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# SUMMARY REPORT

WIND POWER CONSULTANT MISSION
SHELADIA ASSOCIATES INC.
RIVERSIDE, MARYLAND, U.S.A.

PROJECT: USAID SPONSORED LABORATOIRE DE L'ENERGIE SOLAIRE
BAMAKO, MALI

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WIND POWER CONSULTANT

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This report presents the summary findings and conclusions of the author during a six week wind power consultancy mission in Mali. All opinions, recommendations or conclusions expressed herein are solely those of the author, and do not necessarily reflect opinions or position of Sheladia Associates or USAID.

# WIND POWER CONSULTANT MISSION
# LABORATOIRE DE L'ENERGIE SOLAIRE - BAMAKO, MALI

## Forward

This document has been prepared as a summary report for a wind power consultancy on behalf of Sheladia Associates Inc. to the USAID sponsored Laboratoire de l'Energie Solaire (LESO) in Bamako Mali.

A wind power group, group energie eolienne (GEE), had been set up within LESO. The purpose of this consultancy was to provide technical assistance to the GEE as set out in the scope of work. As some work had been done by the group prior to the arrival of the consultant, this will be reviewed first.

## Status and Accomplishments of GEE Prior to Arrival

The status and accomplishments of the GEE prior to the arrival of the consultant are as follows:

1. Group had been organized with M.B. Toure as group leader; F. Kamissoko, support engineer; S. Diarra, technician.

2. Group leader Toure had visited various windpower organizations and installations in USA and Canada late in 1983. Report is included as Appendix 10.

3. Review of the project and report had been completed by ITDG "The Future Development of the LESO I Wind Pump" Report is included as Appendix 11.

4. Schedule for planning activities during 1984 had been prepared and is attached as Appendix 12. Most of the activities scheduled had been delayed 4-6 months pending arrival of wind consultant.

5. A comprehensive library of reference material had been assembled by LESO as a technical literature resource.

6. The LESO I windmill had been designed and tested at LESO test site.

7. The LESO I prototype had been installed at site in Konate just outside Bamako on new 12m tower, in May 1984.

8. New design for LESO II transmission had been started by workshop advisor, M. Andre Charette.

9. Initial attempts had been made a wind data logging and site assessment for various locales around the country.

# WIND POWER CONSULTANCY REPORT

## Scope of Work

The scope of work for the consultancy was established as the following guidelines:

1. Review the fundamental concepts of wind-powered water pumping and electrical generation systems with the LESO "Groupe Eolienne."

2. Conduct training in small wind energy conversion system design, and address structural and fatigue elements influencing system life.

3. Review blade design procedures, braking systems, tower design, etc.; and propose methods of wind system manufacturing applicable to the Malian situation.

4. Review or propose wind energy system monitoring procedures and recommend instrumentation for system performance data acquisition.

5. Introduce computer-assisted design modelling and system performance analysis into the LESO wind pump design program. Examine available software and recommend procurements.

6. Establish the procedure for a wind resource assessment program using available data, and recommend supplemental data acquisition hardware to expand the wind resource data base for Mali.

Two further items 7 and 8 were initially included, however, were deleted due to time constraints for the wind consultant. This was subsequently incorporated into the scope of work for the workshop advisor.

## Overall Work Plan

In order to carry out the field work in a systematic and comprehensive manner, an overall work plan was developed for implimentation.

Principle objectives for the work plan as established were:

1. Review and categorize the wind regime within the regions of interest.

2. Determine the types of wind mills and end uses that would be most suitable for the available wind regime.

3. Improve existing hardware and develop new designs to provide efficient and reliable machines to meet the criteria in item 2.

4. Establish techniques to monitor performance of field prototype installations.

By achieving these objectives it would be possible to ensure that all the important aspects of wind power utilization were well covered and understood by the GEE.

Further, work done in achieving these objectives would also involve considerable use of the computer facilities at the lab for modelling and analytic work. This would also enhance the wind team's capabilities for using computer techniques for further wind power for development work.

Finally, having completed this comprehensive work plan, it was felt that all the items included in the scope of work would be well addressed, and would thus allow the terms of the consultancy contract to be met.

## Scheduling

In order to maximize the benefits from the consultancy for the GEE, considerable planning and preparation was done for the schedules applicable to the field work. The schedules show the flow of the work and accomplishments of the consultancy for its duration.

They are presented directly following in summary form and as a readily accessible reference.

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## WEEK NO. 1

JUNE 30, 1984

### Goals:

1. Meet LESO and GEE project staff.
2. Review background information.
3. Prepare work plan for six week consultancy.

### Achievements

1. Goals as above realized.

## WEEK NO. 2

JULY 7, 1984

### Goals:

1. Complete review of project background information.
2. Review computer programmes and capabilities on hand.
3. Prepare comparison report on wind systems for continued development work by LESO/GEE.
4. Study tower cost effectiveness for optimization analysis.
5. Attend July "reunion consieul scientifique."

### Accomplishments:

1. Two basic computer programs received and reviewed.
   Software on Weibull wind analysis and height variations does not appear to be useful in context of project.
2. Comparison report was completed and submitted for typing report entitled, "Comparative Analysis for Wind Pumping Machine Development."
3. Tower cost effectiveness reviewed and correlations to be documented in report.

WEEK No. 3 JULY 14.84

Goals:

1. compilation and presentation of data for wind resource assessment.
2. commencement of tower no. 2 in workshop.
3. develop design of new transmission for LESO II to working stage so drawings for fab. can be completed.
4. design a new 4 m dia. rotor for LESO II
5. calculate the HMT exploitable for current and new rotors given the use of the available 60 mm dia piston pumps.
6. put LESO I machine back in operation (new cam req'd).
7. evaluate the cost of a 5 m dia rotor using local materials.

Accomplishments:

1. compilation and presentation of resource data underway (MBT)
2. work on tower commenced 14.7.84, however not all materials necessary to complete are available
3. system and design for new transmission & chassis finalized
4. new 4 m dia rotor design finalized, to be drawn up
5. HMT exploitable curves completed for windpumps using available piston pumps.
6. LESO I fitted with new cam and operational again.
7. more information on Whirlwind electric generating system received. Meeting for further evaluation to follow.
8. costs for 5 m dia rotor based on 12PU500 design summarized and included in comparative study.

WEEK No. 4 Goals

1. program computer to do pumping predictions based on mean wind speed data and standard Weibull function analysis.
2. start shop drawings for 4m dia rotor.
3. design tail for new 4 m dia machine and check structural connections
4. finish summary of 4 m dia rotor design work.
5. establish technique for field monitoring wind pumping systems.

July 21.84

WEEK No. 4

Goals:

1. program computer to do pumping predictions based on mean wind speed data and standard Weibull function analysis.
2. start shop drawings for 4m dia rotor.
3. design tail for new 4 m dia machine and check structural connections
4. finish summary of 4 m dia rotor design work.
5. establish technique for field monitoring wind pumping systems.

Accomplishments:

1. Drawings for new 4 m dia rotor started. However entire process is not proceeding too well and efforts will have to be made to improve the situation.
2. transmission/chassis design was modified to incorporate additional forward offset of the rotor, required so that the rotor will not strike the tower. Platform will have to be modified or moved lower. Further modifications were required as not all materials originally specified were available. Changes were made to incorporate the round stock and flat plate stock that could be obtained and used to complete the hub assembly.
3. the computer programme to predict wind speed-hourly probabilities and resulting wind pumping outputs has been developed. Documentation and familiarization with the program remains to be done.
4. a mathematical model and computer programme has been developed to describe the performance of a hinged tail on an offset rotor windmill. The existing SWD model was found to be too complex and unmanageable. The new model gives good correlation with wind tunnel test results. Documentation and familiarization with the model has commenced.

- pump rod on LESO I in field was repaired. Further work will likely be required to replace entire rod with 25 mm dia pipe or 12 mm dia round stock, to prevent further failures.
- familiarization with the Apple IIe and fortran and wordstar wordprocessing was undertaken with some frustrating moments
- techniques and programme for field monitoring machine performance not undertaken and will be carried forward.

WEEK No. 5 July 28.84

Goals:

1. complete documentation of wind regime computer model
2. complete documentation & familiarization of hinged tail mathematical and computer model.
3. design new tail for LESO II using hinged tail programme.
4. develop curved blade rotor model to computer programme. as time allows.
5. establish techniques for monitoring field performance of windpumping systems.
6. review information on Whirlwind electric system and decide on further action regarding proposed procurement and installation.

Accomplishments:

1. documentation of wind regime computer model completed and sent for copying and distribution

2. documentation for hinged tail model completed, and final report is being detailed. Computer model works on SWD wind tunnel test rotor data. Familiarization with parameters and model completed.

3. parameters for LESO II new tail finalized and programme to be run to verify and optimize these parameters.

4. curved blade model forwarded to week 6.

5. techniques for monitoring field performance study under review and will be forwarded for completion after field work completed.

6. review of information on Whirlwind electric system carried out in meeting with Messrs Dicko, Hart, Toure & Schmidt. Output predictions were given using model for wind regime analysis, see item 1 also. Final decision to be made by LESO on information and presentation given. Outlook is not favourable for wind regimes where average velocity is less than 10 m/s as payback is too long.

7. list of recommended reference material prepared.

8. drawings for LESO II rotor improved, for review week 6

9. list of computer programmes and files prepared see NAMES

10. report on findings with 12FU500 rotor prepared

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August 2,1984

Week No. 6

Goals:

1. complete reports to LESO direction as required

2. distribute information on LESO II hinged tail model & analysis

3. finish curved blade rotor fortran program, report and complete familiarization with results.

4. review construction details for LESO II rotor and tail vane with SAT.

5. order materials for LESO II rotor and tail vane so construction may start in shop.

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Accomplishments:

1. curved blade model completed and results reviewed. see ROTOR.FOR and RRR.FOR. Predictions for LESO II rotor completed.

2. LESO II rotor details reviewed for construction in meeting with S.A.T. & G.E.E.

3. bill of materials prepared for ordering LESO II rotor and tail materials

4. familiarization with all fortran programmes now on board

5. reviewed programme and accomplishments over course of consultancy with Toure, Dicko & Hart

6. presented hinged tail model and results for LESO II rotor for discussion and review. Design looks good as proposed, with operation maintaining 80+ degrees orientation for start-up and furling completely in 12-15 m/s winds.

7. final documentation and reports to be completed following termination of field work August 2,1984.

## SUMMARY OF WORK CARRIED OUT WITH GROUP ENERGIE EOLIENNE

As mentioned, an overall plan was developed for the field. The presentation and discussion of the objectives and achievements follows:

Objective No. 1: Review and categorize the wind regime within the region of interest.

There is considerable interest in having the LESO establish a better data base for the wind regime within Mali. This would serve two purposes, to be able to evaluate the use of wind derived energy vs. other sources of energy and to permit wind systems to be optimized for the available wind regime.

For data collection some previous work had been done by the GEE. Wind records for several met. stations had been collected, and a report on standardizing this data base was being undertaken by B. Toure.

Equipment for up to six wind data collection stations was on hand to do site-specific wind monitoring. This equipment had been installed at several locations. However, none had continued in operation in mid-1984. Minor problems and tower collapses due to cattle, had plagued the installations and put them out of service. As these difficulties were not unsurmountable, it was indicated that these stations could be put back in operation to continue to add to the data base.

Further work was done to utilize the data base to predict wind potential and optimize wind systems for the wind regime.

After reviewing the computer based analysis packages on hand, one of the programs for determining wind averages and standard deviations was deemed useful. This would take the available met. data and produce mean data from which further predictions could be made. Other programmes for Weibull distribution and height vs. wind speed were either too elementary, inaccurate or useful only for wind analysis outside the scope of standard wind pumping, ie. height vs speed correlations at heights greater than 50'. Copies of this software are found in Appendix 7.

A new computer based model for wind power output predictions was developed for the GEE. It is entitled "Wind Analysis for Estimated Velocity-Frequency of Wind Regime Based on Average Velocity," and is presented in Appendix 2. This model, makes it possible to use the limited field data to predict wind pumping or wind electric outputs for given wind regimes. With this information, wind utilization for power generation could be compared to other non-wind sources. Specific examples were done. Based on this information it was found that wind electric generation would not be cost effective unless regions with wind averages greater than 12 m/s could be identified.

Objective No. 2: Determine the types of windmills and end uses that would be most suitable for the available wind regime.

From the information available of the wind regimes for the regions of interest, it was possible to establish parameters and criteria for wind machines to operate in these regions. This was one of the initial tasks carried out during the field mission. The report covering this work is entitled, "Comparative Analysis for Wind Pumping Machine Development," see Appendix 1.

In summary, the report compares the various types of wind mills in terms of operating characteristics, and suitability for local operation and manufacture. Comparisons are also made using limited information on material and labour for fabrication costs. The report explains that the wind regime is too low for any uses other than low speed water pumping. Electrical generation requires much greater average wind speeds, and was therefore deemed not to be practical. A recommendation was made to continue the work on the LESO I type multi-bladed wind mill for water pumping as it is suited to the available winds and should be cost effective provided that a reasonable system life may be expected.

While the work done on this comparison study was to some degree beyond the scope of work for the consultancy, it was considered to be a good starting point for the field work, and was able to address some basic design philosophy for wind pumping systems.

The evaluation of electrical power generating windmills was also undertaken, as mentioned in Objective No. 1. As a Whirlwind system was under consideration for installation by LESO/GEE, this system was used as an example to predict expected power outputs from a given wind regime. As mentioned, the analysis indicated that outputs would be too low to be cost effective, see Appendix 2. For this reason, no further work was undertaken on wind electric generating systems for the GEE. Final discussion on the procurement of an electric system was referred to the next meeting of the scientific council.

Objective No. 3:

Improve existing hardware and develop new designs to provide efficient and reliable systems for water pumping applications.

The program to improve and develop designs for the wind mills was divided into three, rotor design, hinged tail control system design and tower design.

Rotor Design

As the existing LESO I multi-bladed rotor was suitable for a 3 m Ø design, work was undertaken to develop a 4 m Ø rotor. There were two objectives here, to produce a new more powerful rotor for the LESO II prototype machine, and to encourage the development of in-house design capabilities. A computer model was developed so that comparative analysis of various parameters such as blade shape, blade angle, blade camber etc. could be carried out. This program and description is found in Appendix 3. Sketches of complete design details for a new 4 m Ø rotor were given to the GEE so that the shop working drawings could be prepared.

Hinged Tail Control System Design

A mathematical model was developed for the hinged tail control system, so that the detailed design work for the new LESO II prototype could be completed. As there are more than 20 possible configurations to be considered as well as several thousand simultaneous equations to be solved in the optimization process, the model was programmed in fortran for the Apple IIe. This allowed the detailed design parameters to be selected which would permit detailed shop drawings to be drawn up.

The mathematical model and summary of computer model are presented in Appendix 4.

Tower Design

As the cost analysis in the comparison studies showed the tower to be a significant part of the system costs, it was of interest to show how costs could possibly be optimized, to improve the cost effectiveness of the total wind pump system. It was found that costs vs. height and rotor diameter are basically linear and if wind regime characteristics are known, some optimization can be done to maximize power outputs and cost effectiveness within a range of overall parameters.

A summary of these findings is presented in Appendix 5.

Objective No. 4: Establish techniques to monitor performance of field installations.

This is a long term objective, essentially one which will provide the final justification of whether wind powered systems should be used for specific applications in the renewable and remote energy utilization envisaged by LESO.

In summary, the report on performance monitoring entitled, "Evaluation of Wind Powered System Performance," shows that such monitoring can be done, however, will likely be very expensive and time consuming, and will likely prove to be most useful for trouble shooting systems which are not realizing their expected performance levels. A full report is contained in Appendix 6.

As time constraints on field portion of consulting limited the amount of effort that could be directed to this study, it was completed immediately following the field mission.

## RESPONSE TO SCOPE OF WORK

In order to ensure that the work carried out under the overall comprehensive work program also fulfilled the original scope of work, this was monitored throughout the consultancy, and reviewed in a meeting just prior to field termination.

The reponse to individual items in the scope of work is as follows:

1. Review fundamental concepts of wind powered pumping and electrical generation systems with the LESO/GEE.

   The pumping systems fundamentals were thoroughly reviewed during the field consultancy throught the course of designing the new LESO II prototype rotor and tail, establishing the HMT vs. V and rotor Ø for the existing 60 mm pumps. Other background fundamentals were well comprehended by the GEE prior to the start of the field work, and this allowed more time to be spent concentrating on more advanced development work.

   The fundamentals of electric systems were reviewed, and evaluations of electric systems for Mali carried out. The results have already been noted under Objectives No. 1 and 2.

   During the review meeting M.B. Toure noted that he had asked that this item be included in the scope of work, and concurred it had been satisfactorily completed.

2.&3. Conduct training in small WECS design, and address structural and fatigue elements influencing system life. Review blade design procedures, braking systems, tower design etc., and propose methods of wind system manufacturing applicable to Mali. These items are dealt with together as they both involve system design.

   Blade and rotor design methodology was discussed in depth, and the computer programs ROTOR.FOR and RRR.FOR were developed so that blade/rotor comparisons could be readily made. This would also provide information on torque and power loadings for structural calculations.

   Braking systems & hinged tart design was dealt with by developing hinged tail model and computer program TAIL.FOR and TSWD.FOR to do the iterative solutions. As noted in Objective 3, further information is found in Appendix 4.

   As the SWD report 77-3, "Static and Dynamic Loadings on the Tower of a Windmill," by E.C. Klaver covers the analysis of rotor loads for tower design, the only other work done on towers was the cost benefit analysis as presented in Appendix 5.

Having established the models to predict rotor and tail forces and incorporating the SWD static and dynamic load calculations, enough information is available to carry out a complete set of loading calculations for the wind rotor/tower system. Using results obtained from this, enough information is then available to the structural engineers so that the designs will be adequate to handle the expected normal operating loads, storm wind loads and cyclic fatigue loads.

Further discussions and training on design was carried out by demonstrating the techniques for determining starting to torques and characteristics, matching to pumps and system sizing for given wind regimes.

Finally a close liason was maintained with the S.A.T. and its advisor A. Charette, to ensure that proposed methods of manufacture would be appropriate for implimentation in the existing workshop.

4. Review or propose wind energy system monitoring procedures and recommend instrumentation for system performance data acquisition.

The report "Evaluation of Wind Powered System Performance" was prepared to directly address this requirement. See Appendix 6 for further information.

5. Introduce computer assisted design modelling and system performance analysis into the LESO wind-pump design program. Examine available software and recommend procurements.

Computer design and analysis models were developed for the following:

i rotor blade design
ii hinged tail design
iii wind analysis for estimated velocity-frequency of wind regime

With these programmes it is possible to predict the energy input to a wind system, design a wind rotor to produce the required power from the predicted wind input and design a hinged tail control system to protect the windmill. This provides the essential elements for a complete wind energy development program and greatly reduces the amount of manual calculations required to develop suitable systems for given sites and wind regimes. As mentioned, software for calculating average wind velocities and standard deviations were already on hand, and are adequate for the needs of the GEE. A listing of the new software is found in Appendix 8.

6. Establish the procedure for a wind resource assessment program using available data, and recommend supplemental data acquisition hardware to expand the wind resource base for Mali.

The report "Wind Analysis for Estimated Velocity-Frequency of Wind Regimes" addresses the question of wind resource assessment, and demonstrates how the standard Weibull function may be used to predict the energy available from specific wind regimes when the average velocity is known.

As six complete data acquisition systems were on hand at LESO, this should be adequate equipment to help expand the wind resource base for Mali. This, of course, will only be true if the equipment is installed in the field and kept operational for extensive periods of time. To date, this programme has not been entirely successful. Further recommendations will be addressed later in this report.

## Other Work Carried Out

Several other tasks were carried out which were beyond the scope of work for the project.

1. List of additional reference material for the LESO library was compiled, see Appendix 13.

2. Listing of all computer programmes and report files on disc was compiled, see Appendix 8.

3. Summary of the experiences by Kenya Industrial Estates with similar wind pump development program was prepared, see Appendix 9.

4. Constant liason with A. Charette was maintained to assist with design for new LESO II transmission.

5. Comparative study to justify direction of programme for GEE was prepared for discussion by the "consieul scientifique."

## CONCLUSION AND RECOMMENDATIONS

The wind power project being carried out by LESO/GEE can generally be said to be in good shape. The capabilities of the wind power group have already been demonstrated by the development of the LESO I prototype. Team members are enthusiastic towards the development program and have been building a good theoretical and practical hands-on base of experience.

The GEE program has identified most of the typical pitfalls that can plague similarly oriented projects. Such things as lack of good field data, problems keeping field instruments operational, difficulties in information exchange with other projects, quality control in fabrication, limited local materials, transportation difficulties and poor communications to field sites are frequently encountered problems elsewhere as well as in Mali.

However, these problems are by no means major obstacles, and are being handled relatively well by the GEE. In addition, the group has several advantages not necessarily enjoyed elsewhere on similar projects.

The program for the GEE has established realistic goals in developing wind hardware and establishing a wind data resource base. Other unrelated but often included developments such as pumping hardware or establishing full irrigation schemes are not included in the scope of work, as has been done frequently elsewhere.

The two Apple computers provide more than adequate capabilities for wind systems hardware design and analysis. The software programs developed during this consultancy should prove to be very useful for further wind machine development.

The resource people to turn wind power concepts into shop drawings and field hardware are available within the LESO. The workshops are equipped adequately enough to carry out all the fabrication tanks required.

And, materials such as angle iron, galvanized flat sheet, flat stock, bearings and fasteners can be obtained locally in Bamako.

The recommendations for the GEE for continued work are as follows:

1. Continue work on LESO II prototype and field installations.

2. Continue to develop design expertise and computer analysis capabilities. Design philosophy recommended on Comparison Study should be followed.

3. Continue programme for wind monitoring at selected sites, and insure that equipment is kept operational on a long term basis.

4. Establish and maintain good technical liasons with wind support group such as SWD, TOOL, IT Power, for continued technical back-up.

5. Forgo further work with electric systems unless sites with $V>12$ m/s can be identified, or if other systems are not cost effective.

Further long range goals could include:

1. Establishment of a wind systems field team that would visit instalations on regular intervals, performing maintenance and monitoring outputs. The establishment of such a team would be a new venture for a wind energy development group as it has not been done with other similar projects in Kenya, Botswana, Ethiopia, Sudan, Tunisia etc. This team would do much to ensure the long term success of a country wind program by keeping the wind pumps operational.

2. Procurement or development of a very low cost wind run meter which does not start to register until the wind passes the Vcut-in for a suitable wind pump system. This wind-run meter would give a low cost prediction of pumping potential while automatically compensating for periods of calm and very low winds.

3. Continue the evolutionary design work based on the experience with LESO I & II to develop the LESO III.

4. Procurement of a computer software design package that would facilitate the structural design analysis for windmill towers. Hopefully a lower cost, small computer based version of STRUDL or equivalent will become available.

