’s Government of Cangxian County, Hebei Province, China – Hand-made windpump on local farm which the Stage II prototype will replace

Occasionally, local availability dictated the use of a non-specified alternative material for certain components. In particular, the standard angle-iron specified in the tower design is not available in three of the partner countries, so slightly over-sized angle is used instead. In all cases, the use of non-specified material or bought-in components has been cleared with the UK designers, to ensure structural soundness is maintained.

The visits also stimulated some useful discussions and generated several ideas for possible improvements to the design to make production easier, or to improve operational performance / reliability / ease of maintenance. It is hoped that these modifications can be addressed through follow-on research activities.

The key findings of the final missions to each of the in-country partners are presented in **Error! Reference source not found.**2. More detailed reports of the visits, including details of the modifications implemented by the overseas partners, and of the proposals for possible enhancement of the present design are given in Annex II.

Figure 3.23 : WindFab, India – Stage II prototype installed at the company's testing site outside Coimbatore, Southern India

4. IMPLICATIONS OF THE RESULTS/FINDINGS FOR ACHIEVING THE OBJECTIVES OF THE PROJECT

The project objective, namely to transfer the IT Power small windpump development from the test-bed to pre-production prototype manufacture in several developing countries has, to all intents, been achieved, as borne out by the results outlined in Section **Error! Reference source not found.** above, with the prototype unit now manufactured in China, India, South Africa and Zimbabwe, to be installed on a suitable test site in the locality.

The results, and in particular the visits to, and discussions with, the manufacturing partners, have highlighted a number of issues which might serve to make production, operation and/or maintenance of the machine simpler and/or more cost-effective and therefore more attractive to potential customers in the specific local markets. These issues are addressed in Section 5 below.

5. PRIORITY TASKS FOR FOLLOW-UP

It is clear that there is a real market for this product, which could fill an important niche role for applications where windpumps currently available on the market are either too large or too expensive (or both). In China, for example, the manufacturing partners are located close to the recently constructed Ta Liang Tin reservoir, which could support the installation of some 7500 small windpumps to irrigate small farm holdings. Assuming the prototype unit performs well, there is potential for a large number of IT Power Small Windpumps to be installed in the next three to five years. In India there is clearly a potential market, WindFab are continually receiving enquiries for sales of windpumps. Examples of letters of enquiry are presented in Annex II.

Discussions with the manufacturing partners throughout the course of R6242, and in particular as the partners approached completion of the prototype production and installation, have highlighted a number of priority areas for follow-on work to prove the viability of the machine in the field, to make the design more attractive for the various local markets, and to raise awareness of the machine among potential customers.

A proposal has been submitted to DFID under the TDR call for proposals for 1998, in a bid to address these follow-on tasks. In addition thaere are minor issues which should be addressed which include items such as continued liaison with the partners and continued testing to confirm performance.

5.1 Continued Manufacturing Liaison & Support

At the time of completion of R6242, prototypes of the IT Power small windpump will have been produced in four developing countries. Continued liaison is important for continuity, and to ensure that, should problems arise, the manufacturing partners have the support to solve problems and further develop the machine. It is vital that the manufacturing partners do not feel they have simply been deserted otherwise they may either cease windpump manufacture altogether or they may inadvertently degrade the design by making ad hoc changes.

5.2 Design Enhancements

To make the new IT Power system competitive in some markets, various important enhancements to the current design, are envisaged. The key areas to be addressed include:

- The development and testing of a winch and linkage for furling the windpump from ground level;
- The development and testing of a platform to facilitate easier maintenance of the rotor, gearbox and furling mechanism without requiring the tower to be lowered;
- The development and testing of a pump and well-head to enable the machine to be marketed as a complete pumping solution, without requiring components to be bought-in;
- Design for a taller tower for location in areas with tree cover or other obstructions.

5.3 Supplementary Design Package

The marketability of the IT Power Windpump would be improved by increasing the range of operating windspeeds and/or pumping head capabilities. To address this issue, it is proposed to extend the IT Power Windpump range to include machines of 3m and 4m rotor diameter based on the existing 2m design. To achieve this, supplementary design packages in line with the overall design and the design enhancements above would be essential.

5.4 Production Tooling And Manufacturing Manual

Suitable jigs, fixtures and tools are needed to ensure consistent, high quality production of the windpump. The development of jigs and fixtures is one of the highest priority follow-on tasks; without them the accurate and repeatable production of components can not be ensured. This would undoubtedly lead to problems, for example, in fitting future spares during machine maintenance.

A clear and informative manual giving the precise tooling requirements and methods of production for every system component would ensure that the entire windpump manufacturing process can be successfully replicated by the existing partners (for instance in the event of re-training). This would also ensure that new partners could quickly be brought up-to-speed on recommended production practices.

5.5 Users' Manual

A users' manual is important for helping to ensure successful, reliable and safe (by operators and manufacturers) operation of the IT Power Small Windpump. The users' manual would effectively serve as a "best-practice procedure" for optimal erection and operation of the machine.

The manual would guide the user through the essential stages of site preparation, tower assembly, drive-train and pump circuit assembly, and system operation and maintenance to ensure that the client realises the optimum performance. The manual could also touch upon the basic principles of resource and needs assessments and system sizing principles, though it is anticipated that the user will necessarily have some knowledge of these procedures prior to selecting the machine.

5.6 Manufacturers' Seminar

During the final visits to the manufacturing partners, each of the partners indicated that they would find a seminar with their counterparts to be very helpful for streamlining the manufacturing process, to discuss marketing tactics and to highlight areas for manufacturing cost reduction. For instance, one area for collaboration could be the manufacture of the gearbox, which is the single most expensive component to produce, particularly in small volumes. It is conceivable that having all of the gearboxes cast in a single country and shipped to the other partners could prove more cost effective than each partner making individual arrangements. A manufacturer's seminar could address this and other key issues.

5.7 Testing Of Equipment In Developing Countries

The new IT Power windpump has been functioning well under the local test conditions encountered at the Silsoe College test site. However, the system's performance in various extreme environments, for instance at extremely high or low temperatures, or dry and dusty/sandy conditions, as will be encountered in some of the potential markets, has still to be established. From a marketing perspective, potential users are keen to see new technologies proven in environments which closely match their own. A programme of field-testing is required to prove system performance under such regimes and to highlight early on any problem areas that need to be resolved.

5.8 Local Market Studies

To assist in the establishment of worthwhile manufacturing joint-ventures for the IT Power Windpump, it is vital that the key markets for small windpumps are clearly identified and that specific local needs are investigated. Such an assessment has already been carried out in South Africa, where positive feedback led to the manufacturing license being granted to Joffe Sheet Metal (Pty) Ltd. It is proposed that similar studies be undertaken in other suitable countries to determine the demand for the product and to identify possible manufacturing and marketing collaborators.

5.9 Information Dissemination / Initiating New Manufacturing Partners

Dissemination of information about the IT Power Small Windpump, for example through the printing of technical / marketing brochures, would help to raise the profile of the new machine, and windpumps in general, to potential customers and potential manufacturers in other developing countries.

6. SUMMARY OF FINANCIAL EXPENDITURE

Expenditure on the project has been in-line with that predicted in the proposal. There have been no significant variations. The budget has now been spent.

7. NAME AND SIGNATURE OF THE AUTHOR OF THIS REPORT

This report has been prepared by Peter Fraenkel, Director/Senior Engineer; Frances Crick and Paul Cowley, Project Engineers.

Name	**Signature**
Peter Fraenkel	
Frances Crick	
Paul Cowley	