## APPENDICES

| APPENDIX NO. | TITLE |
|---|---|
| 1 | COMPARATIVE ANALYSIS FOR WIND PUMPING MACHINE DEVELOPMENT |
| 2 | WIND ANALYSIS FOR ESTIMATED VELOCITY-FREQUENCY OF WIND REGIME BASED ON AVERAGE VELOCITY |
| 3 | WIND TURBINE ROTOR DESIGN ANALYSIS USING COMPUTER MODELLING TECHNIQUES |
| 4 | WINDMILL CONTROL AND BRAKING SYSTEMS |
| 5 | ESTIMATED TOWER COSTS VS. HEIGHTS FOR WIND PUMPING SYSTEMS |
| 6 | EVALUATION OF WIND POWERED SYSTEMS PERFORMANCE |
| 7 | EXISTING PROGRAMS FOR APPLE COMPUTER ON-HAND |
| 8 | LISTING OF FORTRAN AND WORDSTAR PROGRAMS PREPARED FOR GEE |
| 9 | REPORT ON FINDINGS BY KIE ON WORK WITH 12PU500 |
| 10 | TRIP REPORT BY M.B. TOURE (REF. ONLY) |
| 11 | FUTURE DEVELOPMENT OF LESO MARK I WIND PUMP ITP REPORT (REF. ONLY) |
| 12 | SST PLANNING DES TACHES 1984/GEE, (REF. ONLY) |
| 13 | LIST OF ADDITIONAL REFERENCES FOR LESO LIBRARY |

# APPENDIX 1

## COMPARATIVE ANALYSIS FOR WIND PUMPING MACHINE DEVELOPME

W. SCHMIDT
GEE/LESO
JULY 1984

17

# COMPARATIVE ANALYSIS FOR WIND PUMPING MACHINE DEVELOPMENT

LESO Wind Power Group - Groupe Energie Eolienne

There are basically two groups of wind machines to be considered overall for capturing the wind's potential energy. They are horizontal axis wind machines and vertical axis wind machines. The axis refers to the axis about which the main rotor turns. And, within these groups there is a range of solidities for the various rotors (ie the total surface area of the blades vs. the total projected swept area of the rotor), which generally dictates the tipspeed ratio, the speed of the tips of the blades relative to the wind, and hence the torque output of the machine (since coefficient of performance Cp equals tip speed ratio, $\lambda$, times the coefficient of torque, Ct, machines with equal diameters producing equal power output at different tipspeed ratios will have torque outputs in the inverse ratio of the tipspeeds).

Before the comparative analysis is carried out between the vertical and horizontal axis machines, there are several general remarks to be made which relate to either configuration, and are specific to the project at hand within the LESO G.E.E.

i) The pumps to be used are those available locally here in Bamako, manufactured under licence. In all cases, costs and operation will not be discussed as they will be taken to be equal for all systems. The locally made pumps are 60 mm dia. reciprocating piston type with a leather cup seal, a lift check foot valve and a bronze/plastic plate valve on top of the piston. They have essentially constant torque requirements and have an estimated total efficiency in the 80% range. Piston and rod speeds will be limited to maximum values to prevent rod buckling and waterhammer as is typical for this configuration.

ii) Wind rotors and systems will have to be designed for the moderate regional winds. The design velocity, Vdesign, for the more southern regions of the country is in the 3 meter/second range with cut-in velocities, Vcut-in, set at Vcut-in = 2 m/s. Cut-out velocities, Vcut-out, may be set quite low, in the 7-10 m/s range, as little benefits will be realised by trying to capture the infrequent energy developed at these higher velocities. However, survival wind speed design values should not be compromised as winds in excess of 35m/s have been recorded near Gao.

iii) machines to be manufactured entirely from locally made or available materials and components to ensure ease of fabrication and maintenance.

iv) consistant design philosophy should be used throughout the prototyping and development of the machines. Key design strategy should include:

a) long-term survivability in terms of overall structural integrity must be incorporated into all parts of the system.

Nothing will undermine a development programme for wind machine more quickly than losing even one machine, no matter the circumstances, prior to completing the development work. Component duplication to avoid catastropic damage due to a single failure (ie leg in a 3 leg tower, or only one bolt at a connection where two can be installed) is to be encouraged.

b) facility to carry out modifications and maintenance in the field should be permitted as long as it doesn't compromise the durability of the machine.

c) close fits and tolerances, bearing assemblies, etc. should be completed in the shop and sent to the field as assembled units wherever possible.

d) quoting from the World Bank Report (ref. no. 1): "In general, promoters of unconventional windmills should be asked to demonstrate at early stages that there are specific quantifiable advantages other than 'novelty' to their proposals." Early stages should be interpreted to mean prior to the detailed design stage.

e) system cut-in and design points: a big rotor driving a small pump will deliver much more water than a small rotor coupled to a larger pump waiting to start at a less frequent higher wind speed. This is especially true for systems which are to be designed and matched for operation in lower average speed wind regimes, where typically they will spend 30-40% of the time operating in the winds just marginally above Vcut-in.

f) Components should be designed to be lightly stressed, reasonably easy to make and serviceable. The elegance and appeal of the design should be in its straightforward simplicity and robustness.

g) threaded fasteners should, wherever possible, be double locked, preferably with lock-tabs, to prevent loosening under cyclic vibratory loads.

h) windmill rotors and systems should be developed with a strategy to providing basic concepts which may be scaled up (or down) based on the experience of previously successful work. The design detailing used in machines such as the Comet, Aeromoter or Dempster machines should be considered to be an excellent guide for the development of any new rotors.

And finally:

v) while the wind is free, one should never expect the wind systems to be 'free'. However, the economic and competitive comparisons should not be ignored; and, where high transportation costs are involved for other systems, these often prove to be a leading advantage, especially for regions with good wind regimes.

## VERTICAL AXIS WIND-POWERED SYSTEMS

Advantages and disadvantages:

The vertical axis machines are those which gain power whil running with and across the wind, and show a net surplus when tallie against losses while running back into the wind. They turn on an axi perpendicular and usually vertically oriented to the oncoming wind They are characterised by their 'simplicity', although this can b deceptive, as will be explained later. Examples of vertical axi machines include the Savonius, Filippini and ITP 4 bladed rotors a high solidity devices; and the Darrieus in its various forms, th Musgrove Variable Geometry (VAWVG), the Pinson and McDonnell-Dougla gyro-rotors as low solidity machines.

The low solidity machines can be dismissed outright as they are not suitable prime movers for constant torque piston pumps. First, they are not self-starting, and, in addition, exhibit "un-nested" torque characteristics. This undesirable feature, as explained ir work done at Sandia Labs USA (ref. no. 2), means that the rotor and pump system will actually lose rpm when exposed to a significant gust of wind, falling on the the corresponding curve on the left side of the torque peak. At this point the system is unstable. Any further perturbation in the Torque-RPM relationship causes the system to slide back along the curve until it finally reaches zero rpm,stalled. Due to the negligible starting torque, it will not restart. (see attachment no. 2 for further information)

The high solidity machines have enjoyed some attention in research carried out at various institutions around the world. However, as far as shown in the lierature, only one system has been developed through to the commercial production stage. As that is in Brazil, few details are known on the success of this commercial venture.

In general, despite the mentioned 'simplicity' of the rotors, a large part of be coming from there being no need to provide means to orient the rotor into the wind, this feature appears to be a major problem in the design. The mechanisms required to protect the rotor against damaging highwind velocities are often complex or unreliable. The Filippini rotor, suggested to be self-limiting under high wind conditions, has shown this not to be the case during field trials with a 4 m dia. x 4 m high rotor in Botswana. Even the complex and expensive 200 KW Darrieus prototype built in Canada by National Research Council late in the '70's self-destructed during tests in 1978 when the aerodynamic braking systems failed.

The mechanisms for horizontal axis machines which orient the rotors to the wind also provide a very effective means whereby the rotors may be turned out of the wind. They then present only 10-15% of the total swept area to the higher winds, increasing the chances of survivability, a feature not enjoyed in the vertical axis concept.



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The Savonius rotor was thought to be a design worthy of further consideration due to the publicity given to it by the Brace Research Institute and VITA in the early 1970's. While it is true that this rotor will produce power from the wind, most research work has been with small low cost systems. These have been typically two 200 l. (45 gal.) drums cut in half or at best systems 2 m dia. x 8 m high such as that built here in Bamako early in 1980's. After the investigations are completed, or sometimes before, the work is generally abandoned so that other designs within the wind rotor field may be pursued. There are several possible explanations for this:

i) the overall power co-efficient for the Savonius is low, only 50% that for the multi-bladed American-style windpumping rotor (see attachment no. 1).

ii) corresponding starting torque: although the rotor self-starts (when built up in more than one stage) unlike the lower solidity cousins, its net starting torque is low, due to the lower overall performance. In fact, for a single stage rotor, the starting torque is negative in some orientations.

iii) the geometry of the rotor requires a central gap for maximum performance. Any obstructions in this gap, such as a shaft will decrease the overall output levels accordingly.

iv) the solidity of the rotor ie. the surface area of the blades vs. the swept surface area from which the power is extracted is very high: approximately 1.5x for the blades alone and up to 2.0x for rotors using end-plates as required for good performance. This increases total costs, as it makes the rotors quite heavy on a specific swept area basis.

v) the rotor is not well suited to scaling up. As mentioned, the largest rotor built that has been documented has been in the 2 m dia x 8 m high range, or 16 $m^2$. This is comparable to a 4.5 m dia horizontal rotor in swept area and a 3 m dia rotor, when Cp=.30, in output. Horizontal windpump rotors have gone to 8 m dia on a commercial scale to produce useable power for high output or deep well locations. At nearly 50 $m^2$ area, it would require a Savonius rotor 10 m dia x 10 m high or equivalent to match this performance. The level of effort required from an engineering and structural stand point to develop such a rotor would make this a very expenesive if not impractical goal.

vi) tower and support design for the Savonius rotor is perhaps its greatest shortcoming. As mentioned already, the central gap geometry requirements put restrictions on shafts for support. As well, the high solidity and vertical axis makes support from anywhere but below and above the rotor difficult, unlike the Filippini or VAWVG designs and horizontal rotors which may be supported at or near a central point in the rotor. Guy wires and top supports, when used for non-cantilevered towers are awkward. For example: for the 2 m dia x 8 m high machine with a mean rotor high of only 6 metres, the upper support was at 13 m to clear the tips of the blades at only 2 m dia.

Furthermore, field experiences are showing that guyed towers have a poor reliability in less than optimum conditions.

Forces transmitted to the tower are quite high as well. The 200% area factor required for equivalent power means double loadings on the tower, especially critical in high winds when the rotor cannot be "furled". Also, the Savonius develops a "Magnus Effect" force perpendicular to the wind direction, requiring 50% additional structural strength in the tower to resist this while the rotor is turning. As tower costs vs. loading are linear, and the greatest percentage of the system costs are in the tower, increased loads and increased rotor weights have large negative cost benefits. Increased tower loads must also be reflected in the amounts of concrete and foundation work required for the tower.

vii) unless large diameter rotors are used, the high rotational speeds of the small diameter rotors even when only running at tipspeed ratios in the 1.0 - 1.5 range, generally require some sort of gear reduction so that reasonable pump rod and piston velocities may be maintained. This, of course, means additional complications in the transmission systems.

viii) as large rotors have not been pursued, there is no significant body of design or experimental information available to assist in prototype problem solving.

In summary, the drawbacks of the Savonius rotor are primarily in its low efficiency, difficulty in scaling up to good commercial size, difficulty in providing tower and other supports to easily raise the rotor up out of the low velocity sub-boundary layer winds, and its high specific weights leading to higher overall costs. So, although this rotor design enjoyed considerable publicity during the early stages of the renewed look at wind systems, it has become apparent that its uses will continue to be very limited. These will only be for very small rotors when the nearly negligable power outputs are offset by using low cost surplus materials; and, for small "sailing" craft which can utilise its magnus effects.

An economic comparison is appended. (see attachment no. 5).

## HORIZONTAL AXIS WIND-POWERED SYSTEMS

Advantages and disadvantages:

The horizontal axis wind rotors are the more typical windmill style machines. They range in variety from the high solidity fan-type "American" windpumpers to the 4-bladed Dutch windmills used for low-head water lifting and grain grinding, and on to the high speed 3-bladed, 2-bladed and even single-bladed propeller style low solidity rotors used in wind electric systems.

While the low-solidity high-speed machines generally enjoy the highest peak efficiencies, in the 35-50% range, their low starting torques due to the low-solidity makes them a poor choice for constant torque pumping systems. Even the variable pitch rotors, which are much more complex and expensive, do not exhibit good starting performance as required unless used with torque multiplying drive systems, again due to the low rotor solidity.

The high-solidity multi-bladed "American" style sheet metal rotor has been the traditional choice for water pumping systems using reciprocating down-well piston pumps. They often have back-geared transmissions for reducing shaft speeds on the smaller diameter (up to 5 m dia.) rotors. This configuration enjoys several advantages:

1. high starting torque, ideal for constant torque piston pumping systems.

2. low tipspeed ratios, generally $\lambda = 1.0$ for Cp max., minimizing gear ratios required to limit pump rod speeds. In many cases, rpms are low enough to directly drive the pumps.

3. "nested" torque curves so that the rotor and system do not "fall off the curve" under gusty conditions (see attachment no 2)

4. lightweight, strong rotor designs permitting economy of materials, field assembly, and replaceable components. The majority of the commercial machines use a stressed hoop design in which two concentric hoops are pulled into compression by radial tension spokes, similar to a bicycle wheel, albeit much larger. The blades are fastened to the hoops and may be easily replaced if damaged, corroded or "shot through with rifle bullet holes".

5. effective furling and braking systems using the tail vane and additional manual "pull-out" levers protect the system from high wind loads.

6. often, one section of wooden pump rod is provided as a weak link to protect the rotor and transmission should the pump jam or the rods buckle.

7. the design information and field experience gathered over the more than 100 years of use has produced a large range of sizes, from 1.8 m dia. to 8.0 m dia., having very good reliability and survivability with minimal maintenance requirements (in the order of 20% of that required for automobiles), demonstrating the possibilities for successful scaling up of similar designs.



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The commercially produced systems have one distinct disadvantage when considered with a worldwide perspective. They are becoming increasingly more expensive. Furthermore, they are produced in limited numbers of factories located in the areas of traditional widespread usage, the American Great Plains, Argentina, Australia. The same heavy cast-iron construction which makes them so durable is adding to current costs and adds to transporation costs.

Considering this, there has been considerable interest in producing lightweight steel fabricated designs, using available standard sized materials and local labour within the countries where they will finally be installed. Several rotor designs and systems have been developed along these lines, including the Kijito machine, the German sail-wing, the Ghazipur 12PU500, Dutch WEU rotor, the LESO I and Jensen's high speed 6 & 8 m dia. SK rotors.

In order for these systems to be competitive with the commercially available systems, they must sit favourably on the charts showing the f.o.b. prices vs. size and power outputs. (see attachment no. 6). Furthermore, they must be developed to a state in which they are to be considered to be reliable, requiring only yearly or twice-yearly maintenance, or else religated for use only in low lift irrigation pumping systems where constant attention is available.

Of the systems mentioned above, the Jensen design and Dutch WEU rotor will not be discussed as they are either too experimental or too little information is available for comparative purposes.

<u>The KITJITO machine</u>, developed in Kenya by BHEL with the assistance of ITPower, while showing advantages on the graphs, may not enjoy these benefits when transportation and importation costs are included. (note too that the Kijito machine was developed in collaboration with ITP, the authors of the World Bank report, so there could be some tendency to show this design in its most favourable light).

<u>The Ghazipur 12PU500 system</u>, developed in India by Dutch WOT, has been produced in numbers, 50 or so, and used successfully for irrigation pumping. For uses above 10 m pumping head, experience in Kenya where several machines have been built by the Kenya Industrial Estates Renewable Energy Group has shown that more development is needed. The transmission has been inadequate under sustained operation. This design does show good promise for continued work, especially as the rotor has already been scaled to 5 m dia. and prototype tests on 8 m dia have been undertaken in Holland. Cost comparisons have been summarized and included in this report (see attachment no. 4).

<u>The German sail-wing design</u> may merit further consideration after field trials demonstrate its reliability and cost effectiveness. Several key points must be kept in mind, however:

1) furling, braking and overspeed protection - the machine is a down-wind self-orienting design. As such, it does not employ or require a tail vane. However, as with the vertical axis rotors,

this may be a false economy. Provisions for overspeed protection must be provided by other means. In this case, a manual disc brake is incorporated into the design, along with a ~~verbal~~ note of caution: prior to storms, high winds (or long periods of inattention) the sails must be manually furled and the brake locked to prevent damage to the rotor and entire system. There is no automatically deploying protection system so the machine must be relegated to the rank of the well-attended for the time being.

2) the use of imported sail-cloths especially in a country which does not use sailing vessels as a major means of transportation along a sea coast, may prove to be a large problem unless adequate supply or an acceptable local substitute can be guarenteed.

3) the tower design, although incorporating double guys for redundancy, may still not enjoy the long term security of a steel-angle, four legged tower. Of course, if field experience dictates the need for this greater security, a suitable tower design may be used to replace it.

Cost comparisons may be available after the field trials.

<u>The LESO I design</u> has been developed and prototyped at LESO and has demonstrated that the rotor and transmission systems should provide adequate reliability for pumping applications below 10 m. The rotor provides good starting torque and the high wind furling is operative. The system lends itself to optimization for the available wind regimes throughout the country.

The cost comparisons have illustrated that the design sits favourably on the specific cost curves. Prototype costs in the $500 US/m$^2$ range sit below the small scale production curve, and projected costs for additional machines including tower indicate $200-$250 US/m$^2$ may be possible, comparing favourably with mass production figures on the same chart. (see attachments no. 3 & 6)

The design and prototype work has shown that the system is suitable for fabrication in the present workshop facilities. It also has shown the required reliability (for up to 10 m pumping loads) and survivability. The design lends itself well to being scaled up based on the expertise and experience available within LESO.

The design and development work for the transmission and rotors required to pump at heads above 10 m can be provided through the present GEE and SAT.



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## CONCLUSIONS:

The work in the wind pumping machine development should emphasize the use of the horizontal axis high-solidity rotors with good starting torque. The experience to date with the LESO I has shown this design to be cost effective on an overall basis and shows good promise for continued successful development.
Further work based on this should also be continued with the LESO II design which will provide a more robust transmission, chassis and larger diameter rotor which will be suitable for use with pumping applications from depths greater than 10 m.

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## Attachments:

1. Co-efficient of performance vs. tipspeed ratio curves
2. "nested" and "un-nested" torque vs. RPM curves
3. LESO I cost summary
4. Ghazipur 12PU500 rotor cost summary
5. Savonius rotor cost summary & comparison
6. Rotor area specific cost vs. dia curves (World Bank fig. 12)

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## References:


1). "World Bank Report" Wind Technology Assessment, vol 1 and vol. 2, UNDP Project GLO/80/003 executed by the World Bank, IT Power, February 1983.

2). Engineering of Wind Energy Systems, Banas et al., Sandia Labs, USA, Wind Technology Journal, vol. 1, Spring 1977. AWEA.




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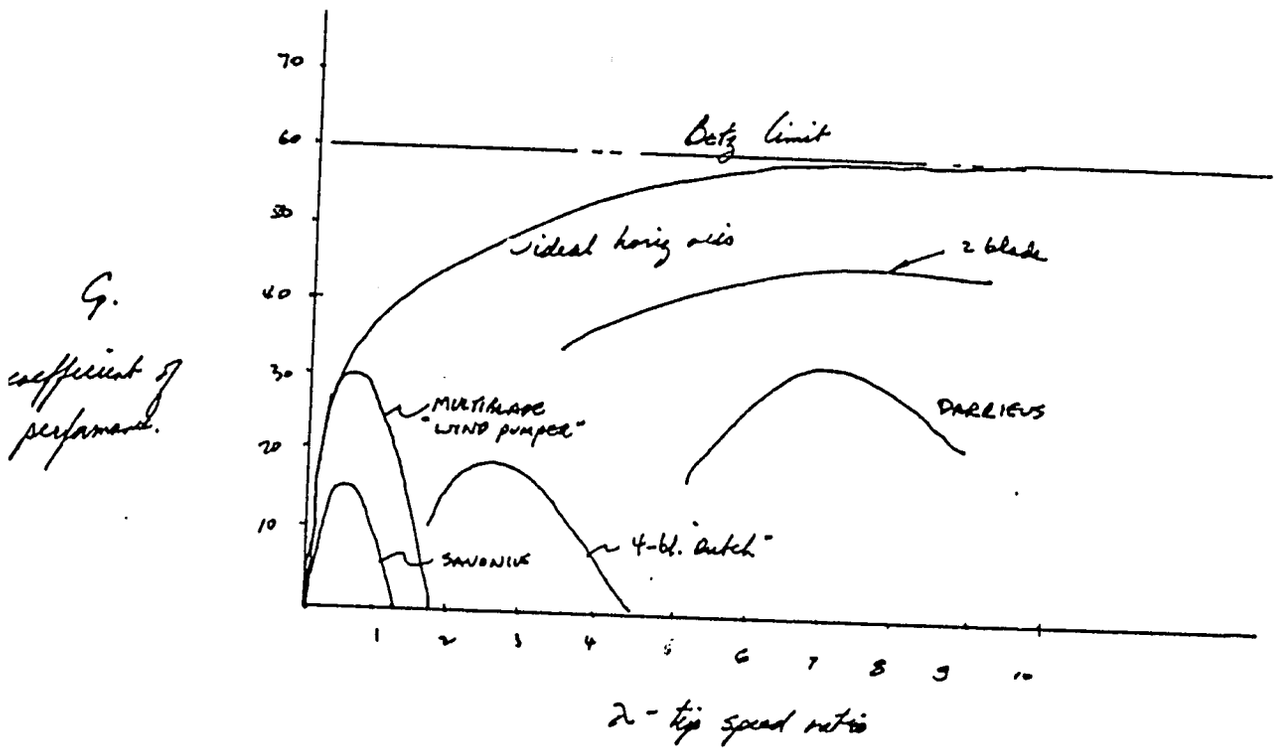
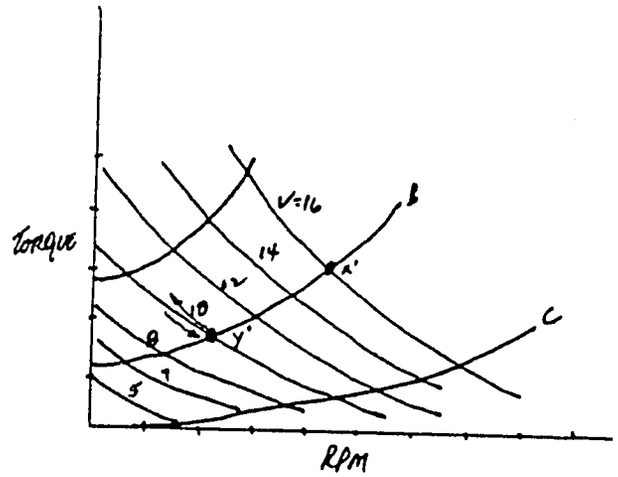


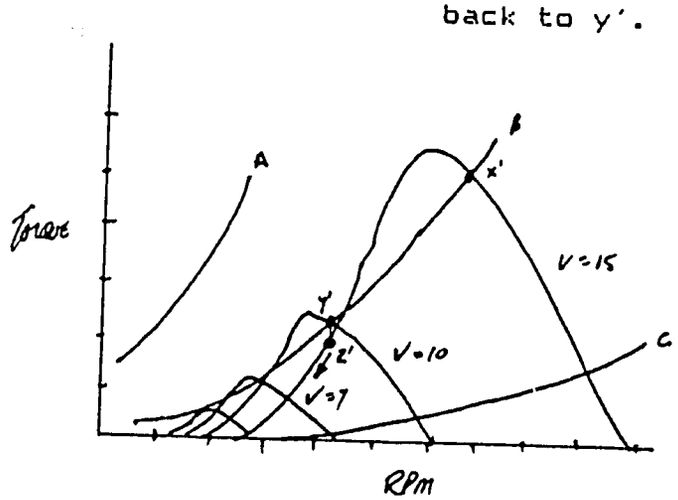

ATTACHMENT No. 1: Co-efficient of power vs. tipspeed rati

reference: "Wind Machines", Edridge




(A) "NESTED" TORQUE CURVE

system operating at x', when wind falls to V=10, system matches at y', small chang in rpm and the system ride along the curve, falling back to y'.




(B) "UN-NESTED" TORQUE CURVE

system matches at x', when wind drops to V=10, system matches at y'. Wind returns to V=15 and system goes to z', when rpm fluctuates match point continues to fall down curve to zero torque and rpm.

ATTACHMENT No. 2: Torque vs. RPM curves

ref: Eng. of WES, Banas et al, Sandia WTJ, vol 1, no 1, 1977. AWEA.

## COST SUMMARY FOR LESO I (1982)

| Summary of materials: | mtl. | quantity | total |
|---|---|---|---|
| tower | angle - 50x50x5 | 60m | 139kg |
| | angle - 40x40x4 | 85m | 157kg |
| | rod - 12 mm dia | 34m | 30kg |
| | pipe - 55 mm dia | 1.3m | - |

| | | |
|---|---|---|
| Total cost for tower | 195,000 | CFA |
| Total cost for tail & rotor | 45,000 | CFA |
| Total cost for chassis & transmisson | 6,000 | CFA |
| Total costs for materials | 246,000 | CFA (1982) |
| Shop labour prices per hour | 2,000 | CFA (1984) |

Total labour estimated for 1st prototype 10 man-weeks

Total labour estimated for production 4 man weeks

Size of LESO I machine rotor 3 m dia

| | | |
|---|---|---|
| Total cost per $m^2$ for 1st prototype | 15.000 | CFA/$m^2$ |
| Total cost per $m^2$ for production | 8,000 | CFA/$m^2$ |

ATTACHMENT No. 3: Cost summary for LESO I.

ref: GEE (7.84)



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## COST SUMMARY FOR GHAZIPUR 12PU500 5 M DIA ROTOR

Prices in CFA for Bamako (1984)

| Summary of materials | CFA/unit | amount | total |
|---|---|---|---|
| 1. 1 mm galvanized sheet | 6,000 (1mx2m) | 4 1/2 | 29,000 |
| 2. 2 mm galvanized sheet | 21,000/$m^2$ | .75$m^2$ | 7,500 |
| 3. rings 30mmx6mm flat | 3,125/6m | 18m | 9,500 |
| 4. angle 40x40x4 | 6,00/6m | 13.75m | 13,750 |
| 5. bolts, nuts washers | | | |
| 6x90 | 100/each | 120 | 12,600 |
| 12x100 | 100/each | 4 | |
| 12x125 | 100/each | 2 | |
| 6. paint | 2500/kg | 5kg | 12,500 |
| | sub-total | | 84,490 |
| | gasoline etc | | 5,200 |
| | misc. | | 3,125 |
| | overhead 15% | | 13,929 |
| | TOTAL CFA | | 106,737 |

Cost per unit area of rotor 6000 CFA / $m^2$

Size of the rotor 5 m diameter

ATTACHMENT No. 4: Cost Summary of 5 m dia Ghazipur 12PU500

ref: GEE (7.84)



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ATTACHMENT No. 5: Savonius Rotor Cost Comparison

As the Savionius rotor has not been costed out by LESO on an as built basis, comparison will be shown as a ratio against equivalent costs for the LESO I design, the Savonius being scaled to produce equivalent power. This will then be compared with the cost figures used by the Ecole National des Ingenieurs when they built the 2 m dia x 8 m high rotor in 1982.

LESO I Technical :

| | | |
|---|---|---|
| estimated Cp | 0.25 | |
| rotor area | $7.2m^2$ | |
| hub height | 12m | |
| No. blades | 16 | |
| est solidity | 0.80 | |

Cost summary

| | | |
|---|---|---|
| Tower 12m high | 195,000 | CFA |
| 3m rotor & tail | 45,000 | |
| transmission & chassis | 6,000 | |

Savonius rotor Technical summary:

| | |
|---|---|
| estimated Cp | 0.13 |
| average rotor height | 9m |
| rotor solidity est. | 1.6 |

To compare the costs of a Savonius and LESO I producing equal power two ratios will be applied to the rotor area to give this equivalence

Factor to correct for difference in Cp: P'=CpLESO/CpSav.

Factor to correct for difference in average rotor height using the power law to equate the heights and then cubing to give power:

$$V' = (H\ LESO/\ H\ Sav)^{\frac{1}{5}}$$ where 1/5 is roughness coefficient

$$PP' = (H\ LESO/\ H\ Sav)^{\frac{1}{5}\times 3}$$

Therefore the correction which must be applied to the area of a Savionius rotor is:

$$A\ Savonius/A\ LESO = P' \times PP'$$

And, as the Savonius has a much higher solidity for the rotor area, this factor must be applied as well to reflect in the costs:

solidity correction S' = solidity Sav/solidity LESO

Therefore the ratio of the costs will be the ratio of the areas times the ratio of the solidities:

Cost Savonius/cost LESO $C'' = P' \times P'' \times S'$

Therefore $C'' = .25/.13 \times (12/8)^{\frac{3}{5}} \times 1.6/.8$
$= 4.9$

The estimated costs of a Savonius rotor to a LESO rotor producing



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the same rated power will be 4.9 times.

Now, to calculate the same factor for the cost of the tower, corrections will have to be applied for the tower height and the increased drag forces.

As the power produced by the two rotors is equal, the net drag developed across the rotors should be equal as well. However, the Savonius develops a Magnus force equal to the drag force, directed at right angles to the drag vector. Therefore the total orce generated on a Savonius tower will be 1.42 x drag.

As tower costs have been found to be proportional to the rotor diameter ( area $^{1/2}$ , and drag force is a function of area) and tower height, a tower cost factor can be found:

$$\text{tower cost factor } T' = (\text{drag force})^{1/2} \times h\ \text{Sav}/\ h\ \text{LESO}$$
$$= (1.42)^{1/2} \times 8\text{m}/12\text{m}$$
$$= 0.79$$

Therefore a factor of 0.6 can be applied to ratio the cost of a tower required for a Savonius rotor to that required for a LESO rotor producing the same power.

Next, from the LESO cost summary, it is estimated that the cost breakdown between the rotor and the tail is .75/.25, required as the Savonius rotor doesn't require a tail.

Therefore the total estimated costs for and equivalent Savonius rotor using the correction factors would be:

| | | |
|---|---|---|
| rotor cost x .75 x area cost factor | = | 45,000 x .75 x 4.9 |
| | = | 166,000 |
| tower cost x tower cost factor | = | 195,000 x 0.79 |
| | = | 154,000 |
| transmission cost, (same) | = | 6,000 |
| Total cost estimated for Savonius | | 325,400 CFA |

The total cost ratio is approximately 135% for materials only.

Labour costs would also be increased due to the larger and heavier size of the Savonius, and would be estimated to increase total costs by an additional 130-150%.

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Previous cost figures for the 2 m dia x 8 m high Savonius built at the Ecole National des Ingenieurs are available: (1982)

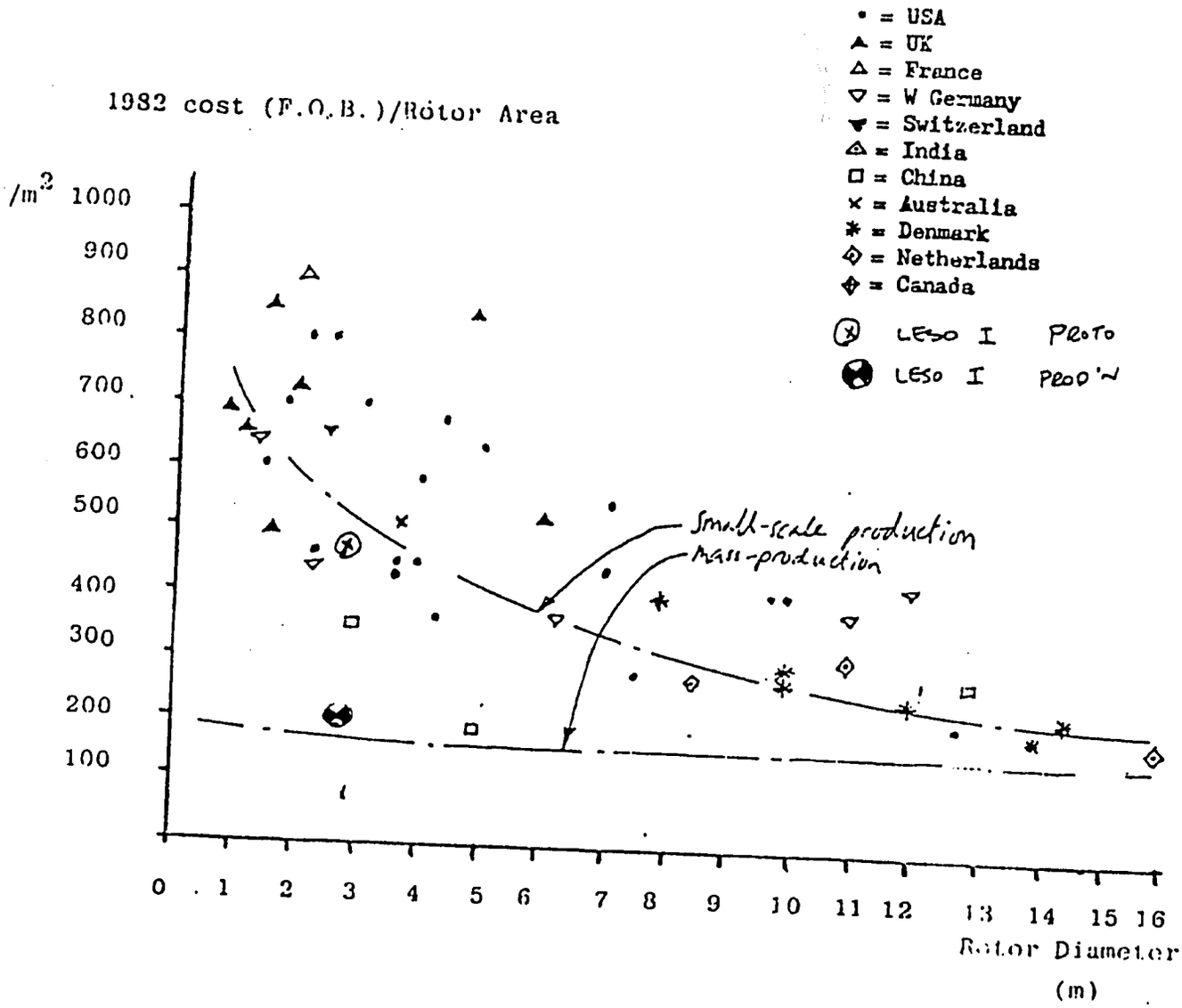
| Component | total price | material/labour | materials only |
|---|---|---|---|
| rotor | 151,250 | 50/50 | 75,625 CFA |
| tower | 225,000 | 50/50 | 112,500 CFA |

Using the previous figures for increased rotor area costs become

| | |
|---|---|
| rotor x 4.9 x 7.3/16 | 390,980 |
| tower x 2.2 % (incr. area) x 8/6 incr. height | 223,000 |

These figures indicate that the previous ratios are f reasonable and can be used to indicated predicted costs for a Savonius rotor producing equivalent power to a LESO rotor.

In summary, it is indicated that for the 3 m dia sized LESO rotor a Savonius rotor producing the same power would cost approximately 150 - 200% more. As the sizes increase, the proportional costs would also increase due to the higher specific weight of the Savonius rotor.




ATTACHMENT NO. 6: ROTOR AREA SPECIFIC COST VS DIAMETER

ref: World Bank Report, 1983, ref no.1

# APPENDIX 2

## WIND ANALYSIS FOR ESTIMATED VELOCITY-FREQUENCY OF WIND REGIME BASED ON AVERAGE VELOCITY, V, AND COMPUTERIZED MODELLING OF PREDICTED WATER AND ELECTRICAL POWER OUTPUTS

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GEE/LESO
JULY 1984

WIND ANALYSIS FOR ESTIMATED VELOCITY - FREQUENCY OF WIND REGIME BASED ON AVERAGE VELOCITY, V, AND COMPUTERIZED MODELLING OF PREDICTED WATER AND ELECTRICAL POWER OUTPUTS.

This discussion paper develops a technique to provide standardized Weibull function wind predictions for local wind regimes when only V average wind speeds are known. It also provides a computer simulation for water delivery from a wind pump located at the site, or for electrical generation for a wind generator at the site.

The technique is based on using the Weibull function. This is basically a function that has been developed from the analysis of empirical data which indicated that the wind regimes may be characteristized in most regions by the use of this Weibull function and two modifying parameters, k and c. Note that the function is also standardized by using the values for average velocity at 30 feet, the standard reference height for wind measurements by WMO.

Several assumptions and estimations are used in developing this technique based on the Weibull function:

1. as the wind regimes in Mali are not influenced by any major regional geographic features, ie hills, lakes, extensive forests, but more by world scale factors, ie large land mass with considerable desert areas, some distance to ocean etc. the characteristics are assumed to be well represented by a standard Weibull function.

2. as detailed information is lacking on wind characteristics which would facilitate the calculation of the applicable k and c values, these will be estimated based on information by Frost et al. ref no. 1, see figure (1) for c and by Justus, ref no. 2, see figure (2) for k. Following the inital evaluations of the Weibull function using these estimated values for the k and c parameters, a sensitivity analysis will be peformed to indicate any trends in errors that these estimations may introduce.

3. as the wind speeds are low in Mali, particular attention will be given to the velocity-duration values near the cut-in speeds, and less to the high wind values which contribute little on an overall basis to power and pumping production.

4. annual average wind speeds will be used, however in regions where there is expected to be signficant variations in seasonal averages, some consideration will have to be given to these factors in further analysis.

5. wind-pump performance will be modelled with a variety of cut-in speeds and average velocities. The system is considered to start pumping at the cut-in speed and stop when the wind falls below it again. No credit will be given for inertia or dynamic effects which will allows the wind pump to actually run below the cut-in velocity or to give more than 100% volumetric efficiency as is possible at

some pumping speeds. This can be modified later by changing the effective cut-in velocity based on field data if deemed necessary.

6. Wind pump characteristics are assumed to be linear after start-up so that the rotor speed may be approximated by wind run. Characteristics of electrical generating systems will be taken as those given by the manufascturers or in the literature, generally following the power curve up from cut-in to rated power and then remaining constant until cut-out velocity is exceeded, when power is no longer produced.

7. The values for the velocity intervals will be kept small and the arithematic mean for the interval will be used as the value for calculating wind run or power production.

The programme used for calculating the Weibull function is a fortran programme, as follows:

```
      PROGRAM GROG
       REAL VN(30),V(30),H(30)
       HT=0.0
       WTR=0.0
       WBAR=6.0
       WK=2.0
       C=WBAR/.887
      VCUT=2.0
      ALAMB=1.5
      DIA=4.0
      WRITE(2,28)WBAR,WK,C
28    FORMAT('  AVER. WIND SPEED',F5.1,'M/S   K=',F3.1,'  C=',F4.2)
      WRITE(2,29)DIA,ALAMB
29    FORMAT(' ROTOR DIA USED =',F5.1,'   LAMBDA =',F4.2)
20    DO 20 I=1,21
      VN(I)=(VCUT-.25)+(I*.25)
      H(I)=8760*EXP(-(VN(I)/C)**WK)
      IF(I.GT.1)GOTO34
      WRITE(2,88)H(1)
88    FORMAT('  NO. HOURS GT VCUT-IN  ',F7.1,' HRS')
34    CONTINUE
      IF(I.EQ.1)GOTO20
      H(I-1)=H(I-1)-H(I)
      HT=HT+H(I-1)
      WR=(VN(I)*ALAMB/(3.1415*DIA))*3600*H(I-1)
      WTR=WTR+WR
      WRITE (2,12)VN(I-1),H(I-1),VN(I)
12    FORMAT('  LOWER VEL RANGE',F6.2,F10.0,'  HOURS',
     *       UPPER VEL. RANGE',F6.2)
      WRITE(2,32)WR
32    FORMAT('  STROKES IN THIS VEL. RANGE =',F10.0)
      IF(I.EQ.21)GOTO200
20    CONTINUE
200   CONTINUE
      WRITE(2,18)HT,WTR
```

```
18      FORMAT('  HRS OPERATION IN YR : 8760 ...',F8.1,'  ',
     F 'STROKES IN YR',F12.0)
        STOP
        END
```

Program "GROG"

This is a general program to calculate the hours of wind velocity per year using a given average velocity and estimated values for k and c.

The variables used in the fortran language are:

| | |
|---|---|
| WBAR | is the average wind velocity |
| WK | is the value of the parameter k |
| C | is the value of the parameter c |
| VCUT | is the cut-in velocity |
| ALAMB | is the tip speed ratio |
| DIA | is the rotor diameter |
| HT | is the total hours of operation |
| WTR | is the total for the no. of strokes |
| VN(I) | is the vector containing the wind speeds |
| H(I) | is the vector containing the Weibull values |

The steps in the program are:

1. the counters HT and WTR are set to zero, and the variables are initialized.

2. the initial values are printed out for verification

3. do loop 20 iterates the value of I used for velocity calc.

4. the velocity is varied from the cut-in velocity up to limit of I and stored in VN(I). Increments of .25 m/s are used.

5. the value of the Weibull function at various velocities is calculated and stored in H(I) no. hours expected at velocities greater than current value

6. since some differences are required and Weibull always gives values that are greater than, if ... to 20 initializes H(1)

7. the net value of H( ) is calculated in the range V(I-1) to V(I).

8. HT totals the hours above cut-in

9. WR calculates the number of strokes at that wind velocity by assuming that the rotor will run with the wind at its given tip speed ratio.

10. the print outs are given and the value of velocity incremented.

## Summary of values used for running the Program

The following values were used to run the program and evaluate the sensitivity of the model to variations in k and c.

| | Ym/s | k | c m/s |
|---|---|---|---|
| 1. | 2.5 | 1.35 | 2.28 |
| 2. | 3.0 | 1.36 | 2.78 |
| 3. | 3.0 | 1.50 | 3.32 |
| | 3.3 | 1.5 | 3.56 |
| 4. | 3.5 | 1.45 | 3.87 |
| 5. | 4.0 | 1.50 | 4.43 |
| 6. | 4.5 | 1.50 | 4.98 |
| 7. | 4.5 | 1.80 | 5.06 |
| 8. | 4.5 | 2.10 | 5.08 |
| 9. | 5.0 | 1.90 | 5.64 |
| 10. | 5.5 | 2.00 | 6.21 |
| 11. | 6.0 | 1.50 | 6.64 |
| 12. | 6.0 | 2.00 | 6.77 |
| 13. | 6.0 | 2.50 | 6.76 |

## RESULTS

The results from running the programme is presented in figure 3. The graph shows the predicted no. of strokes per year from a 4 m diameter rotor with a wind running tip speed ratio of 1.5, and a cut-in velocity and cut-out velocities of 2 and 7 m/s respectively.

The parameters of k and c are varied to represent the maximum possible deviations that they could have from the values used for the estimate. The outlines of these under and over-estimating curves are also presented. It is of note that even when the average values used for k and c may be incorrect, the maximum error introduced by making these necessary assumptions are only in the 15%-20% range, well within acceptable limits. The outputs from the programme are in Attachment no. 1.

## FURTHER USES FOR THE PROGRAMMES

As noted, this model can also be used to predict electrical output from a wind electric generator located at a site with a known average wind velocity. It can also be used to show the amout of electricity that will be generated for each average wind speed, giving a good estimation of what wind averages will be required for various machines to make them economically viable. The summary of an assessment done for a 3.3 m dia Whirlwind wind electric generator is in Attachment no. 2.

.....

REFERENCES


1. ENGINEERING HANDBOOK ON THE ATMOSPHERIC ENVIRONMENTAL GUIDELINES FOR THE USE IN WIND TURBINE GENERATOR DEVELOPMENT, W. Frost, B.Long, R. Turner, NASA Technica Paper No. 1359, December 1978, 372 pgs, NASA, Washingtc D.C., USA.

2. Vent et performance des eoliennes, C. G. Justus, 1978 SCM Publishers, Paris.


.....

ATTACHMENTS:

1. Summary of programme for various V, k & c and predictions for water pumping output strokes at site

2. Summary of predictions for Whirlwind electric generator for V=4.5 m/s and V=6.0 m/s.

.....

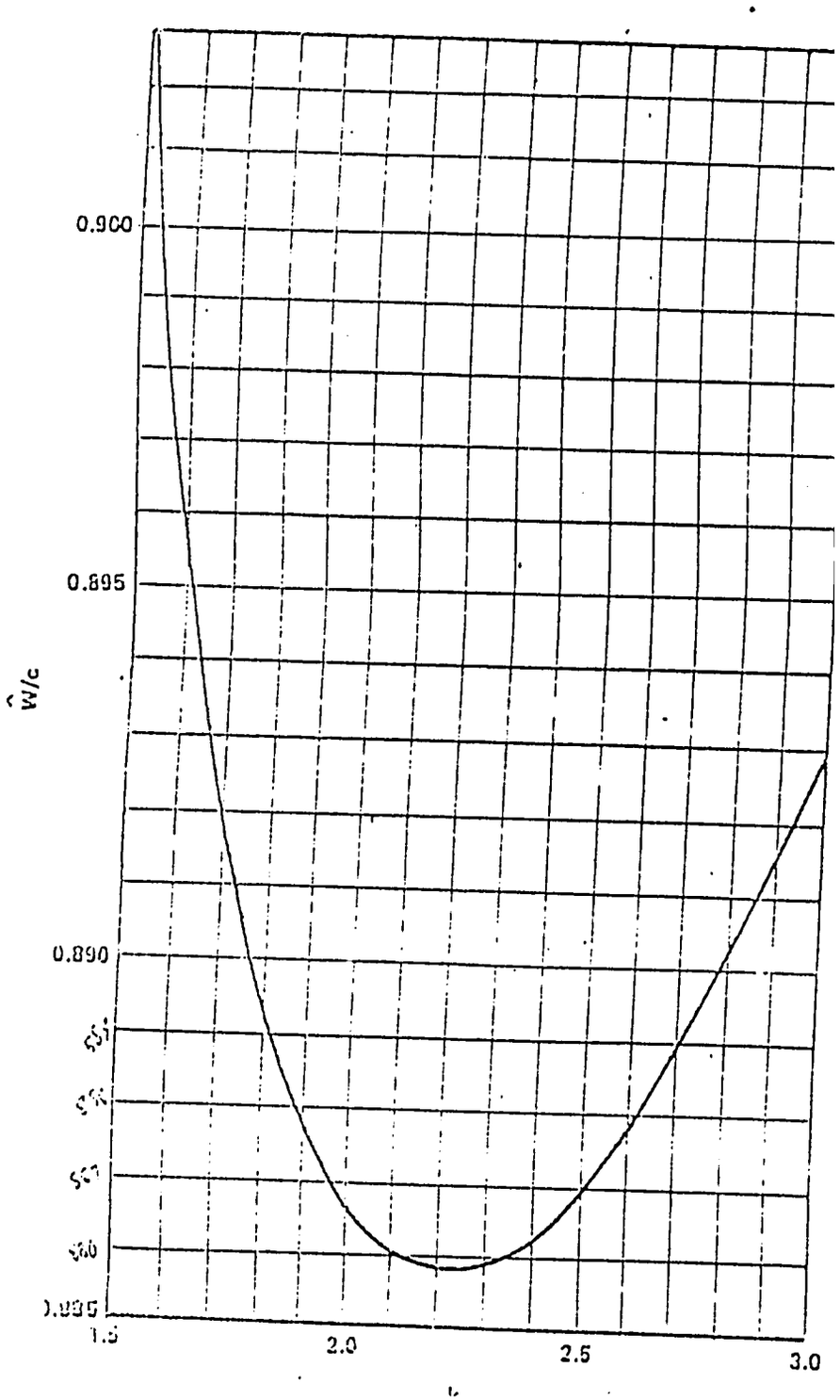
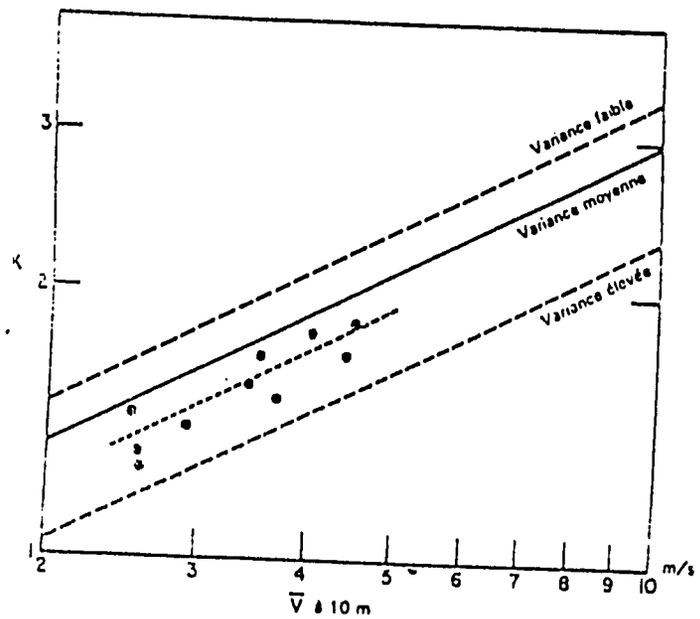



FIGURE 1: Tabulated value of c vs. k and V

Ref: (1) Frost et al.



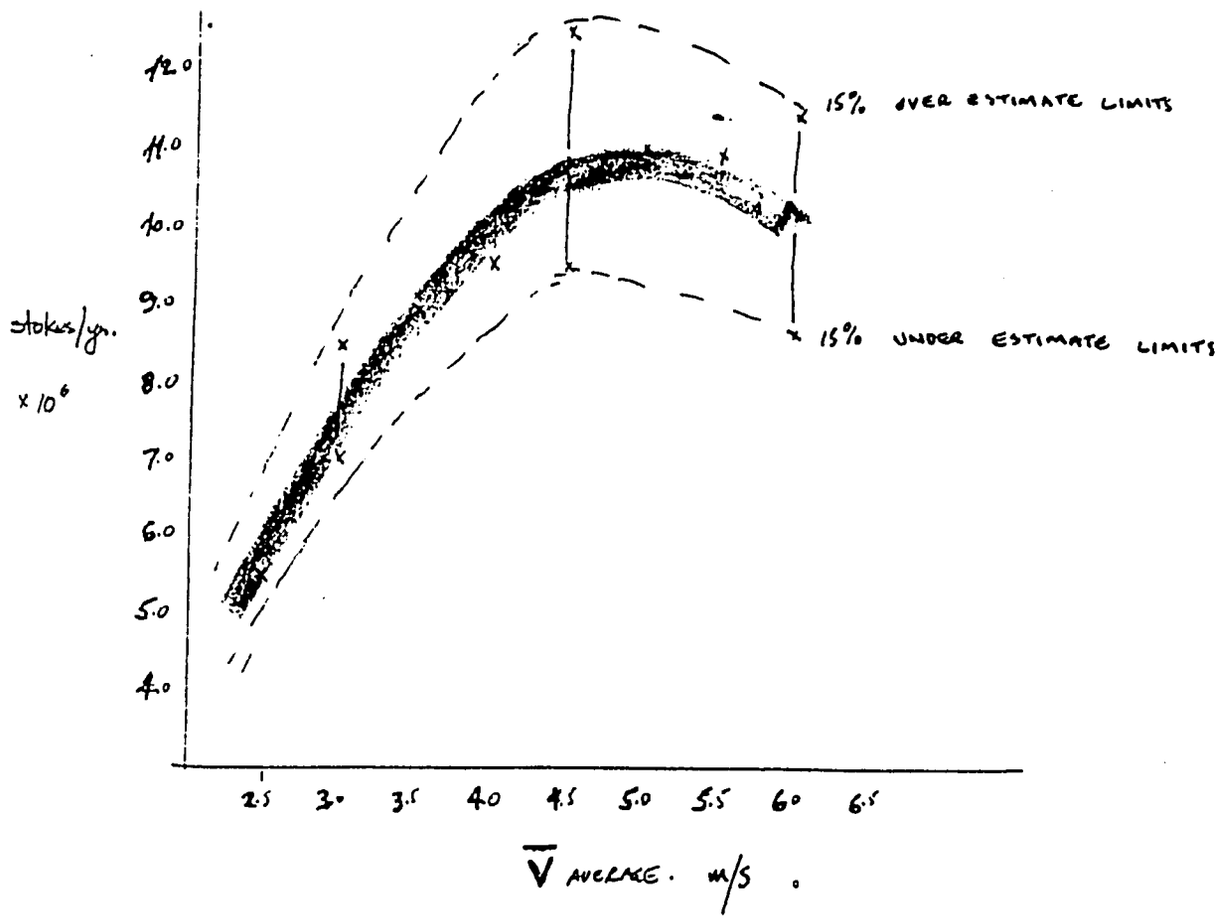

Facteur k de la distribution de Weibull en fonction de la vitesse moyenne du vent

FIGURE 2: Tabulated average values of k vs. $\bar{v}$

Ref: (2) Justus

Standard Weibull Distribution

Predictions for Rotor Dia = 4.0 m
λ mean = 1.5
cut-in speed = 2.0 m/s
cut-out speed = 7.0 m/s.




18·7·84 ws

FIGURE 3: Water output (strokes/year) predicted by standard Weibull Function vs. average wind speed $\bar{V}$.

ATTACHMENT NUMBER 1

SUMMARY OF WEIBULL FUNCTION PREDICTIONS AND WATER OUTPUT PREDICTIONS FOR THE FOLLOWING PARAMETERS

The following values were used to run the program and evaluate the sensitivity of the model to variations in k and c.

| | Vm/s | k | c m/s |
|---|---|---|---|
| 1. | 2.5 | 1.35 | 2.28 |
| 2. | 3.0 | 1.36 | 2.78 |
| 3. | 3.0 | 1.50 | 3.32 |
| | 3.3 | 1.5 | 3.56 |
| 4. | 3.5 | 1.45 | 3.87 |
| 5. | 4.0 | 1.50 | 4.43 |
| 6. | 4.5 | 1.50 | 4.98 |
| 7. | 4.5 | 1.80 | 5.06 |
| 8. | 4.5 | 2.10 | 5.09 |
| 9. | 5.0 | 1.90 | 5.64 |
| 10. | 5.5 | 2.00 | 6.21 |
| 11. | 6.0 | 1.50 | 6.64 |
| 12. | 6.0 | 2.00 | 6.77 |
| 13. | 6.0 | 2.50 | 6.76 |

WINDMILL PARAMETERS

Tip speed Ratio = 1.5

Diameter = 4.0 meters

Vcut-in = 2.0 m/s

sample. $\bar{V}=6.0$
WK=2.5
C = WBAR/.337

```
      PROGRAM GROG
       REAL VN(30),V(30),H(30)
       HT=0.0
       WTR=0.0
       WBAR=6.0
       WK=2.5
       C=WBAR/.887
       VCUT=2.0
       ALAMB=1.5
       DIA=4.0
       WRITE(2,28)WBAR,WK,C
28     FORMAT('  AVER. WIND SPEED',F5.1,'M/S   K=',F3.1,'  C=',F4.2
       WRITE(2,29)DIA,ALAMB
29     FORMAT('  ROTOR DIA USED =',F5.1,'   LAMBDA =',F4.2)
10     DO 20 I=1,21
       VN(I)=(VCUT-.25)+(I*.25)
       H(I)=8760*EXP(-(VN(I)/C)**WK)
       IF(I.GT.1)GOTO34
       WRITE(2,88)H(I)
88     FORMAT('  NO. HOURS GT VCUT-IN  ',F7.1,' HRS')
34     CONTINUE
       IF(I.EQ.1)GOTO20
       H(I-1)=H(I-1)-H(I)
       HT=HT+H(I-1)
       WR=(VN(I)*ALAMB/(3.1415*DIA))*3600*H(I-1)
       WTR=WTR+WR
       WRITE (2,12)VN(I-1),H(I-1),VN(I)
12     FORMAT('  LOWER VEL RANGE',F6.2,F10.0,'  HOURS',
     * '      UPPER VEL. RANGE',F6.2)
       WRITE(2,32)WR
32     FORMAT('  STROKES IN THIS VEL. RANGE =',F10.0)
       IF(I.EQ.21)GOTO200
20     CONTINUE
200    CONTINUE
       WRITE(2,18)HT,WTR
18     FORMAT('  HRS OPERATION IN YR : 8760 ...',F8.1,'
     F 'STROKES IN YR',F12.0)
       STOP
       END
```

SAMPLE

$\bar{V} = 3.3$
$K = 1.5$
$c = 3.56$

MEAN WIND SPEED [illegible] K [illegible] C [illegible]
ROTOR DIA [illegible] LAMBDA [illegible]
NO. HOURS [illegible] [illegible] HRS

| | | | |
|---|---|---|---|
| LOWER VEL RANGE [illegible] | [illegible] HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | [illegible] | | |
| LOWER VEL RANGE [illegible] | [illegible] HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | [illegible] | | |
| LOWER VEL RANGE [illegible] | [illegible] HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | [illegible] | | |
| LOWER VEL RANGE [illegible] | 401. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - 517933. | | |
| LOWER VEL RANGE [illegible] | 366. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - [illegible] | | |
| LOWER VEL RANGE [illegible] | 307. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - 53[illegible]767. | | |
| LOWER VEL RANGE [illegible] | 333. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - [illegible] | | |
| LOWER VEL RANGE [illegible] | 309. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - 531766. | | |
| LOWER VEL RANGE [illegible] | 246. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | [illegible] | | |
| LOWER VEL RANGE [illegible] | 202. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - [illegible] | | |
| LOWER VEL RANGE [illegible] | 239. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - 488803. | | |
| LOWER VEL RANGE [illegible] | 218. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - 467849. | | |
| LOWER VEL RANGE [illegible] | 197. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - [illegible] | | |
| LOWER VEL RANGE [illegible] | 178. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - [illegible] | | |
| LOWER VEL RANGE [illegible] | 179. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - 394075. | | |
| LOWER VEL RANGE [illegible] | 172. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - [illegible] | | |
| LOWER VEL RANGE [illegible] | 127. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - [illegible] | | |
| LOWER VEL RANGE [illegible] | 113. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - 314937. | | |
| LOWER VEL RANGE [illegible] | 100. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | - 289257 | | |
| LOWER VEL RANGE [illegible] | 86. HOURS | UPPER VEL. RANGE [illegible] | |
| STROKES IN THIS VEL. RANGE | [illegible] | | |
| [illegible] | [illegible] | [illegible] | |

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46

① $\dot{V} = 2.5$ m/s

AVER. WIND [illegible] 1.35 [illegible] 2.28
ROTOR DIA [illegible]
[illegible] HOURS [illegible]
LOWER VEL [illegible]
[illegible]
LOWER VEL [illegible] 107. HOURS UPPER VEL. RANGE [illegible]
STROKES IN [illegible] VEL. RANGE = 491277
LOWER VEL [illegible] 2??. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 480??2.
LOWER VEL RANGE [illegible] 2??. HOURS UPPER VEL. RANGE [illegible]
STROKES IN TH[illegible] [illegible] RANGE = 442806.
LOWER VEL RANGE [illegible] 2??. HOURS UPPER VEL. RANGE [illegible]
STROKES IN [illegible] RANGE = 4?7?01.
LOWER VEL RANGE [illegible] 27?. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 409776.
LOWER VEL RANGE [illegible] 233. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 37?0?0.
LOWER VEL RANGE [illegible] 202. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 347?51.
LOWER VEL RANGE [illegible] 172. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 3147?8.
LOWER VEL RANGE ?.20 146. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 283352.
LOWER VEL RANGE [illegible] 124. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 252451.
LOWER VEL RANGE [illegible] 104. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 22??12.
LOWER VEL RANGE [illegible] 87. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 196636.
LOWER VEL RANGE [illegible] 73. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 171812.
LOWER VEL RANGE [illegible] ?. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 14?217.
LOWER VEL RANGE [illegible] ?. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 128845.
LOWER VEL RANGE [illegible] 41. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 110603.
LOWER VEL RANGE [illegible] 34. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 91541.
LOWER VEL RANGE [illegible] 28. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = 2?372.
LOWER VEL RANGE [illegible] ?. HOURS UPPER VEL. RANGE [illegible]
STROKES IN THIS VEL. RANGE = ?682?2.
HRS OPERATION [illegible] ... 3698.9 STROKES IN YR [illegible]

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②

V = 3.0 m/s

AVER. WIND SPEED 3.0M/S K=1.36 C=2.76
ROTOR DIA USED = 4.0 LAMBDA =1.50
NO. HOURS GT VCUT-IN 4623.7 HRS

| | | | | |
|---|---|---|---|---|
| LOWER VEL RANGE | 2.00 | 486. HOURS | UPPER VEL. RANGE | 2.25 |
| STROKES IN THIS VEL. RANGE = | 469741. | | | |
| LOWER VEL RANGE | 2.25 | 452. HOURS | UPPER VEL. RANGE | 2.50 |
| STROKES IN THIS VEL. RANGE = | 485106. | | | |
| LOWER VEL RANGE | 2.50 | 416. HOURS | UPPER VEL. RANGE | 2.75 |
| STROKES IN THIS VEL. RANGE = | 491828. | | | |
| LOWER VEL RANGE | 2.75 | 381. HOURS | UPPER VEL. RANGE | 3.00 |
| STROKES IN THIS VEL. RANGE = | 490820. | | | |
| LOWER VEL RANGE | 3.00 | 346. HOURS | UPPER VEL. RANGE | 3.25 |
| STROKES IN THIS VEL. RANGE = | 483266. | | | |
| LOWER VEL RANGE | 3.25 | 313. HOURS | UPPER VEL. RANGE | 3.50 |
| STROKES IN THIS VEL. RANGE = | 470167. | | | |
| LOWER VEL RANGE | 3.50 | 281. HOURS | UPPER VEL. RANGE | 3.75 |
| STROKES IN THIS VEL. RANGE = | 452593. | | | |
| LOWER VEL RANGE | 3.75 | 251. HOURS | UPPER VEL. RANGE | 4.00 |
| STROKES IN THIS VEL. RANGE = | 431557. | | | |
| LOWER VEL RANGE | 4.00 | 223. HOURS | UPPER VEL. RANGE | 4.25 |
| STROKES IN THIS VEL. RANGE = | 407962. | | | |
| LOWER VEL RANGE | 4.25 | 198. HOURS | UPPER VEL. RANGE | 4.50 |
| STROKES IN THIS VEL. RANGE = | 382635. | | | |
| LOWER VEL RANGE | 4.50 | 175. HOURS | UPPER VEL. RANGE | 4.75 |
| STROKES IN THIS VEL. RANGE = | 356296. | | | |
| LOWER VEL RANGE | 4.75 | 153. HOURS | UPPER VEL. RANGE | 5.00 |
| STROKES IN THIS VEL. RANGE = | 329544. | | | |
| LOWER VEL RANGE | 5.00 | 134. HOURS | UPPER VEL. RANGE | 5.25 |
| STROKES IN THIS VEL. RANGE = | 302934. | | | |
| LOWER VEL RANGE | 5.25 | 117. HOURS | UPPER VEL. RANGE | 5.50 |
| STROKES IN THIS VEL. RANGE = | 276952. | | | |
| LOWER VEL RANGE | 5.50 | 102. HOURS | UPPER VEL. RANGE | 5.75 |
| STROKES IN THIS VEL. RANGE = | 251606. | | | |
| LOWER VEL RANGE | 5.75 | 88. HOURS | UPPER VEL. RANGE | 6.00 |
| STROKES IN THIS VEL. RANGE = | 227540. | | | |
| LOWER VEL RANGE | 6.00 | 76. HOURS | UPPER VEL. RANGE | 6.25 |
| STROKES IN THIS VEL. RANGE = | 204769. | | | |
| LOWER VEL RANGE | 6.25 | 66. HOURS | UPPER VEL. RANGE | 6.50 |
| STROKES IN THIS VEL. RANGE = | 183431. | | | |
| LOWER VEL RANGE | 6.50 | 56. HOURS | UPPER VEL. RANGE | 6.75 |
| STROKES IN THIS VEL. RANGE = | 163599. | | | |
| LOWER VEL RANGE | 6.75 | 48. HOURS | UPPER VEL. RANGE | 7.00 |
| STROKES IN THIS VEL. RANGE = | 145310. | | | |

HRS OPERATION IN YR : 8760 ... 4342.1 STROKES IN YR 7000/3...

48

(3)

V = 3.0 m/s

```
AVER. WIND [illegible]    F 1.5  C-3.32
ROTOR DIA [illegible]    [illegible]DA -1.56
NO. HOURS [illegible]    [illegible] MPS
LOWER VEL [illegible]
[illegible]    HOURS    UPPER VEL. [illegible]
[illegible]    [illegible]
STROKES IN [illegible]    HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL [illegible]    [illegible]
STROKES IN [illegible]    135.  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL [illegible]    514411
STROKES IN [illegible]    [illegible].  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    [illegible]
STROKES IN [illegible]    [illegible].  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    [illegible]
STROKES IN THIS VEL. RANGE =    [illegible]    HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    [illegible]
STROKES IN THIS VEL. RANGE =    [illegible]    HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    [illegible]
STROKES IN THIS VEL. RANGE =    303.  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    [illegible]
STROKES IN THIS VEL. RANGE =    [illegible]  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    504540.
STROKES IN THIS VEL. RANGE =    250.  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    481253.
STROKES IN THIS VEL. RANGE =    224.  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    460878.
STROKES IN THIS VEL. RANGE =    [illegible]23.  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    435241.
STROKES IN THIS VEL. RANGE =    181.  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    407985.
STROKES IN THIS VEL. RANGE =    1[illegible].  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    377827.
STROKES IN THIS VEL. RANGE =    142.  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    351340.
STROKES IN THIS VEL. RANGE =    [illegible]23.  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    323965.
STROKES IN THIS VEL. RANGE =    110.  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    295205.
STROKES IN THIS VEL. RANGE =    95.  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    268309.
STROKES IN THIS VEL. RANGE =    [illegible]  HOURS    UPPER VEL. RANGE [illegible]
LOWER VEL RANGE [illegible]    [illegible]
STROKES IN THIS VEL. RANGE =    [illegible]  HOURS    UPPER VEL. RANGE [illegible]
[illegible]    218169.
HRS OPERATION [illegible] ...  5079.[illegible]  STROKES IN YR    [illegible]
```

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④

$V_1 = 3.5$ m/s

AVER. WIND SPEED 3.5M/S K=1.45 C=3.87
ROTOR DIA USED = 1.0 LAMBDA =1.50
NO. HOURS GT VOUT=IN 8760.3 HRS

| | | | | | |
|---|---|---|---|---|---|
| LOWER VEL RANGE | 1.00 | 412. HOURS | UPPER VEL. RANGE | 1.25 |
| STROKES IN THIS VEL. RANGE | = | 398017. | | |
| LOWER VEL RANGE | 1.25 | 402. HOURS | UPPER VEL. RANGE | 1.50 |
| STROKES IN THIS VEL. RANGE | = | 432104. | | |
| LOWER VEL RANGE | 1.50 | 390. HOURS | UPPER VEL. RANGE | 1.75 |
| STROKES IN THIS VEL. RANGE | = | 460143. | | |
| LOWER VEL RANGE | 1.75 | 375. HOURS | UPPER VEL. RANGE | 2.00 |
| STROKES IN THIS VEL. RANGE | = | 482959. | | |
| LOWER VEL RANGE | 2.00 | 358. HOURS | UPPER VEL. RANGE | 2.25 |
| STROKES IN THIS VEL. RANGE | = | 499736. | | |
| LOWER VEL RANGE | 2.25 | 340. HOURS | UPPER VEL. RANGE | 2.50 |
| STROKES IN THIS VEL. RANGE | = | 510979. | | |
| LOWER VEL RANGE | 2.50 | 321. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 516992. | | |
| LOWER VEL RANGE | 2.75 | 301. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 518197. | | |
| LOWER VEL RANGE | 3.00 | 282. HOURS | UPPER VEL. RANGE | 3.25 |
| STROKES IN THIS VEL. RANGE | = | 514984. | | |
| LOWER VEL RANGE | 3.25 | 263. HOURS | UPPER VEL. RANGE | 3.50 |
| STROKES IN THIS VEL. RANGE | = | 507347. | | |
| LOWER VEL RANGE | 3.50 | 244. HOURS | UPPER VEL. RANGE | 3.75 |
| STROKES IN THIS VEL. RANGE | = | 497256. | | |
| LOWER VEL RANGE | 3.75 | 225. HOURS | UPPER VEL. RANGE | 4.00 |
| STROKES IN THIS VEL. RANGE | = | 483768. | | |
| LOWER VEL RANGE | 4.00 | 207. HOURS | UPPER VEL. RANGE | 4.25 |
| STROKES IN THIS VEL. RANGE | = | 467663. | | |
| LOWER VEL RANGE | 4.25 | 190. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 449612. | | |
| LOWER VEL RANGE | [illegible] | 174. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 429939. | | |
| LOWER VEL RANGE | [illegible] | 157. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 409096. | | |
| LOWER VEL RANGE | [illegible] | 144. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 387410. | | |
| LOWER VEL RANGE | [illegible] | 131. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 365278. | | |
| LOWER VEL RANGE | [illegible] | 118. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 342900. | | |
| LOWER VEL RANGE | [illegible] | 107. HOURS | UPPER VEL. RANGE | 7.00 |
| STROKES IN THIS VEL. RANGE | = | 320651. | | |

HRS OPERATION [illegible] : 8760 ... 5141.3 STROKES IN YR [illegible]

②

V = 4.0 m/s

AVER. WIND SPEED [illegible] K=1.5 C=4.43
ROTOR DIA USED [illegible] LAMBDA =1.50
NO. HOURS [illegible] 4[illegible].7 HRS

| | | | | |
|---|---|---|---|---|
| LOWER VEL RANGE | 2.00 | 368. HOURS | UPPER VEL. RANGE | [illegible].5 |
| STROKES IN THIS VEL. RANGE | = | 396084. | | |
| LOWER VEL RANGE | 2.25 | 367. HOURS | UPPER VEL. RANGE | 2.50 |
| STROKES IN THIS VEL. RANGE | = | 393812. | | |
| LOWER VEL RANGE | 2.50 | 362. HOURS | UPPER VEL. RANGE | 2.75 |
| STROKES IN THIS VEL. RANGE | = | 427392. | | |
| LOWER VEL RANGE | 2.75 | 354. HOURS | UPPER VEL. RANGE | 3.00 |
| STROKES IN THIS VEL. RANGE | = | 456481. | | |
| LOWER VEL RANGE | 3.00 | 344. HOURS | UPPER VEL. RANGE | 3.25 |
| STROKES IN THIS VEL. RANGE | = | 460899. | | |
| LOWER VEL RANGE | 3.25 | 333. HOURS | UPPER VEL. RANGE | 3.50 |
| STROKES IN THIS VEL. RANGE | = | 500589. | | |
| LOWER VEL RANGE | 3.50 | 320. HOURS | UPPER VEL. RANGE | 3.75 |
| STROKES IN THIS VEL. RANGE | = | 515575. | | |
| LOWER VEL RANGE | 3.75 | 306. HOURS | UPPER VEL. RANGE | 4.00 |
| STROKES IN THIS VEL. RANGE | = | 525993. | | |
| LOWER VEL RANGE | 4.00 | 291. HOURS | UPPER VEL. RANGE | 4.25 |
| STROKES IN THIS VEL. RANGE | = | 532124. | | |
| LOWER VEL RANGE | 4.25 | 276. HOURS | UPPER VEL. RANGE | 4.50 |
| STROKES IN THIS VEL. RANGE | = | 534010. | | |
| LOWER VEL RANGE | 4.50 | 261. HOURS | UPPER VEL. RANGE | 4.75 |
| STROKES IN THIS VEL. RANGE | = | 532214. | | |
| LOWER VEL RANGE | 4.75 | 245. HOURS | UPPER VEL. RANGE | 5.00 |
| STROKES IN THIS VEL. RANGE | = | 526904. | | |
| LOWER VEL RANGE | 5.00 | 230. HOURS | UPPER VEL. RANGE | 5.25 |
| STROKES IN THIS VEL. RANGE | = | 518466. | | |
| LOWER VEL RANGE | 5.25 | 215. HOURS | UPPER VEL. RANGE | 5.50 |
| STROKES IN THIS VEL. RANGE | = | 507311. | | |
| LOWER VEL RANGE | 5.50 | 200. HOURS | UPPER VEL. RANGE | 5.75 |
| STROKES IN THIS VEL. RANGE | = | 493795. | | |
| LOWER VEL RANGE | 5.75 | 185. HOURS | UPPER VEL. RANGE | 6.00 |
| STROKES IN THIS VEL. RANGE | = | 478126. | | |
| LOWER VEL RANGE | 6.00 | 172. HOURS | UPPER VEL. RANGE | 6.25 |
| STROKES IN THIS VEL. RANGE | = | 460822. | | |
| LOWER VEL RANGE | 6.25 | 158. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 442182. | | |
| LOWER VEL RANGE | 6.50 | 145. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 422491. | | |
| LOWER VEL RANGE | 6.75 | 134. HOURS | UPPER VEL. RANGE | 7.00 |
| STROKES IN THIS VEL. RANGE | = | 402047. | | |
| HRS OPERATION IN YR = | 2760 ... | 5266.0 | STROKES IN YR | [illegible] |

5

⑥

V = 4.5 m/s

```
AVER. WIND SPEED  4.5M/S   K=1.8  C=5.06
ROTOR DIA USED =  4.0   LAMBDA =1.50
NO. HOURS GT VOUT-IN   7358.9 HRS
LOWER VEL RANGE  2.00          315.  HOURS      UPPER VEL. RANGE  2.25
STROKES IN THIS VEL. RANGE =    304754.
LOWER VEL RANGE  2.25          329.  HOURS      UPPER VEL. RANGE  2.50
STROKES IN THIS VEL. RANGE =    353338.
LOWER VEL RANGE  2.50          339.  HOURS      UPPER VEL. RANGE  2.75
STROKES IN THIS VEL. RANGE =    400309.
LOWER VEL RANGE  2.75          345.  HOURS      UPPER VEL. RANGE  3.00
STROKES IN THIS VEL. RANGE =    444761.
LOWER VEL RANGE  3.00          348.  HOURS      UPPER VEL. RANGE  3.25
STROKES IN THIS VEL. RANGE =    485812.
LOWER VEL RANGE  3.25          348.  HOURS      UPPER VEL. RANGE  3.50
STROKES IN THIS VEL. RANGE =    522790.
LOWER VEL RANGE  3.50          344.  HOURS      UPPER VEL. RANGE  3.75
STROKES IN THIS VEL. RANGE =    555121.
LOWER VEL RANGE  3.75          339.  HOURS      UPPER VEL. RANGE  4.00
STROKES IN THIS VEL. RANGE =    582416.
LOWER VEL RANGE  4.00          331.  HOURS      UPPER VEL. RANGE  4.25
STROKES IN THIS VEL. RANGE =    604397.
LOWER VEL RANGE  4.25          321.  HOURS      UPPER VEL. RANGE  4.50
STROKES IN THIS VEL. RANGE =    620906.
LOWER VEL RANGE  4.50          310.  HOURS      UPPER VEL. RANGE  4.75
STROKES IN THIS VEL. RANGE =    631935.
LOWER VEL RANGE  4.75          297.  HOURS      UPPER VEL. RANGE  5.00
STROKES IN THIS VEL. RANGE =    637680.
LOWER VEL RANGE  5.00          283.  HOURS      UPPER VEL. RANGE  5.25
STROKES IN THIS VEL. RANGE =    638106.
LOWER VEL RANGE  5.25          268.  HOURS      UPPER VEL. RANGE  5.50
STROKES IN THIS VEL. RANGE =    633777.
LOWER VEL RANGE  5.50          253.  HOURS      UPPER VEL. RANGE  5.75
STROKES IN THIS VEL. RANGE =    624880.
LOWER VEL RANGE  5.75          237.  HOURS      UPPER VEL. RANGE  6.00
STROKES IN THIS VEL. RANGE =    611847.
LOWER VEL RANGE  6.00          222.  HOURS      UPPER VEL. RANGE  6.25
STROKES IN THIS VEL. RANGE =    595165.
LOWER VEL RANGE  6.25          206.  HOURS      UPPER VEL. RANGE  6.50
STROKES IN THIS VEL. RANGE =    575273.
LOWER VEL RANGE  6.50          191.  HOURS      UPPER VEL. RANGE  6.75
STROKES IN THIS VEL. RANGE =    552705.
LOWER VEL RANGE  6.75          175.  HOURS      UPPER VEL. RANGE  7.00
STROKES IN THIS VEL. RANGE =    527922.
HRS OPERATION ... 6766 ...   5799.7  STROKES IN YR=  [illegible]
```

52

(2)

V = 4.5 m/s

AVER. WIND SPEED [illegible] K-1.5 C-4.98
ROTOR DIA USED = [illegible] LAMBDA =1.50
NO. HOURS GT V [illegible] = [illegible]3.4 HRS

| | | | | | |
|---|---|---|---|---|---|
| LOWER VEL RANGE | [illegible] | 326. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 314927. | | | |
| LOWER VEL RANGE | 2.25 | 327. | HOURS | UPPER VEL. RANGE | 2.50 |
| STROKES IN THIS VEL. RANGE | = | 351696. | | | |
| LOWER VEL RANGE | 2.50 | 326. | HOURS | UPPER VEL. RANGE | 2.75 |
| STROKES IN THIS VEL. RANGE | = | 385639. | | | |
| LOWER VEL RANGE | 2.75 | 323. | HOURS | UPPER VEL. RANGE | 3.00 |
| STROKES IN THIS VEL. RANGE | = | 416362. | | | |
| LOWER VEL RANGE | 3.00 | 318. | HOURS | UPPER VEL. RANGE | 3.25 |
| STROKES IN THIS VEL. RANGE | = | 443605. | | | |
| LOWER VEL RANGE | 3.25 | 311. | HOURS | UPPER VEL. RANGE | 3.50 |
| STROKES IN THIS VEL. RANGE | = | 467222. | | | |
| LOWER VEL RANGE | 3.50 | 302. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 487118. | | | |
| LOWER VEL RANGE | [illegible] | 293. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 503259. | | | |
| LOWER VEL RANGE | 4.00 | 282. | HOURS | UPPER VEL. RANGE | 4.25 |
| STROKES IN THIS VEL. RANGE | = | 515759. | | | |
| LOWER VEL RANGE | 4.25 | 271. | HOURS | UPPER VEL. RANGE | 4.50 |
| STROKES IN THIS VEL. RANGE | = | 524657. | | | |
| LOWER VEL RANGE | 4.50 | 260. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 530126. | | | |
| LOWER VEL RANGE | [illegible] | 248. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 532299. | | | |
| LOWER VEL RANGE | 5.00 | 236. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 531507. | | | |
| LOWER VEL RANGE | [illegible] | 223. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 527856. | | | |
| LOWER VEL RANGE | 5.50 | 211. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 521649. | | | |
| LOWER VEL RANGE | [illegible] | 199. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 513101. | | | |
| LOWER VEL RANGE | 6.00 | 187. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 502467. | | | |
| LOWER VEL RANGE | 6.25 | 175. | HOURS | UPPER VEL. RANGE | 6.50 |
| STROKES IN THIS VEL. RANGE | = | 490070. | | | |
| LOWER VEL RANGE | [illegible] | 164. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 476103. | | | |
| LOWER VEL RANGE | [illegible] | 153. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 460778. | | | |

HRS OPERATION IN YR = [illegible]740 ... 5130.7 STROKES IN YR [illegible]

53

(8)

V = 4.5 m/s

AVER. WIND SPEED 4.5M/S K=2.1 C=5.08
ROTOR DIA USED = 4.0 LAMBDA =1.50
NO. HOURS GT VOUT-IN 7606.0 HRS

| | | | | | |
|---|---|---|---|---|---|
| LOWER VEL RANGE | 2.00 | 296. HOURS | | UPPER VEL. RANGE | 2.25 |
| STROKES IN THIS VEL. RANGE | | = 255830. | | | |
| LOWER VEL RANGE | 2.25 | 320. HOURS | | UPPER VEL. RANGE | 2.50 |
| STROKES IN THIS VEL. RANGE | | = 344083. | | | |
| LOWER VEL RANGE | 2.50 | 341. HOURS | | UPPER VEL. RANGE | 2.75 |
| STROKES IN THIS VEL. RANGE | | = 402966. | | | |
| LOWER VEL RANGE | 2.75 | 358. HOURS | | UPPER VEL. RANGE | 3.00 |
| STROKES IN THIS VEL. RANGE | | = 460975. | | | |
| LOWER VEL RANGE | 3.00 | 370. HOURS | | UPPER VEL. RANGE | 3.25 |
| STROKES IN THIS VEL. RANGE | | = 516554. | | | |
| LOWER VEL RANGE | 3.25 | 378. HOURS | | UPPER VEL. RANGE | 3.50 |
| STROKES IN THIS VEL. RANGE | | = 568337. | | | |
| LOWER VEL RANGE | 3.50 | 382. HOURS | | UPPER VEL. RANGE | 3.75 |
| STROKES IN THIS VEL. RANGE | | = 615055. | | | |
| LOWER VEL RANGE | 3.75 | 381. HOURS | | UPPER VEL. RANGE | 4.00 |
| STROKES IN THIS VEL. RANGE | | = 655618. | | | |
| LOWER VEL RANGE | 4.00 | 377. HOURS | | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | | = 689231. | | | |
| LOWER VEL RANGE | [illegible] | 370. HOURS | | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | | = 715124. | | | |
| LOWER VEL RANGE | 4.50 | 359. HOURS | | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | | = 733052. | | | |
| LOWER VEL RANGE | 4.75 | 346. HOURS | | UPPER VEL. RANGE | 5.00 |
| STROKES IN THIS VEL. RANGE | | = 742819. | | | |
| LOWER VEL RANGE | 5.00 | 330. HOURS | | UPPER VEL. RANGE | 5.25 |
| STROKES IN THIS VEL. RANGE | | = 744435. | | | |
| LOWER VEL RANGE | 5.25 | 312. HOURS | | UPPER VEL. RANGE | 5.50 |
| STROKES IN THIS VEL. RANGE | | = 738362. | | | |
| LOWER VEL RANGE | 5.50 | 293. HOURS | | UPPER VEL. RANGE | 5.75 |
| STROKES IN THIS VEL. RANGE | | = 724963. | | | |
| LOWER VEL RANGE | 5.75 | 273. HOURS | | UPPER VEL. RANGE | 6.00 |
| STROKES IN THIS VEL. RANGE | | = 704919. | | | |
| LOWER VEL RANGE | 6.00 | 253. HOURS | | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | | = 679006. | | | |
| LOWER VEL RANGE | [illegible] | 232. HOURS | | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | | = 648091. | | | |
| LOWER VEL RANGE | 6.50 | 211. HOURS | | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | | = 613135. | | | |
| LOWER VEL RANGE | [illegible] | 191. HOURS | | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | | = 575020. | | | |
| HRS OPERATION IN YR : 8760 | | ... 5373.8 | STROKES IN YR | [illegible] | |

SK

(9)

V = 5.0 m/s

AVER. WIND SPEED [illegible] 1.-1.9 C-0.64
ROTOR DIA USED [illegible] LAMBDA -1.50
NO. HOURS OF [illegible] [illegible]6.4 HRS

| | | | | | |
|---|---|---|---|---|---|
| LOWER VEL RANGE | 2.00 | 282. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | [illegible] | | | |
| LOWER VEL RANGE | 2.[illegible] | 279. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 300052. | | | |
| LOWER VEL RANGE | 2.50 | 293. | HOURS | UPPER VEL. RANGE | 2.75 |
| STROKES IN THIS VEL. RANGE | = | 346822. | | | |
| LOWER VEL RANGE | 2.75 | 305. | HOURS | UPPER VEL. RANGE | 3.00 |
| STROKES IN THIS VEL. RANGE | = | 392917. | | | |
| LOWER VEL RANGE | 3.00 | 313. | HOURS | UPPER VEL. RANGE | 3.25 |
| STROKES IN THIS VEL. RANGE | = | 437434. | | | |
| LOWER VEL RANGE | 3.25 | 319. | HOURS | UPPER VEL. RANGE | 3.50 |
| STROKES IN THIS VEL. RANGE | = | 479618. | | | |
| LOWER VEL RANGE | 3.50 | 322. | HOURS | UPPER VEL. RANGE | 3.75 |
| STROKES IN THIS VEL. RANGE | = | 518742. | | | |
| LOWER VEL RANGE | 3.75 | 322. | HOURS | UPPER VEL. RANGE | 4.00 |
| STROKES IN THIS VEL. RANGE | = | 554267. | | | |
| LOWER VEL RANGE | 4.00 | 321. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 585618. | | | |
| LOWER VEL RANGE | 4.25 | 317. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 612454. | | | |
| LOWER VEL RANGE | 4.50 | 311. | HOURS | UPPER VEL. RANGE | 4.75 |
| STROKES IN THIS VEL. RANGE | = | 634456. | | | |
| LOWER VEL RANGE | 4.75 | 303. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 651453. | | | |
| LOWER VEL RANGE | 5.00 | 294. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 663437. | | | |
| LOWER VEL RANGE | 5.25 | 284. | HOURS | UPPER VEL. RANGE | .50 |
| STROKES IN THIS VEL. RANGE | = | 670284. | | | |
| LOWER VEL RANGE | [illegible] | 272. | HOURS | UPPER VEL. RANGE | 5.75 |
| STROKES IN THIS VEL. RANGE | = | 672354. | | | |
| LOWER VEL RANGE | [illegible] | 260. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | | [illegible]2. | | | |
| LOWER VEL RANGE | [illegible] | 247. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 662428. | | | |
| LOWER VEL RANGE | 6.25 | 233. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 651122. | | | |
| LOWER VEL RANGE | 6.50 | 219. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 636070. | | | |
| LOWER VEL RANGE | [illegible] | 205. | HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 617677. | | | |
| HRS OPERATION IN YR = 8760 | ... | 3681.4 | STROKES IN YR | [illegible] | |

35

(10)

V = 5.5 m/s

AVER. WIND SPEED [illegible] K=2.0 C=6.21
ROTOR DIA USED = [illegible] LAMBDA =1.50
TOT. HOURS OF V[illegible] = [illegible] HRS

| | | | | |
|---|---|---|---|---|
| LOWER VEL RANGE | [illegible] | 215. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 207637. | | |
| LOWER VEL RANGE | 2.25 | 233. HOURS | UPPER VEL. RANGE | 2.50 |
| STROKES IN THIS VEL. RANGE | = | 250434. | | |
| LOWER VEL RANGE | 2.50 | 249. HOURS | UPPER VEL. RANGE | 2.75 |
| STROKES IN THIS VEL. RANGE | = | 294760. | | |
| LOWER VEL RANGE | 2.75 | 264. HOURS | UPPER VEL. RANGE | 3.00 |
| STROKES IN THIS VEL. RANGE | = | 339838. | | |
| LOWER VEL RANGE | 3.00 | 276. HOURS | UPPER VEL. RANGE | 3.25 |
| STROKES IN THIS VEL. RANGE | = | 384879. | | |
| LOWER VEL RANGE | 3.25 | 285. HOURS | UPPER VEL. RANGE | 3.50 |
| STROKES IN THIS VEL. RANGE | = | 429176. | | |
| LOWER VEL RANGE | 3.50 | 293. HOURS | UPPER VEL. RANGE | 3.75 |
| STROKES IN THIS VEL. RANGE | = | 471981. | | |
| LOWER VEL RANGE | [illegible] | 298. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | [illegible]2607. | | |
| LOWER VEL RANGE | [illegible] | 301. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 558478. | | |
| LOWER VEL RANGE | [illegible] | 303. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 585020. | | |
| LOWER VEL RANGE | [illegible] | 302. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 61[illegible]814. | | |
| LOWER VEL RANGE | 4.75 | 299. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 642463. | | |
| LOWER VEL RANGE | 5.00 | 295. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 664601. | | |
| LOWER VEL RANGE | [illegible] | 287. HOURS | UPPER VEL. RANGE | 5.50 |
| STROKES IN THIS VEL. RANGE | = | 682141. | | |
| LOWER VEL RANGE | [illegible] | 281. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 694895. | | |
| LOWER VEL RANGE | [illegible] | [illegible] HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | [illegible]56. | | |
| LOWER VEL RANGE | [illegible] | 263. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 706138. | | |
| LOWER VEL RANGE | [illegible] | 252. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 704920. | | |
| LOWER VEL RANGE | [illegible] | 241. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 699206. | | |
| LOWER VEL RANGE | [illegible] | 229. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 689386. | | |

HRS OPERATION [illegible] = 8760 ... 5440.1 STROKES IN YR [illegible]

(11)

V = 6.0 m/s

AVER. WIND SPEED [illegible] K=2.0 C=6.77
ROTOR DIA (MM) = [illegible] LAMBDA =1.50
NO. HOURS GT [illegible] IN [illegible] HRS

| | | | | |
|---|---|---|---|---|
| LOWER VEL RANGE | 2.00 | 179. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 172922. | | |
| LOWER VEL RANGE | 2.25 | 196. HOURS | UPPER VEL. RANGE | 2.50 |
| STROKES IN THIS VEL. RANGE | = | 210859. | | |
| LOWER VEL RANGE | 2.50 | 212. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 250887. | | |
| LOWER VEL RANGE | 2.75 | 227. HOURS | UPPER VEL. RANGE | 3.00 |
| STROKES IN THIS VEL. RANGE | = | 292420. | | |
| LOWER VEL RANGE | 3.00 | 240. HOURS | UPPER VEL. RANGE | 3.25 |
| STROKES IN THIS VEL. RANGE | = | 334810. | | |
| LOWER VEL RANGE | 3.25 | 251. HOURS | UPPER VEL. RANGE | 3.50 |
| STROKES IN THIS VEL. RANGE | = | 377455. | | |
| LOWER VEL RANGE | 3.50 | 260. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 419755. | | |
| LOWER VEL RANGE | 3.75 | 268. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 461073. | | |
| LOWER VEL RANGE | 4.00 | 274. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 500838. | | |
| LOWER VEL RANGE | 4.25 | 278. HOURS | UPPER VEL. RANGE | 4.50 |
| STROKES IN THIS VEL. RANGE | = | 538530. | | |
| LOWER VEL RANGE | 4.50 | 281. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 573637. | | |
| LOWER VEL RANGE | 4.75 | 282. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 605721. | | |
| LOWER VEL RANGE | 5.00 | 281. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 634421. | | |
| LOWER VEL RANGE | 5.25 | 279. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 659376. | | |
| LOWER VEL RANGE | 5.50 | 275. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 680427. | | |
| LOWER VEL RANGE | 5.75 | 270. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 697293. | | |
| LOWER VEL RANGE | 6.00 | 264. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 709869. | | |
| LOWER VEL RANGE | 6.25 | 257. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 718284. | | |
| LOWER VEL RANGE | [illegible] | 249. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 723313. | | |
| LOWER VEL RANGE | [illegible] | 241. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 722163. | | |

HRS OPN IN YR: 8760 → 5065

STROKES IN YR 10.25 30.35

51

(12)

V-6.0 —/s

AVER. WIND SPEED [illegible] K=1.5 C=6.24
ROTOR DIA USED = 4.4 LAMBDA =1.50
NO. HOURS GT [illegible]-IN 7126.5 HRS

| | | | | |
|---|---|---|---|---|
| LOWER VEL RANGE | 2.00 | 233. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 225532. | | |
| LOWER VEL RANGE | 2.25 | 239. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 256379. | | |
| LOWER VEL RANGE | 2.50 | 242. HOURS | UPPER VEL. RANGE | 2.75 |
| STROKES IN THIS VEL. RANGE | = | 286404. | | |
| LOWER VEL RANGE | 2.75 | 245. HOURS | UPPER VEL. RANGE | 3.00 |
| STROKES IN THIS VEL. RANGE | = | 315329. | | |
| LOWER VEL RANGE | 3.00 | 246. HOURS | UPPER VEL. RANGE | 3.25 |
| STROKES IN THIS VEL. RANGE | = | 342933. | | |
| LOWER VEL RANGE | 3.25 | 245. HOURS | UPPER VEL. RANGE | 3.50 |
| STROKES IN THIS VEL. RANGE | = | 368917. | | |
| LOWER VEL RANGE | 3.50 | 244. HOURS | UPPER VEL. RANGE | 3.75 |
| STROKES IN THIS VEL. RANGE | = | 393231. | | |
| LOWER VEL RANGE | [illegible] | 242. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 415677. | | |
| LOWER VEL RANGE | 4.00 | 239. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 436170. | | |
| LOWER VEL RANGE | 4.25 | 235. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 454627. | | |
| LOWER VEL RANGE | 4.50 | 231. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 471007. | | |
| LOWER VEL RANGE | 4.75 | 226. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 485740. | | |
| LOWER VEL RANGE | 5.00 | 221. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | [illegible] | | |
| LOWER VEL RANGE | [illegible] | 215. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 507663. | | |
| LOWER VEL RANGE | 5.50 | 209. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 515739. | | |
| LOWER VEL RANGE | [illegible] | 202. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | [illegible] | | |
| LOWER VEL RANGE | [illegible] | 196. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | [illegible] | | |
| LOWER VEL RANGE | [illegible] | 189. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | 528527. | | |
| LOWER VEL RANGE | [illegible] | 182. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | [illegible] | | |
| LOWER VEL RANGE | [illegible] | 176. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | = | [illegible] | | |
| HRS OPERATING [illegible] | 4756 | ... 1455.6 | STROKES IN [illegible] | [illegible] |

**Best Available Document**

58

(13)

V = 6.0 m/s

AVER. WIND SPEED [illegible] K=2.5 C=6.76
ROTOR DIA USED [illegible] LAMBDA =1.50
NO. HOURS GT [illegible] [illegible]3.3 HRS

| | | | | |
|---|---|---|---|---|
| LOWER VEL RANGE | [illegible] | [illegible] HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | [illegible] | [illegible] | | |
| LOWER VEL RANGE | [illegible] | [illegible] HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | - | 168156. | | |
| LOWER VEL RANGE | 2.50 | 178. HOURS | UPPER VEL. RANGE | 2.75 |
| STROKES IN THIS VEL. RANGE | - | 210503. | | |
| LOWER VEL RANGE | 2.75 | 199. HOURS | UPPER VEL. RANGE | 3.00 |
| STROKES IN THIS VEL. RANGE | - | 256965. | | |
| LOWER VEL RANGE | 3.00 | 220. HOURS | UPPER VEL. RANGE | 3.25 |
| STROKES IN THIS VEL. RANGE | - | 306960. | | |
| LOWER VEL RANGE | 3.25 | 239. HOURS | UPPER VEL. RANGE | 3.50 |
| STROKES IN THIS VEL. RANGE | - | 359762. | | |
| LOWER VEL RANGE | 3.50 | 257. HOURS | UPPER VEL. RANGE | 3.75 |
| STROKES IN THIS VEL. RANGE | - | 414362. | | |
| LOWER VEL RANGE | [illegible] | 274. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | - | 470418. | | |
| LOWER VEL RANGE | [illegible] | 288. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | - | 526371. | | |
| LOWER VEL RANGE | [illegible] | 301. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | - | 581372. | | |
| LOWER VEL RANGE | 4.00 | 311. HOURS | UPPER VEL. RANGE | 4.25 |
| STROKES IN THIS VEL. RANGE | - | 633381. | | |
| LOWER VEL RANGE | 4.25 | 319. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | - | 684436. | | |
| LOWER VEL RANGE | [illegible] | 324. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | - | 730112. | | |
| LOWER VEL RANGE | [illegible] | 326. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | - | 771579. | | |
| LOWER VEL RANGE | [illegible] | 327. HOURS | UPPER VEL. RANGE | 5.75 |
| STROKES IN THIS VEL. RANGE | - | 806994. | | |
| LOWER VEL RANGE | [illegible] | 321. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | - | 834014. | | |
| LOWER VEL RANGE | [illegible] | 320. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | - | 858261. | | |
| LOWER VEL RANGE | [illegible] | 313. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | - | 873032. | | |
| LOWER VEL RANGE | [illegible] | 304. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | - | 880593. | | |
| LOWER VEL RANGE | [illegible] | 293. HOURS | UPPER VEL. RANGE | [illegible] |
| STROKES IN THIS VEL. RANGE | - | 880155. | | |
| NO. OPERATING [illegible] | [illegible] | [illegible] | STROKES IN AP | [illegible] |

ATTACHMENT NUMBER 2

SUMMARY OF PREDICTIONS FOR WHIRLWIND WIND ELECTRIC GENERATOR FOR V = 4.0 m/s AND V = 6.0 m/s.

Wind Electric System Parameters:

Hub height = 30 feet

Rotor diameter = 3.3 meters

Vcut-in = 2.5 m./s.

```
      PROGRAM GGBLEC
            REAL VN(30),V(30),H(30)
            HT=0.0
            WTR=0.0
            WBAR=4.0
            WK=2.0
            C=WBAR/.887
            VCUT=2.5
            CP=.266
            DIA=3.35
            WRITE(2,28)WBAR,WK,C
   28       FORMAT('  AVER. WIND SPEED',F5.1,'M/S   K=',F3.1,'  C=',F1.2)
            WRITE(2,29)DIA,CP
   29       FORMAT('  ROTOR DIA USED =',F5.3,'   CPERF =',F4.2)
            DO 20 I=1,30
            VN(I)=(VCUT-.5)+(I*.50)
            H(I)=8760*EXP(-(VN(I)/C)**WK)
            IF(I.EQ.1)GOTO34
            WRITE(2,88)H(I)
   88       FORMAT('  NO. HOURS GT VCUT-IN  ',F7.1,' HRS')
   34       CONTINUE
            IF(I.EQ.1)GOTO20
            H(I-1)=H(I-1)-H(I)
            HT=HT+H(I-1)
            WR=(VN(I)-.25)**3.0*CP*.5*1.229*DIA*DIA*.25*3.1415
     *      *H(I-1)*.001
            WTR=WTR+WR
            WRITE (2,12)VN(I-1),H(I-1),VN(I)
   12       FORMAT('   LOWER VEL RANGE',F6.2,F10.0,'  HOURS',
     *      '       UPPER VEL. RANGE',F6.2)
            WRITE(2,32)WR
   32       FORMAT('  KWHR PER YR IN THIS VEL. RANGE =',F12.2)
            IF(I.EQ.21)GOTO200
   20       CONTINUE
  200       CONTINUE
            WRITE(2,18)HT,WTR
   18       FORMAT('  HRS OPERATION IN YR : 8760 ...',F8.1,'  ',
     *      'KWHR PRODUCED IN YR...',F12.2)
            STOP
            END
```

AVER. WIND SPEED 4.0M/S K=2.5 C=4.51
ROTOR DIA USED =3.350 CPeff ~~LAMBDA~~ = .27
NO. HOURS GT VOUT-IN 6968.3 HRS
LOWER VEL RANGE 2.50 863. HOURS UPPER VEL. RANGE 3.00
KWHR PER YR IN THIS VEL. RANGE = 25.84
LOWER VEL RANGE 3.00 953. HOURS UPPER VEL. RANGE 3.50
KWHR PER YR IN THIS VEL. RANGE = 47.13
LOWER VEL RANGE 3.50 977. HOURS UPPER VEL. RANGE 4.00
KWHR PER YR IN THIS VEL. RANGE = 74.25
LOWER VEL RANGE 4.00 936. HOURS UPPER VEL. RANGE 4.50
KWHR PER YR IN THIS VEL. RANGE = 103.48
LOWER VEL RANGE 4.50 839. HOURS UPPER VEL. RANGE 5.00
KWHR PER YR IN THIS VEL. RANGE = 129.55
LOWER VEL RANGE 5.00 706. HOURS UPPER VEL. RANGE 5.50
KWHR PER YR IN THIS VEL. RANGE = 147.19
LOWER VEL RANGE 5.50 558. HOURS UPPER VEL. RANGE 6.00
KWHR PER YR IN THIS VEL. RANGE = 152.77
LOWER VEL RANGE 6.00 414. HOURS UPPER VEL. RANGE 6.50
KWHR PER YR IN THIS VEL. RANGE = 145.50
LOWER VEL RANGE 6.50 288. HOURS UPPER VEL. RANGE 7.00
KWHR PER YR IN THIS VEL. RANGE = 127.57
LOWER VEL RANGE 7.00 198. HOURS UPPER VEL. RANGE 7.50
KWHR PER YR IN THIS VEL. RANGE = 103.17
LOWER VEL RANGE 7.50 115. HOURS UPPER VEL. RANGE 8.00
KWHR PER YR IN THIS VEL. RANGE = 77.06
LOWER VEL RANGE 8.00 66. HOURS UPPER VEL. RANGE 8.50
KWHR PER YR IN THIS VEL. RANGE = 53.19
LOWER VEL RANGE 8.50 35. HOURS UPPER VEL. RANGE 9.00
KWHR PER YR IN THIS VEL. RANGE = 33.95
LOWER VEL RANGE 9.00 18. HOURS UPPER VEL. RANGE 9.50
KWHR PER YR IN THIS VEL. RANGE = 20.03
LOWER VEL RANGE 9.50 8. HOURS UPPER VEL. RANGE 10.00
KWHR PER YR IN THIS VEL. RANGE = 10.92
LOWER VEL RANGE 10.00 4. HOURS UPPER VEL. RANGE 10.50
KWHR PER YR IN THIS VEL. RANGE = 5.50
LOWER VEL RANGE 10.50 1. HOURS UPPER VEL. RANGE 11.00
KWHR PER YR IN THIS VEL. RANGE = 2.56
LOWER VEL RANGE 11.00 1. HOURS UPPER VEL. RANGE 11.50
KWHR PER YR IN THIS VEL. RANGE = 1.10
LOWER VEL RANGE 11.50 . HOURS UPPER VEL. RANGE 12.00
KWHR PER YR IN THIS VEL. RANGE = .44
LOWER VEL RANGE 12.00 . HOURS UPPER VEL. RANGE 12.50
KWHR PER YR IN THIS VEL. RANGE = .16
HRS OPERATION IN YR : 8760 ... 6968.3 KWHR PRODUCED IN YR... 1261.37

62

$\bar{V} = 6.4$ m/s

```
      PROGRAM GGELEC
            REAL VN(30),V(30),H(30)
            HT=0.0
            WTR=0.0
            WBAR =6.0
            WK=2.5
            C=WBAR/.887
            VCUT=2.5
            CP=.266
            DIA=3.05
            WRITE(2,28)WBAR,WK,C
28          FORMAT('  AVER. WIND SPEED',F5.1,'M/S   K=',F3.1,'  C=',F4.2)
            WRITE(2,29)DIA,CP
29          FORMAT('  ROTOR DIA USED =',F5.3,'   CPERF =',F4.2)
20          DO 20 I=1,30
            VN(I)=(VCUT-.5)+(I*.50)
            H(I)=8760*EXP(-(VN(I)/C)**WK)
            IF(I.GT.1)GOTO34
            WRITE(2,88)H(I)
88          FORMAT('  NO. HOURS GT VCUT-IN  ',F7.1,' HRS')
34          CONTINUE
            IF(I.EQ.1)GOTO20
            H(I-1)=H(I-1)-H(I)
            HT=HT+H(I-1)
            WR=(VN(I)-.25)**3.0*CP*.5*1.229*DIA*DIA*.25*3.1415
     *      *H(I-1)*.001
            WTR=WTR+WR
            WRITE (2,12)VN(I-1),H(I-1),VN(I)
12          FORMAT('  LOWER VEL RANGE',F6.2,F10.0,'  HOURS',
     *      '      UPPER VEL. RANGE',F6.2)
            WRITE(2,32)WR
32          FORMAT('  KWHR PER YR IN THIS VEL. RANGE =',F12.2)
            IF(I.EQ.21)GOTO200
20          CONTINUE
200         CONTINUE
            WRITE(2,18)HT,WTR
18          FORMAT('  HRS OPERATION IN YR : 8760 ...',F8.1,'  ',
     *      'KWHR PRODUCED IN YR...',F12.2)
            STOP
            END
```

```
AVER. WIND SPEED  6.0M/S   K=2.5  C=6.76
ROTOR DIA USED =3.350   CPEF = .27
NO. HOURS GT VCUT-IN   8062.0 HRS
LOWER VEL RANGE  2.50        377.  HOURS      UPPER VEL. RANGE  3.00
KWHR PER YR IN THIS VEL. RANGE =        11.31
LOWER VEL RANGE  3.00        459.  HOURS      UPPER VEL. RANGE  3.50
KWHR PER YR IN THIS VEL. RANGE =        22.70
LOWER VEL RANGE  3.50        531.  HOURS      UPPER VEL. RANGE  4.00
KWHR PER YR IN THIS VEL. RANGE =        40.34
LOWER VEL RANGE  4.00        589.  HOURS      UPPER VEL. RANGE  4.50
KWHR PER YR IN THIS VEL. RANGE =        65.12
LOWER VEL RANGE  4.50        629.  HOURS      UPPER VEL. RANGE  5.00
KWHR PER YR IN THIS VEL. RANGE =        97.17
LOWER VEL RANGE  5.00        650.  HOURS      UPPER VEL. RANGE  5.50
KWHR PER YR IN THIS VEL. RANGE =       135.55
LOWER VEL RANGE  5.50        651.  HOURS      UPPER VEL. RANGE  6.00
KWHR PER YR IN THIS VEL. RANGE =       178.26
LOWER VEL RANGE  6.00        632.  HOURS      UPPER VEL. RANGE  6.50
KWHR PER YR IN THIS VEL. RANGE =       222.33
LOWER VEL RANGE  6.50        596.  HOURS      UPPER VEL. RANGE  7.00
KWHR PER YR IN THIS VEL. RANGE =       264.16
LOWER VEL RANGE  7.00        546.  HOURS      UPPER VEL. RANGE  7.50
KWHR PER YR IN THIS VEL. RANGE =       300.00
LOWER VEL RANGE  7.50        487.  HOURS      UPPER VEL. RANGE  8.00
KWHR PER YR IN THIS VEL. RANGE =       326.49
LOWER VEL RANGE  8.00        422.  HOURS      UPPER VEL. RANGE  8.50
KWHR PER YR IN THIS VEL. RANGE =       341.17
LOWER VEL RANGE  8.50        355.  HOURS      UPPER VEL. RANGE  9.00
KWHR PER YR IN THIS VEL. RANGE =       342.83
LOWER VEL RANGE  9.00        291.  HOURS      UPPER VEL. RANGE  9.50
KWHR PER YR IN THIS VEL. RANGE =       331.67
LOWER VEL RANGE  9.50        232.  HOURS      UPPER VEL. RANGE 10.00
KWHR PER YR IN THIS VEL. RANGE =       309.20
LOWER VEL RANGE 10.00        179.  HOURS      UPPER VEL. RANGE 10.50
KWHR PER YR IN THIS VEL. RANGE =       277.95
LOWER VEL RANGE 10.50        135.  HOURS      UPPER VEL. RANGE 11.00
KWHR PER YR IN THIS VEL. RANGE =       241.07
LOWER VEL RANGE 11.00         98.  HOURS      UPPER VEL. RANGE 11.50
KWHR PER YR IN THIS VEL. RANGE =       201.78
LOWER VEL RANGE 11.50         70.  HOURS      UPPER VEL. RANGE 12.00
KWHR PER YR IN THIS VEL. RANGE =       163.04
LOWER VEL RANGE 12.00         48.  HOURS      UPPER VEL. RANGE 12.50
KWHR PER YR IN THIS VEL. RANGE =       127.21
HRS OPERATION IN YR : 8760 ...   7977.5  KWHR PRODUCED IN YR...      3999.30
```

Conclusions: This is quite low and shows that this $\phi$ and $\bar{V}$ is not likely to be cost-competitive if initial capital costs are high.

# APPENDIX 3

## WIND TURBINE ROTOR DESIGN ANALYSIS USING COMPUTER MODELLING TECHNIQUES

W. SCHMIDT
GEE/LESO
JULY 1984

# WIND TURBINE ROTOR DESIGN ANALYSIS USING COMPUTER MODELLING TECHNIQUES

In order to facilitate the analysis of rotor design at LESO it was necessary to develo a simplified mathematical model for the GEE. As this would only be a "first-order model, using several simplifying assumptions, the information generated would onl give approximate values. However, these results would be more than adequate fo comparative purposes. This way, designs and rotor configurations could be analyze and comparisons between different rotors could be made. For example, two rotor with different blade angles or differing blade shapes could be evaluated and compare to each other. By systematically analyzing all the important configurations for a roto geometry, an optimum design would result from this iterative design process (Hopefully, initial design parameters would be reasonably close to begin with, so th number of iterations required would be minimized.)

## Blade Element Model

The analytic procedure developed takes the lift and drag valves for a given angle o attack of a blade element, and calculates the net lift and net drag. Using the resultant net differenc in force the torque generated by the blade element is then calculated as net force times moment arm. The total of the elemental torques along the blade is summed up, times the number of blades to give the total estimated torque. The product of tip speed ratio ($\lambda$) and torque will give power output. The torque and power coefficients CT & CP can be found by dividing through by the respective total input values.

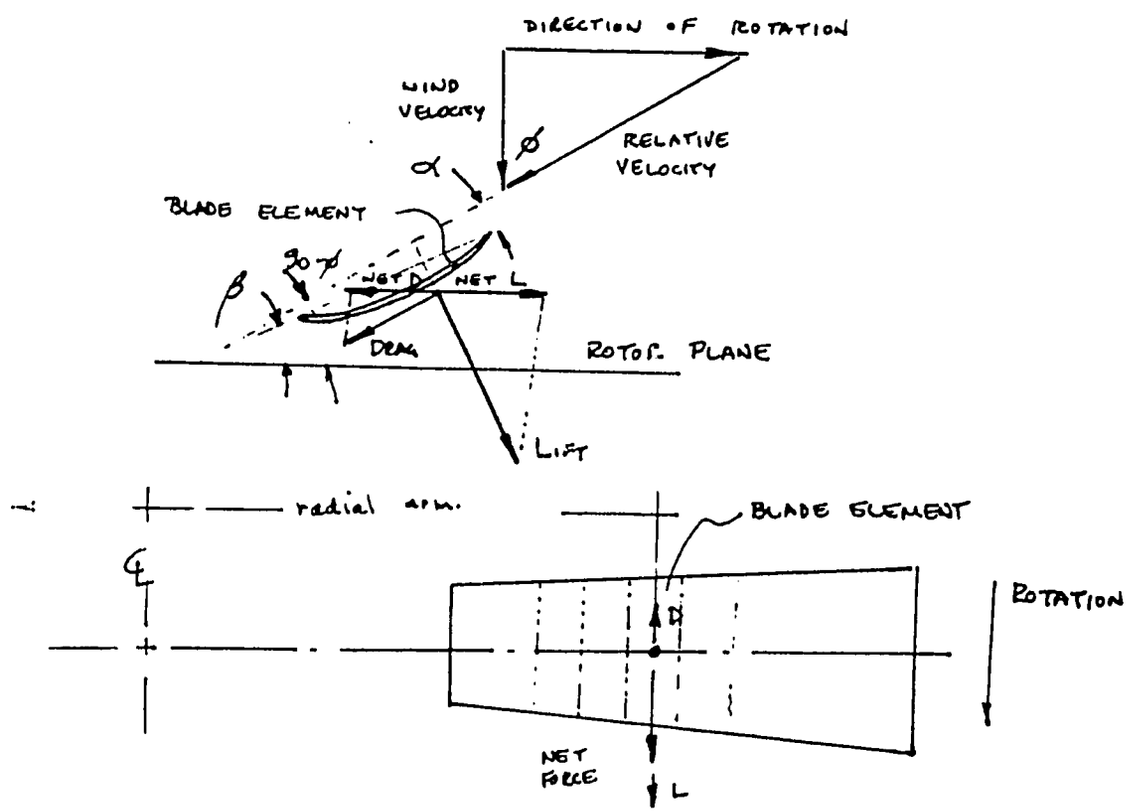



Figure 1: Blade Element Force Diagram

The angle of attack for the blade element is found by determining the relativ approach angle of the wind and comparing this to the fixed blade angle. The lift an drag valves are then taken from the curves given in the reference figures fc cambered plate air foils. A copy of valves for 5%, 10% and 15% plates is included a the end of the report. Net drag and lift in the respective directions is then computed.

**Equation used:**

1. relative wind angle $\phi = \tan^{-1}(\lambda \times R \times \text{radial station})$
2. fixed angle = $\beta$
3. angle of attack, $\alpha = 90^{o} - \beta - \phi$
4. lift (+ve) in plane of rotation = CL cos $\phi$
5. drag (-ve) in plane of rotation = CD sin $\phi$
6. torque = (CL cos $\phi$ - CD sin $\phi$) x moment arm/cos $\phi^2$ where cos $\phi^2$ corrects foı wind velocity to element
7. coeff. torque = torque x nº blades x area/rotor area
8. coeff. performance = CT $*\lambda$

## Computer Model

In the computer model the following variables are used:

| | | |
|---|---|---|
| AREA | is | elemental area |
| BLADES | is | no. of blades |
| FBYL | is | the % camber of blade |
| RR | is | the rotor radius |
| ALAMB | is | tip speed ratio $\lambda$ |
| PI | is | $\pi$ |
| RS | is | radial station of blade element, moment arm |
| BC | is | blade correction for non-rectangular blades |
| THETA | is | $\phi$ relative wind angle |
| BETA | is | $\beta$ blade angle |
| ALFA | is | $\alpha$ angle of attack |
| THETA B, BETA B, ALFA B | are | valves of $\phi$, $\beta$ and $\alpha$ in degrees (trig functions use value in radians) |
| CL | is | coefficient of lift from reference figure |
| CD | is | coefficient of drag from reference figure |
| T | is | torque generated by blade element |
| CT | is | sum of torque for blade |
| CTA | is | coefficient of torque |
| CP | is | coefficient of performance |

The computer model calculates the angle of attack, finds the nearest valves for CL and CD and then finds T, CT and CP. Tip losses are approximated by using only half the CL valve for the tip blade element. While the calculations may be done manually this program is largely a rapid way to calculate the multiple equations.

## Results

In order to evaluate the model, the 12PU500 rotor was used for comparative purposes. As a performance curve was given for this rotor, it was assumed that if a model could predict this curve relatively well, it would be a fairly good model. Figure 2 shows the results of using the model to predict the 12PU500 performance curve.

As the initial valves predicted by the model do not reproduce the given 12PU500 curve, a "swirl factor" is added to the model to modify the actual velocity seen by each blade element. This factor is used to force the model to predict the required curve. As the figure shows, using a swirl factor of 1.3 does give quite a good matching for the curves. (This would represent a velocity reduction to 88% across the blade element, not unreasonable.)

With the model now able to predict the 12PU500 rotor performance reasonably well, it was used to evaluate the LESO II 4m Ø rotor. The results are shown in Figure 3. As the LESO II has 18 blades, a higher solidity, a "swirl factor" of 1.4 is used as an approximation.

A comparison is also made for the LESO II rotor with rectangular blades vs trapezodial blades. The results are included in Figure 3.

All printouts are appended as attachments.

## Attachments

1. Program ROTOR.FOR, Model for 12PU500
2. Program RRR.FOR, Model for LESO II with rectangular blades
3. Program RRR.FOR, Model for LESO II with trapezodial blades

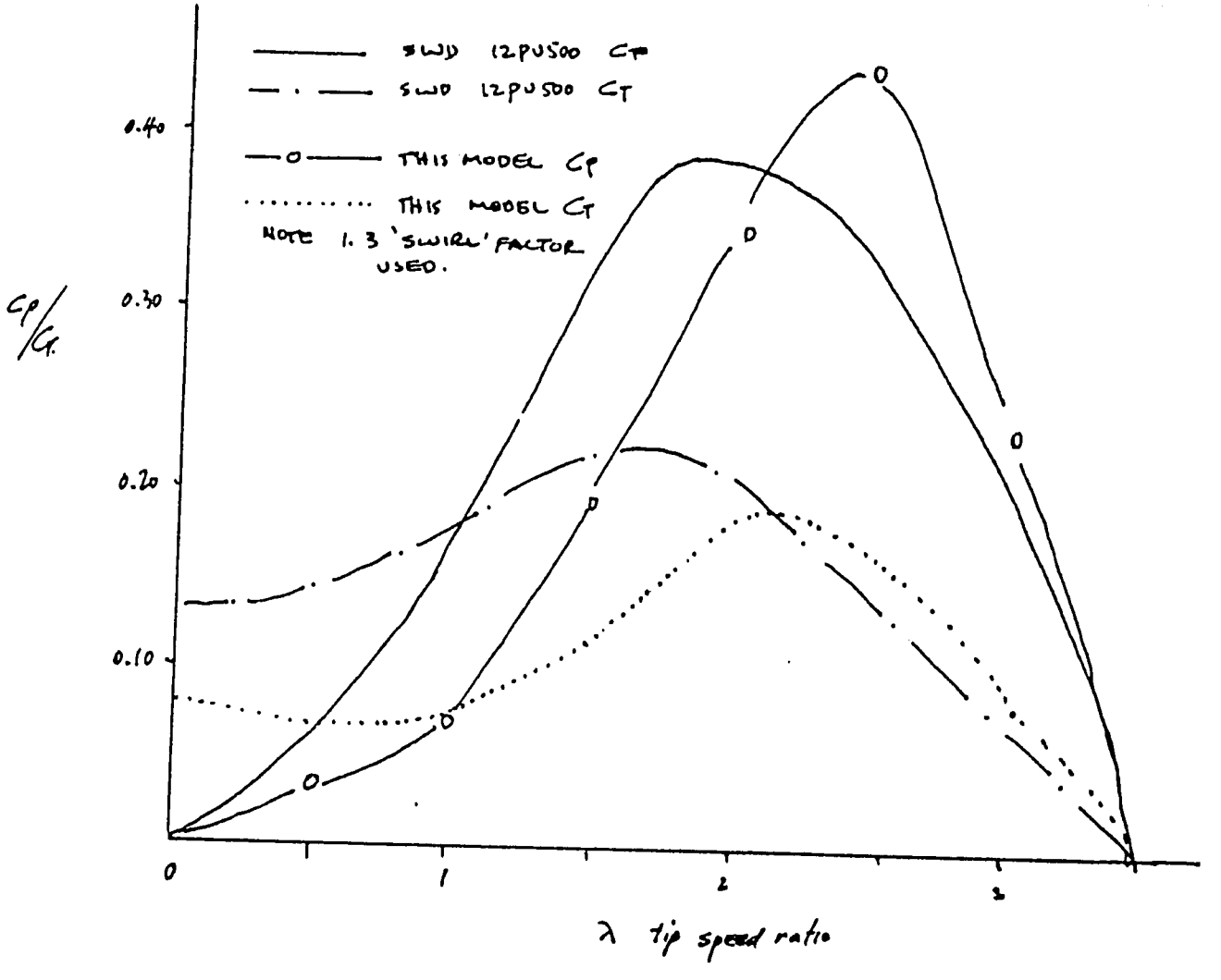



figure 2: Computer model predictions vs. published curves for 12PU500

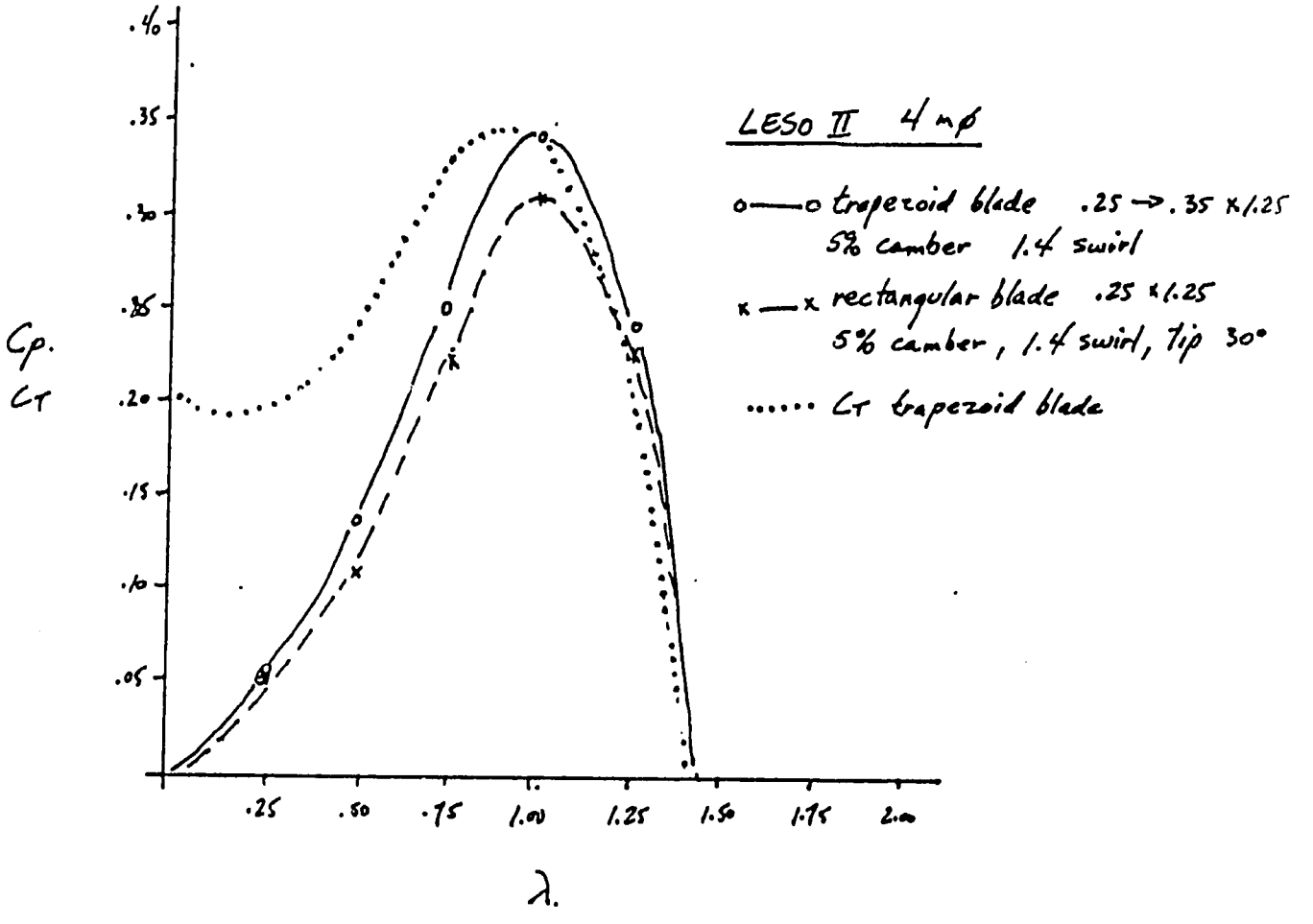
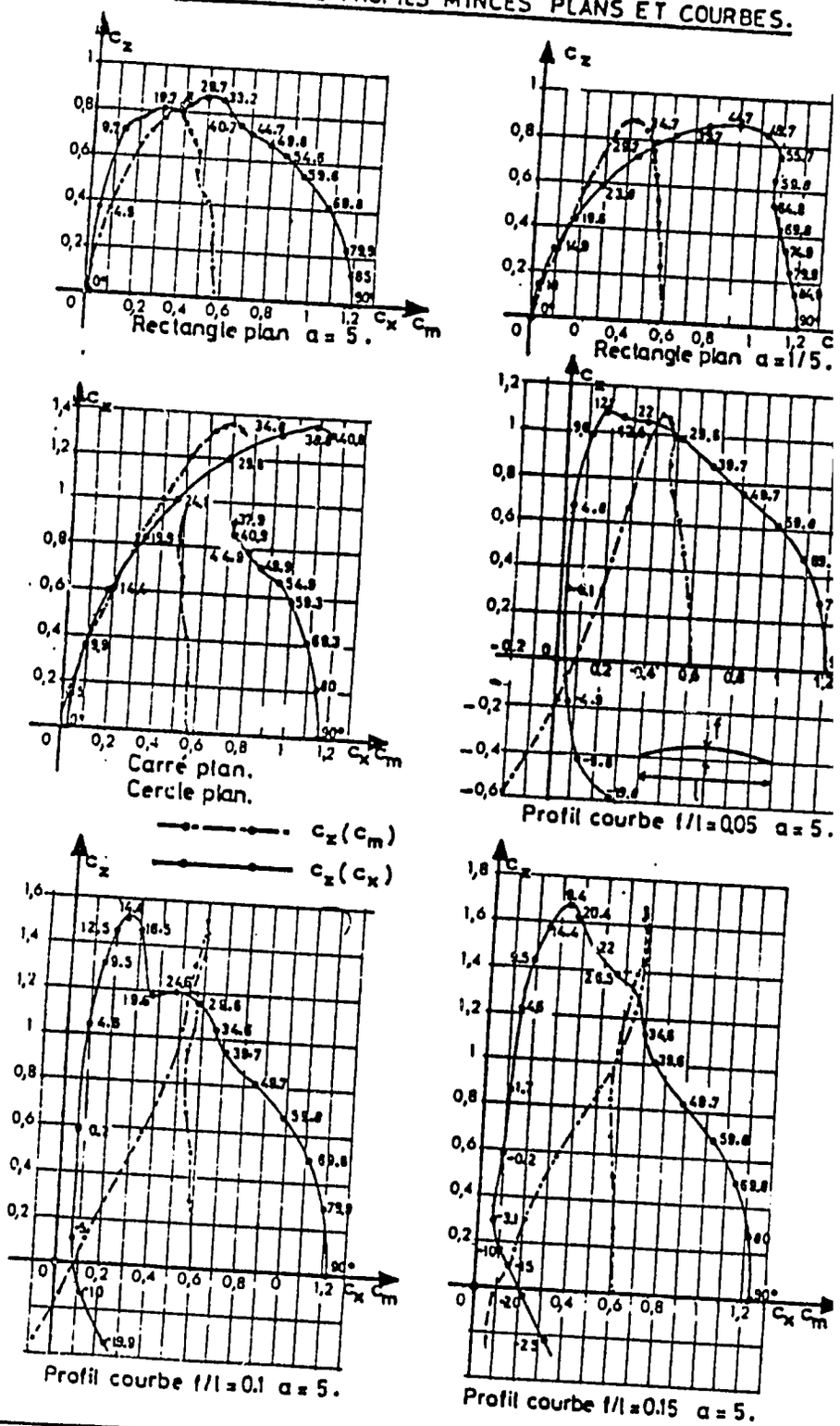



figure 3: COEFFICIENT OF PERFORMANCE VS TIP SPEED RATIO FOR LESO II 4m φ ROTOR

POLAIRES DE PROFILS MINCES PLANS ET COURBES.




REFERENCE FIGURE: LIFT & DRAG CURVES FOR CAMBERED PLATE BLADES.

SOURCE: ENERGIE EOLIENNE

```
      PROGRAM ROTOR
       /////////////     ENTERING SWIRL IN THETA     //////////////
      THIS PROGRAM CALCULATES COEFF OF TORQUE AND PERF FOR --- >
      BASED ON CL AND CD OF BLADE SECTIONS
      DATA ENTRY IF FOR F/L  0.05 AND 0.10 ONLY
      CURVED PLATES ONLY
      MUST ENTER LAMBDA AND RADIUS, MODIFY BLADE CORRECTION
      AND BETA ANGLE OF BLADES TO RUN OTHER CONFIGURATIONS
      ANGLES USED ARE:
      BETAB    ANGLE OF BLADE TO ROTOR PLANE, DEGREES
      BETA    BETAB IN RADIANS
      THETAB  ANGLE OF INCIDENT WIND IN DEGREES
      THETA  THETAB IN RADIANS
      ALFAB    ANGLE OF ATTACK IN DEGREES
      ALFA   ALFAB IN RADIANS
      ALFA = BETA - THETA
      KK IS RADIAL STATION COUNTER, WATCH INNER LIMIT
      WHEN LAMBDA IS ZERO, CD  GOES TO ZERO FOR STARTING TORQUE

      NO CORRECTION IS MADE FOR VELOCITY REDUCTION ACROSS BLADES
      (1-A)
      ****************************
     TIP LOSSES INCL BY SETTING CL = 0.0 @ .95
*****************!!!!!!!!!!!!!!
      PROGRAMME SHOULD BE USED FOR COMPARATIVE PURPOSES ONLY
      SEE PROGRAM RRR.FOR FOR PARAMETERS FOR LESO II ROTOR
      SEE ALSO PROGRAM ROLL.FOR
      REAL PI,RR,THETAB,ALFAB,ALFA,THETA,BETA,BETAB
      AREA=.25*.25
      BLADES=12
      FBYL =.05
      RR=2.5
      DO 25 I=1,17
      ALAMB=(I*.25)-.25
      CT=0.0
      PI=3.1415
      DO 30  KK=25,95,10
      RS=KK/100.0
      BC=(.250-(RS-.25)*RR*.025)/.250
--------------  MODIFY WITH SWIRL --------------
      THETA=ATAN(RS*ALAMB*1.30)
      THETAB=THETA*180./PI
      BETA=(36.9-((RS-.25)*RR*15))*PI/180
      BETA IS BLADE ANGLE INITIATIZATION, CHANGE FOR NEW CONFIGUR'N
      BETAB=BETA*180/PI
      ALFAB=90-BETAB-THETAB
      ALFA=ALFAB*PI/180.
      FORMAT('    ALFA,BETA,THETA',3F6.2,' RS & LAMBDA',2F6.3)
      IF(ALFAB.GT.90)GOTO99
      IF(FBYL.EQ.0.10)GOTO71
      IF(FBYL.EQ..05)GOTO 41
      WRITE(2,31)
      FORMAT(' ...
```

12PU500

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```
41      IF(ALFAB.LT.85)GOTO42
        CL=0.0
        CD=1.2
        GOTO91
42      IF(ALFAB.LT.75)GOTO43
        CL=.30
        CD=1.18
        GOTO91
43      IF(ALFAB.LT.65)GOTO44
        CL=.48
        CD=1.14
        GOTO91
44      IF(ALFAB.LT.55)GOTO45
        CL=.62
        CD=.95
        GOTO91
45      IF(ALFAB.LT.45)GOTO46
        CL=.75
        CD=.80
        GOTO91
46      IF(ALFAB.LT.35)GOTO47
        CL=.88
        CD=.65
        GOTO91
47      IF(ALFAB.LT.25.5)GOTO48
        CL=1.0
        CD=.50
        GOTO91
48      IF(ALFAB.LT.17.6)GOTO49
        CL=1.12
        CD=.35
        GOTO91
49      IF(ALFAB.LT.12.4)GOTO50
        CL=1.13
        CD=.25
        GOTO91
50      IF(ALFAB.LT.10.8)GOTO51
        CL=1.15
        CD=.15
        GOTO91
51      IF(ALFAB.LT.7.3)GOTO52
        CL=1.0
        CD=.10
        GOTO91
52      IF(ALFAB.LT.2.5)GOTO53
        CL=.68
        CD=.04
        GOTO91
53      IF(ALFAB.LT.-2.5)GOTO54
        CL=.30
        CD=.03
        GOTO91
54      IF(ALFAB.LT.-7.5)GOTO55
        CL=-.20
        CD=.08
        GOTO91
55      IF(ALFAB.LT.-15)GOTO56
        CL=-.4
        CD=.10
        GOTO91
56      IF(ALFAB.LT.-19.8)GOTO100
        CL=-.6
        CD=.3
```

```
      CD=1.22
      GOTO91
72    IF(ALFAB.LT.75)GOTO73
      CL=.3
      CD=1.2
      GOTO91
73    IF(ALFAB.LT.65)GOTO74
      CL=.5
      CD=1.1
      GOTO91
74    IF(ALFAB.LT.55)GOTO75
      CL=.68
      CD=1.0
      GOTO91
75    IF(ALFAB.LT.45)GOTO76
      CL=.80
      CD=.85
      GOTO91
76    IF(ALFAB.LT.37)GOTO77
      CL=.96
      CD=.70
      GOTO91
77    IF(ALFAB.LT.32)GOTO78
      CL=1.05
      CD=.65
      GOTO91
78    IF(ALFAB.LT.27)GOTO79
      CL=1.18
      CD=.58
      GOTO91
79    IF(ALFAB.LT.22)GOTO80
      CL=1.2
      CD=.48
      GOTO91
80    IF(ALFAB.LT.18)GOTO81
      CL=1.2
      CD=.35
      GOTO91
81    IF(ALFAB.LT.15.5)GOTO82
      CL=1.45
      CD=.30
      GOTO91
82    IF(ALFAB.LT.13.5)GOTO83
      CL=1.50
      CD=.25
      GOTO91
83    IF(ALFAB.LT.11)GOTO84
      CL=1.454
      CD=.2
      GOTO91
84    IF(ALFAB.LT.7)GOTO85
      CL=1.3
      CD=.15
      GOTO91
      IF(ALFAB.LT.2.2)GOTO86
      CL=1.05
      CD=.15
      GOTO91
86    IF(ALFAB.LT.-2.5)GOTO87
      CL=.6
      CD=.08
      GOTO91
87    IF(ALFAB.LT.-7.5)GOTO88
```

```
      GOTO91
88    IF(ALFAB.LT.-13)GOTO89
      CL=-.12
      CD=.1
      GOTO91
89    IF(ALFAB.LT.-19.8)GOTO100
      CL=-.35
      CD=.35
      GOTO 91
91    CONTINUE
      IF(RS.EQ..95)CL=0.0
      T=(CL*COS(THETA)-CD*SIN(THETA))*RS*BC*1.0/(COS(THETA))
     *  *1.0/(COS(THETA))
      CT=CT+T
      WRITE(2,33)RS,BETAB,THETAB,ALFAB,CL,CD,T
33    FORMAT('  RADIAL STATION=',F4.2,'   BETA=',F4.1,'   THETA='
     *  ,F4.1,'  ALFA=',F6.1,'  CL=',F4.2,'  CD=',F4.2,'    TORQUE=
     *  F5.2)
30    CONTINUE
      CTA=CT*BLADES*AREA/(RR*RR*PI)
      WRITE(2,35)CT,CTA,ALAMB,FBYL
35    FORMAT('  COEFF TORQUE AT RS=',F5.2,'  COEFF TQ CORRECTED=
     *  F6.2,'   LAMBDA=',F4.2,'  F/L=',F4.2)
      CP=CTA*ALAMB
      WRITE(2,103)CP
103   FORMAT('   COEFFICIENT OF PERFORMANCE = ',F6.2)
25    CONTINUE
      GOTO101
99    WRITE(2,37)
37    FORMAT('     **** ALFA .GT.  90 !!!!!!')
      GOTO101
100   WRITE(2,39)ALFAB
39    FORMAT('  **** ALFA LESS THAN -19.6, NO VALUES GIVEN
     *    PROGRAMME ABORTED !!!!!',F8.3)
101   STOP
      END
```

```
RADIAL STATION= .25   BETA=36.9   THETA= 0.0  ALFA=  53.1  CL= .75  CD= .80
TORQUE=  .19
RADIAL STATION= .35   BETA=33.1   THETA= 0.0  ALFA=  56.9  CL= .62  CD= .95
TORQUE=  .21
RADIAL STATION= .45   BETA=29.4   THETA= 0.0  ALFA=  60.6  CL= .62  CD= .95
TORQUE=  .27
RADIAL STATION= .55   BETA=25.6   THETA= 0.0  ALFA=  64.4  CL= .62  CD= .95
TORQUE=  .32
RADIAL STATION= .65   BETA=21.9   THETA= 0.0  ALFA=  68.1  CL= .48  CD=1.14
TORQUE=  .28
RADIAL STATION= .75   BETA=18.1   THETA= 0.0  ALFA=  71.9  CL= .48  CD=1.14
TORQUE=  .31
RADIAL STATION= .85   BETA=14.4   THETA= 0.0  ALFA=  75.6  CL= .30  CD=1.18
TORQUE=  .22
 IAL STATION= .95   BETA=10.6   THETA= 0.0  ALFA=  79.4  CL=0.00  CD=1.18
TORQUE= 0.00
COEFF TORQUE AT RS= 1.79  COEFF TQ CORRECTED=   .07   LAMBDA=0.00.  F/L= .05
 COEFFICIENT OF PERFORMANCE =   0.00
RADIAL STATION= .25   BETA=36.9   THETA= 4.6  ALFA=  48.5  CL= .75  CD= .80
TORQUE=  .17
RADIAL STATION= .35   BETA=33.1   THETA= 6.5  ALFA=  50.4  CL= .75  CD= .80
TORQUE=  .23
```

```
RADIAL STATION= .55    BETA=25.6    THETA=10.1   ALFA=  54.2   CL= .75   CD= .80
TORQUE=  .31
RADIAL STATION= .65    BETA=21.9    THETA=11.9   ALFA=  56.2   CL= .62   CD= .95
TORQUE=  .25
RADIAL STATION= .75    BETA=18.1    THETA=13.7   ALFA=  58.2   CL= .62   CD= .95
TORQUE=  .26
RADIAL STATION= .85    BETA=14.4    THETA=15.4   ALFA=  60.2   CL= .62   CD= .95
TORQUE=  .27
RADIAL STATION= .95    BETA=10.6    THETA=17.2   ALFA=  62.2   CL=0.00   CD= .95
TORQUE= -.24
COEFF TORQUE AT RS= 1.53  COEFF TQ CORRECTED=    .06   LAMBDA= .25   F/L= .05
 COEFFICIENT OF PERFORMANCE =    .01
RADIAL STATION= .25    BETA=36.9    THETA= 9.2   ALFA=  43.9   CL= .88   CD= .65
TORQUE=  .20
RADIAL STATION= .35    BETA=33.1    THETA=12.8   ALFA=  44.0   CL= .88   CD= .65
TORQUE=  .26
RADIAL STATION= .45    BETA=29.4    THETA=16.3   ALFA=  44.3   CL= .88   CD= .65
TORQUE=  .31
RADIAL STATION= .55    BETA=25.6    THETA=19.7   ALFA=  44.7   CL= .88   CD= .65
TORQUE=  .35
RADIAL STATION= .65    BETA=21.9    THETA=22.9   ALFA=  45.2   CL= .75   CD= .80
TORQUE=  .26
RADIAL STATION= .75    BETA=18.1    THETA=26.0   ALFA=  45.9   CL= .75   CD= .80
TORQUE=  .26
RADIAL STATION= .85    BETA=14.4    THETA=28.9   ALFA=  46.7   CL= .75   CD= .80
TORQUE=  .25
RADIAL STATION= .95    BETA=10.6    THETA=31.7   ALFA=  47.7   CL=0.00   CD= .80
TORQUE= -.46
COEFF TORQUE AT RS= 1.43  COEFF TQ CORRECTED=    .05   LAMBDA= .50   F/L= .05
 COEFFICIENT OF PERFORMANCE =    .03
RADIAL STATION= .25    BETA=36.9    THETA=13.7   ALFA=  39.4   CL= .88   CD= .65
TORQUE=  .19
RADIAL STATION= .35    BETA=33.1    THETA=18.8   ALFA=  38.0   CL= .88   CD= .65
TORQUE=  .24
RADIAL STATION= .45    BETA=29.4    THETA=23.7   ALFA=  36.9   CL= .88   CD= .65
TORQUE=  .28
RADIAL STATION= .55    BETA=25.6    THETA=28.2   ALFA=  36.1   CL= .88   CD= .65
TORQUE=  .31
RADIAL STATION= .65    BETA=21.9    THETA=32.4   ALFA=  35.7   CL= .88   CD= .65
TORQUE=  .32
RADIAL STATION= .75    BETA=18.1    THETA=36.2   ALFA=  35.7   CL= .88   CD= .65
TORQUE=  .33
RADIAL STATION= .85    BETA=14.4    THETA=39.7   ALFA=  35.9   CL= .88   CD= .65
TORQUE=  .32
RADIAL STATION= .95    BETA=10.6    THETA=42.8   ALFA=  36.5   CL=0.00   CD= .65
TORQUE= -.64
COEFF TORQUE AT RS= 1.34  COEFF TQ CORRECTED=    .05   LAMBDA= .75   F/L= .05
 COEFFICIENT OF PERFORMANCE =    .04
RADIAL STATION= .25    BETA=36.9    THETA=18.0   ALFA=  35.1   CL= .88   CD= .65
TORQUE=  .18
RADIAL STATION= .35    BETA=33.1    THETA=24.5   ALFA=  32.4   CL=1.00   CD= .50
TORQUE=  .29
RADIAL STATION= .45    BETA=29.4    THETA=30.3   ALFA=  30.3   CL=1.00   CD= .50
TORQUE=  .35
RADIAL STATION= .55    BETA=25.6    THETA=35.6   ALFA=  28.8   CL=1.00   CD= .50
TORQUE=  .40
 DIAL STATION= .65     BETA=21.9    THETA=40.2   ALFA=  27.9   CL=1.00   CD= .50
TORQUE=  .44
RADIAL STATION= .75    BETA=18.1    THETA=44.3   ALFA=  27.6   CL=1.00   CD= .50
TORQUE=  .47
RADIAL STATION= .85    BETA=14.4    THETA=47.9   ALFA=  27.7   CL=1.00   CD= .50
TORQUE=  .48
RADIAL STATION= .95    BETA=10.6    THETA=51.0   ALFA=  28.3   CL=0.00   CD= .50
TORQUE= -.77
```

```
RADIAL STATION= .85    BETA=14.4    THETA=63.7   ALFA=   9.9   CL=1.00   CD= .10
TORQUE= 1.37
RADIAL STATION= .95    BETA=10.6    THETA=68.0   ALFA=  11.4   CL=0.00   CD= .15
TORQUE= -.77
COEFF TORQUE AT RS= 4.79   COEFF TQ CORRECTED=    .18    LAMBDA=2.00   F/L= .05
 COEFFICIENT OF PERFORMANCE =    .37
RADIAL STATION= .25    BETA=36.9    THETA=36.2   ALFA=  16.9   CL=1.13   CD= .25
TORQUE=  .29
RADIAL STATION= .35    BETA=33.1    THETA=45.7   ALFA=  11.2   CL=1.15   CD= .15
TORQUE=  .49
RADIAL STATION= .45    BETA=29.4    THETA=52.8   ALFA=   7.8   CL=1.00   CD= .10
TORQUE=  .61
RADIAL STATION= .55    BETA=25.6    THETA=58.1   ALFA=   6.2   CL= .68   CD= .04
TORQUE=  .59
RADIAL STATION= .65    BETA=21.9    THETA=62.3   ALFA=   5.8   CL= .68   CD= .04
TORQUE=  .76
RADIAL STATION= .75    BETA=18.1    THETA=65.5   ALFA=   6.4   CL= .68   CD= .04
TORQUE=  .94
RADIAL STATION= .85    BETA=14.4    THETA=68.1   ALFA=   7.5   CL=1.00   CD= .10
TORQUE= 1.45
RADIAL STATION= .95    BETA=10.6    THETA=70.2   ALFA=   9.1   CL=0.00   CD= .10
TORQUE= -.64
COEFF TORQUE AT RS= 4.49   COEFF TQ CORRECTED=    .17    LAMBDA=2.25   F/L= .05
 COEFFICIENT OF PERFORMANCE =    .39
RADIAL STATION= .25    BETA=36.9    THETA=39.1   ALFA=  14.0   CL=1.13   CD= .25
TORQUE=  .30
RADIAL STATION= .35    BETA=33.1    THETA=48.7   ALFA=   8.2   CL=1.00   CD= .10
TORQUE=  .46
RADIAL STATION= .45    BETA=29.4    THETA=55.6   ALFA=   5.0   CL= .68   CD= .04
TORQUE=  .47
RADIAL STATION= .55    BETA=25.6    THETA=60.8   ALFA=   3.6   CL= .68   CD= .04
TORQUE=  .63
RADIAL STATION= .65    BETA=21.9    THETA=64.7   ALFA=   3.4   CL= .68   CD= .04
TORQUE=  .81
RADIAL STATION= .75    BETA=18.1    THETA=67.7   ALFA=   4.2   CL= .68   CD= .04
TORQUE= 1.01
RADIAL STATION= .85    BETA=14.4    THETA=70.1   ALFA=   5.5   CL= .68   CD= .04
TORQUE= 1.21
RADIAL STATION= .95    BETA=10.6    THETA=72.1   ALFA=   7.3   CL=0.00   CD= .04
TORQUE= -.31
COEFF TORQUE AT RS= 4.58   COEFF TQ CORRECTED=    .17    LAMBDA=2.50   F/L= .05
 COEFFICIENT OF PERFORMANCE =    .44
RADIAL STATION= .25    BETA=36.9    THETA=41.8   ALFA=  11.3   CL=1.15   CD= .15
TORQUE=  .34
RADIAL STATION= .35    BETA=33.1    THETA=51.4   ALFA=   5.5   CL= .68   CD= .04
TORQUE=  .34
RADIAL STATION= .45    BETA=29.4    THETA=58.1   ALFA=   2.5   CL= .30   CD= .03
TORQUE=  .20
RADIAL STATION= .55    BETA=25.6    THETA=63.0   ALFA=   1.3   CL= .30   CD= .03
TORQUE=  .27
RADIAL STATION= .65    BETA=21.9    THETA=66.7   ALFA=   1.4   CL= .30   CD= .03
TORQUE=  .34
RADIAL STATION= .75    BETA=18.1    THETA=69.5   ALFA=   2.3   CL= .30   CD= .03
TORQUE=  .41
RADIAL STATION= .85    BETA=14.4    THETA=71.8   ALFA=   3.8   CL= .68   CD= .04
TORQUE= 1.29
RADIAL STATION= .95    BETA=10.6    THETA=73.6   ALFA=   5.8   CL=0.00   CD= .04
TORQUE= -.38
COEFF TORQUE AT RS= 2.83   COEFF TQ CORRECTED=    .11    LAMBDA=2.75   F/L= .05
 COEFFICIENT OF PERFORMANCE =    .30
RADIAL STATION= .25    BETA=36.9    THETA=44.3   ALFA=   8.8   CL=1.00   CD= .10
TORQUE=  .32
RADIAL STATION= .35    BETA=33.1    THETA=53.8   ALFA=   3.1   CL= .68   CD= .04
TORQUE=  .36
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```
RADIAL STATION= .55   BETA=25.6   THETA=65.0  ALFA=   -.7  CL= .30  CD= .03
TORQUE=  .28
RADIAL STATION= .65   BETA=21.9   THETA=68.5  ALFA=   -.4  CL= .30  CD= .03
TORQUE=  .36
RADIAL STATION= .75   BETA=18.1   THETA=71.1  ALFA=    .7  CL= .30  CD= .03
TORQUE=  .43
RADIAL STATION= .85   BETA=14.4   THETA=73.2  ALFA=   2.4  CL= .30  CD= .03
TORQUE=  .50
RADIAL STATION= .95   BETA=10.6   THETA=74.9  ALFA=   4.5  CL=0.00  CD= .04
TORQUE= -.45
COEFF TORQUE AT RS= 2.02  COEFF TQ CORRECTED=   .08   LAMBDA=3.00  F/L= .05
 COEFFICIENT OF PERFORMANCE =    .23
RADIAL STATION= .25   BETA=36.9   THETA=46.6  ALFA=   6.5  CL= .68  CD= .04
TORQUE=  .23
RADIAL STATION= .35   BETA=33.1   THETA=55.9  ALFA=    .9  CL= .30  CD= .03
TORQUE=  .16
RADIAL STATION= .45   BETA=29.4   THETA=62.3  ALFA=  -1.7  CL= .30  CD= .03
TORQUE=  .22
RADIAL STATION= .55   BETA=25.6   THETA=66.7  ALFA=  -2.4  CL= .30  CD= .03
TORQUE=  .30
RADIAL STATION= .65   BETA=21.9   THETA=70.0  ALFA=  -1.9  CL= .30  CD= .03
TORQUE=  .37
RADIAL STATION= .75   BETA=18.1   THETA=72.5  ALFA=   -.6  CL= .30  CD= .03
TORQUE=  .45
RADIAL STATION= .85   BETA=14.4   THETA=74.4  ALFA=   1.2  CL= .30  CD= .03
TORQUE=  .52
RADIAL STATION= .95   BETA=10.6   THETA=76.0  ALFA=   3.3  CL=0.00  CD= .04
TORQUE= -.52
COEFF TORQUE AT RS= 1.72  COEFF TQ CORRECTED=   .07   LAMBDA=3.25  F/L= .05
 COEFFICIENT OF PERFORMANCE =    .21
RADIAL STATION= .25   BETA=36.9   THETA=48.7  ALFA=   4.4  CL= .68  CD= .04
TORQUE=  .24
RADIAL STATION= .35   BETA=33.1   THETA=57.9  ALFA=  -1.0  CL= .30  CD= .03
TORQUE=  .16
RADIAL STATION= .45   BETA=29.4   THETA=64.0  ALFA=  -3.4  CL=-.20  CD= .08
TORQUE= -.35
RADIAL STATION= .55   BETA=25.6   THETA=68.2  ALFA=  -3.9  CL=-.20  CD= .09
TORQUE= -.55
RADIAL STATION= .65   BETA=21.9   THETA=71.3  ALFA=  -3.2  CL=-.20  CD= .08
TORQUE= -.80
RADIAL STATION= .75   BETA=18.1   THETA=73.7  ALFA=  -1.8  CL= .30  CD= .03
TORQUE=  .46
RADIAL STATION= .85   BETA=14.4   THETA=75.5  ALFA=    .1  CL= .30  CD= .03
TORQUE=  .53
RADIAL STATION= .95   BETA=10.6   THETA=77.0  ALFA=   2.4  CL=0.00  CD=..03
TORQUE= -.45
COEFF TORQUE AT RS= -.76  COEFF TQ CORRECTED=  -.03   LAMBDA=3.50  F/L= .05
 COEFFICIENT OF PERFORMANCE =   -.10
RADIAL STATION= .25   BETA=36.9   THETA=50.6  ALFA=   2.5  CL= .30  CD= .03
TORQUE=  .10
RADIAL STATION= .35   BETA=33.1   THETA=59.6  ALFA=  -2.8  CL=-.20  CD= .08
TORQUE= -.23
RADIAL STATION= .45   BETA=29.4   THETA=65.5  ALFA=  -4.9  CL=-.20  CD= .08
TORQUE= -.39
RADIAL STATION= .55   BETA=25.6   THETA=69.5  ALFA=  -5.2  CL=-.20  CD= .08
TORQUE= -.60
 DIAL STATION= .65   BETA=21.9   THETA=72.5  ALFA=  -4.4  CL=-.20  CD= .08
TORQUE= -.88
RADIAL STATION= .75   BETA=18.1   THETA=74.7  ALFA=  -2.9  CL=-.20  CD= .08
TORQUE=-1.23
RADIAL STATION= .85   BETA=14.4   THETA=76.4  ALFA=   -.8  CL= .30  CD= .03
TORQUE=  .54
RADIAL STATION= .95   BETA=10.6   THETA=77.8  ALFA=   1.5  CL=0.00  CD= .03
TORQUE= -.52
COEFF ----
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RADIAL STATION= .25    BETA=36.9    THETA=52.4   ALFA=    .7   CL= .30   CD= .03
TORQUE=  .11
RADIAL STATION= .35    BETA=33.1    THETA=61.2   ALFA=  -4.4   CL=-.20   CD= .08
TORQUE= -.24
RADIAL STATION= .45    BETA=29.4    THETA=66.9   ALFA=  -6.3   CL=-.20   CD= .08
TORQUE= -.42
RADIAL STATION= .55    BETA=25.6    THETA=70.7   ALFA=  -6.4   CL=-.20   CD= .08
TORQUE= -.66
RADIAL STATION= .65    BETA=21.9    THETA=73.5   ALFA=  -5.4   CL=-.20   CD= .08
TORQUE= -.97
RADIAL STATION= .75    BETA=18.1    THETA=75.6   ALFA=  -3.8   CL=-.20   CD= .08
TORQUE=-1.35
RADIAL STATION= .85    BETA=14.4    THETA=77.3   ALFA=  -1.7   CL= .30   CD= .03
TORQUE=  .55
RADIAL STATION= .95    BETA=10.6    THETA=78.6   ALFA=    .8   CL=0.00   CD= .03
TORQUE= -.59
COEFF TORQUE AT RS=-3.58  COEFF TQ CORRECTED=  -.14   LAMBDA=4.00  F/L= .05
 COEFFICIENT OF PERFORMANCE =   -.55
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      PROGRAM RRR
      THIS PROGRAM CALCULATES COEFF OF TORQUE AND PERF      -------> LESO II
      //////////////  ENTERING  1.4 SWIRL FACTOR /////////////
      !!!!!!!!!!!!!!   THIS IS WITH RECTANGULAR BLADES 1.25 M X .250M
      BASED ON CL AND CD OF BLADE SECTIONS
      DATA ENTRY IF FOR F/L  0.05 AND 0.10 ONLY
      CURVED PLATES ONLY
      MUST ENTER LAMBDA AND RADIUS, MODIFY BLADE CORRECTION
      AND BETA ANGLE OF BLADES TO RUN OTHER CONFIGURATIONS
      ANGLES USED ARE:
      BETAB   ANGLE OF BLADE TO ROTOR PLANE, DEGREES
      BETA   BETAB IN RADIANS
      THETAB  ANGLE OF INCIDENT WIND IN DEGREES
      THETA  THETAB IN RADIANS
      ALFAB   ANGLE OF ATTACK IN DEGREES
      ALFA   ALFAB IN RADIANS
      ALFA = BETA - THETA
      KK IS RADIAL STATION COUNTER, WATCH INNER LIMIT
      WHEN LAMBDA IS ZERO, CD  GOES TO ZERO FOR STARTING TORQUE

      NO CORRECTION IS MADE FOR VELOCITY REDUCTION ACROSS BLADES
      (1-A)
      PROGRAMME SHOULD BE USED FOR COMPARATIVE PURPOSES ONLY
      ********************
      THIS PROGRAMME HAS  CL= 50% @ RS .95 TO  MODEL TIP LOSSES
      ********************B
      SEE ALSO PROGRAM ROTOR.FOR FOR 12PU500 DATA

      !!!!!!!!!!!!!!!!!
      THIS PROGRAM HAS TIP ANGLE AT 30 DEGREES
      !!!!!!!!!!!!!!!!!!!!!
      SEE ALSO PROGRAM ROLL.FOR
      REAL PI,RR,THETAB,ALFAB,ALFA,THETA,BETA,BETAB
      AREA=.2*.2
      BLADES=18
      FBYL =.05
      RR=2.0
      DO 25 I=1,12
      ALAMB=(I*.25)-.25
      CT=0.0
      PI=3.1415
      DO 30  KK=45,95,10
      RS=KK/100.0
      BC =(((RS-.375)*2.0*.120)+.200)/.200
      BC=1.25
      THIS FORCES BC TO 1.25
      THETA=ATAN(RS*ALAMB*1.4)
       SWIRL FACTOR ENTERED    .... 1.4 ////
      THETAB=THETA*180./PI
      BETA=(45.0-((RS-.375)*RR*12))*PI/180
      BETA IS BLADE ANGLE INITIALIZATION, CHANGE FOR NEW CONFIGUR'N
      BETAB=BETA*180/PI
      ALFAB=90-BETAB-THETAB
      ALFA=ALFAB*PI/180.
      FORMAT('    ALFA,BETA,THETA',3F6.2,' RS & LAMBDA',2F6.3)
      IF(ALFAB.GT.90)GOTO99
      IF(FBYL.EQ.0.10)GOTO71
      IF(FBYL.EQ..05)GOTO 41
      WRITE(2,31)
      FORMAT('    /// CL,CD NOT TABULATED  PROG ABORTED !!!')
      GOTO 101
      F BY L EQUAL 5%
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        GOTO9
RADIAL STATION= .45   BETA=43.2   THETA= 0.0  ALFA=  46.8  CL= .75  CD= .80
TORQUE=  .42
RADIAL STATION= .55   BETA=40.8   THETA= 0.0  ALFA=  49.2  CL= .75  CD= .80
TORQUE=  .52
RADIAL STATION= .65   BETA=38.4   THETA= 0.0  ALFA=  51.6  CL= .75  CD= .80
TORQUE=  .61
RADIAL STATION= .75   BETA=36.0   THETA= 0.0  ALFA=  54.0  CL= .75  CD= .80
TORQUE=  .70
RADIAL STATION= .85   BETA=33.6   THETA= 0.0  ALFA=  56.4  CL= .62  CD= .95
TORQUE=  .66
RADIAL STATION= .95   BETA=31.2   THETA= 0.0  ALFA=  58.8  CL= .31  CD= .95
TORQUE=  .37
COEFF TORQUE AT RS= 3.28  COEFF TQ CORRECTED=   .19   LAMBDA=0.00  F/L= .05
 COEFFICIENT OF PERF  =   0.00
RADIAL STATION= .45   BETA=43.2   THETA= 9.0  ALFA=  37.8  CL= .88  CD= .65
TORQUE=  .44
RADIAL STATION= .55   BETA=40.8   THETA=10.9  ALFA=  38.3  CL= .88  CD= .65
TORQUE=  .53
RADIAL STATION= .65   BETA=38.4   THETA=12.8  ALFA=  38.8  CL= .88  CD= .65
TORQUE=  .61
RADIAL STATION= .75   BETA=36.0   THETA=14.7  ALFA=  39.3  CL= .88  CD= .65
TORQUE=  .69
RADIAL STATION= .85   BETA=33.6   THETA=16.6  ALFA=  39.8  CL= .88  CD= .65
TORQUE=  .76
RADIAL STATION= .95   BETA=31.2   THETA=18.4  ALFA=  40.4  CL= .44  CD= .65
TORQUE=  .28
COEFF TORQUE AT RS= 3.31  COEFF TQ CORRECTED=   .19   LAMBDA= .25  F/L= .05
 COEFFICIENT OF PERF  =    .05
RADIAL STATION= .45   BETA=43.2   THETA=17.5  ALFA=  29.3  CL=1.00  CD= .50
TORQUE=  .50
RADIAL STATION= .55   BETA=40.8   THETA=21.1  ALFA=  28.1  CL=1.00  CD= .50
TORQUE=  .59
RADIAL STATION= .65   BETA=38.4   THETA=24.5  ALFA=  27.1  CL=1.00  CD= .50
TORQUE=  .69
RADIAL STATION= .75   BETA=36.0   THETA=27.7  ALFA=  26.3  CL=1.00  CD= .50
TORQUE=  .78
RADIAL STATION= .85   BETA=33.6   THETA=30.8  ALFA=  25.6  CL=1.00  CD= .50
TORQUE=  .87
RADIAL STATION= .95   BETA=31.2   THETA=33.6  ALFA=  25.2  CL= .56  CD= .35
TORQUE=  .47
COEFF TORQUE AT RS= 3.90  COEFF TQ CORRECTED=   .22   LAMBDA= .50  F/L= .05
 COEFFICIENT OF PERF  =    .11
RADIAL STATION= .45   BETA=43.2   THETA=25.3  ALFA=  21.5  CL=1.12  CD= .35
TORQUE=  .59
RADIAL STATION= .55   BETA=40.8   THETA=30.0  ALFA=  19.2  CL=1.12  CD= .35
TORQUE=  .73
RADIAL STATION= .65   BETA=38.4   THETA=34.3  ALFA=  17.3  CL=1.13  CD= .25
TORQUE=  .94
RADIAL STATION= .75   BETA=36.0   THETA=38.2  ALFA=  15.8  CL=1.13  CD= .25
TORQUE= 1.11
RADIAL STATION= .85   BETA=33.6   THETA=41.8  ALFA=  14.6  CL=1.13  CD= .25
TORQUE= 1.29
RADIAL STATION= .95   BETA=31.2   THETA=44.9  ALFA=  13.9  CL= .56  CD= .25
TORQUE=  .53
COEFF TORQUE AT RS= 5.20  COEFF TQ CORRECTED=   .30   LAMBDA= .75  F/L= .05
 COEFFICIENT OF PERF  =    .22
RADIAL STATION= .45   BETA=43.2   THETA=[illegible]
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TORQUE=   .90                BETA=40.8    THETA=37.6   ALFA=  11.6  CL=1.15  CD= .15
RADIAL STATION= .65   BETA=38.4    THETA=42.3   ALFA=   9.3  CL=1.00  CD= .10
TORQUE= 1.00
RADIAL STATION= .75   BETA=36.0    THETA=46.4   ALFA=   7.6  CL=1.00  CD= .10
TORQUE= 1.22
RADIAL STATION= .85   BETA=33.6    THETA=50.0   ALFA=   6.4  CL= .68  CD= .04
TORQUE= 1.04
RADIAL STATION= .95   BETA=31.2    THETA=53.1   ALFA=   5.7  CL= .34  CD= .04
TORQUE=   .57
COEFF TORQUE AT RS= 5.37  COEFF TQ CORRECTED=   .31   LAMBDA=1.00  F/L= .05
 COEFFICIENT OF PERF  =    .31
RADIAL STATION= .45   BETA=43.2    THETA=38.2   ALFA=   8.6  CL=1.00  CD= .10
TORQUE=   .66
RADIAL STATION= .55   BETA=40.8    THETA=43.9   ALFA=   5.3  CL= .68  CD= .04
TORQUE=   .61
RADIAL STATION= .65   BETA=38.4    THETA=48.7   ALFA=   2.9  CL= .68  CD= .04
TORQUE=   .78
RADIAL STATION= .75   BETA=36.0    THETA=52.7   ALFA=   1.3  CL= .30  CD= .03
TORQUE=   .40
RADIAL STATION= .85   BETA=33.6    THETA=56.1   ALFA=    .3  CL= .30  CD= .03
TORQUE=   .49
RADIAL STATION= .95   BETA=31.2    THETA=59.0   ALFA=   -.2  CL= .15  CD= .03
TORQUE=   .23
COEFF TORQUE AT RS= 3.17  COEFF TQ CORRECTED=   .18   LAMBDA=1.25  F/L= .05
 COEFFICIENT OF PERF  =    .23
RADIAL STATION= .45   BETA=43.2    THETA=43.4   ALFA=   3.4  CL= .68  CD= .04
TORQUE=   .50
RADIAL STATION= .55   BETA=40.8    THETA=49.1   ALFA=    .1  CL= .30  CD= .03
TORQUE=   .28
RADIAL STATION= .65   BETA=38.4    THETA=53.8   ALFA=  -2.2  CL= .30  CD= .03
TORQUE=   .36
RADIAL STATION= .75   BETA=36.0    THETA=57.6   ALFA=  -3.6  CL=-.20  CD= .08
TORQUE= -.57
RADIAL STATION= .85   BETA=33.6    THETA=60.7   ALFA=  -4.3  CL=-.20  CD= .08
TORQUE= -.75
RADIAL STATION= .95   BETA=31.2    THETA=63.4   ALFA=  -4.6  CL=-.10  CD= .08
TORQUE= -.69
COEFF TORQUE AT RS= -.87  COEFF TQ CORRECTED=  -.05   LAMBDA=1.50  F/L= .05
 COEFFICIENT OF PERF  =   -.07
RADIAL STATION= .45   BETA=43.2    THETA=47.8   ALFA=  -1.0  CL= .30  CD= .03
TORQUE=   .22
RADIAL STATION= .55   BETA=40.8    THETA=53.4   ALFA=  -4.2  CL=-.20  CD= .08
TORQUE= -.36
RADIAL STATION= .65   BETA=38.4    THETA=57.9   ALFA=  -6.3  CL=-.20  CD= .08
TORQUE= -.50
RADIAL STATION= .75   BETA=36.0    THETA=61.4   ALFA=  -7.4  CL=-.20  CD= .08
TORQUE= -.68
RADIAL STATION= .85   BETA=33.6    THETA=64.4   ALFA=  -8.0  CL=-.40  CD= .10
TORQUE=-1.49
RADIAL STATION= .95   BETA=31.2    THETA=66.8   ALFA=  -8.0  CL=-.20  CD= .10
TORQUE=-1.30
COEFF TORQUE AT RS=-4.11  COEFF TQ CORRECTED=  -.24   LAMBDA=1.75  F/L= .05
 COEFFICIENT OF PERF  =   -.41
RADIAL STATION= .45   BETA=43.2    THETA=51.6   ALFA=  -4.8  CL=-.20  CD= .08
TORQUE= -.27
 DIAL STATION= .55   BETA=40.8    THETA=57.0   ALFA=  -7.8  CL=-.40  CD= .10
.JRQUE= -.70
RADIAL STATION= .65   BETA=38.4    THETA=61.2   ALFA=  -9.6  CL=-.40  CD= .10
TORQUE= -.98
RADIAL STATION= .75   BETA=36.0    THETA=64.5   ALFA= -10.5  CL=-.40  CD= .10
TORQUE=-1.33
RADIAL STATION= .85   BETA=33.6    THETA=67.2   ALFA= -10.8  CL=-.40  CD= .10
TORQUE=-1.75
RADIAL STATION= .95   BETA=31.2
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 COEFFICIENT OF PERF  =   -.76
RADIAL STATION= .45   BETA=43.2   THETA=54.8  ALFA=  -8.0  CL=-.40  CD= .10
TORQUE= -.53
RADIAL STATION= .55   BETA=40.8   THETA=60.0  ALFA= -10.8  CL=-.40  CD= .10
TORQUE= -.79
RADIAL STATION= .65   BETA=38.4   THETA=64.0  ALFA= -12.4  CL=-.40  CD= .10
TORQUE=-1.12
RADIAL STATION= .75   BETA=36.0   THETA=67.1  ALFA= -13.1  CL=-.40  CD= .10
TORQUE=-1.53
RADIAL STATION= .85   BETA=33.6   THETA=69.5  ALFA= -13.1  CL=-.40  CD= .10
TORQUE=-2.03
RADIAL STATION= .95   BETA=31.2   THETA=71.5  ALFA= -12.7  CL=-.20  CD= .10
TORQUE=-1.87
COEFF TORQUE AT RS=-7.87  COEFF TQ CORRECTED=  -.45   LAMBDA=2.25  F/L= .05
 COEFFICIENT OF PERF  =  -1.01
RADIAL STATION= .45   BETA=43.2   THETA=57.6  ALFA= -10.8  CL=-.40  CD= .10
TORQUE= -.59
RADIAL STATION= .55   BETA=40.8   THETA=62.6  ALFA= -13.4  CL=-.40  CD= .10
TORQUE= -.88
RADIAL STATION= .65   BETA=38.4   THETA=66.3  ALFA= -14.7  CL=-.40  CD= .10
TORQUE=-1.27
RADIAL STATION= .75   BETA=36.0   THETA=69.1  ALFA= -15.1  CL=-.60  CD= .30
TORQUE=-3.65
RADIAL STATION= .85   BETA=33.6   THETA=71.4  ALFA= -15.0  CL=-.60  CD= .30
TORQUE=-4.98
RADIAL STATION= .95   BETA=31.2   THETA=73.3  ALFA= -14.5  CL=-.20  CD= .10
TORQUE=-2.20
COEFF TORQUE AT RS=13*56  COEFF TQ CORRECTED=  -.78   LAMBDA=2.50  F/L= .05
 COEFFICIENT OF PERF  =  -1.94
RADIAL STATION= .45   BETA=43.2   THETA=60.0  ALFA= -13.2  CL=-.40  CD= .10
 ORQUE= -.65
RADIAL STATION= .55   BETA=40.8   THETA=64.7  ALFA= -15.5  CL=-.60  CD= .30
TORQUE=-1.99
RADIAL STATION= .65   BETA=38.4   THETA=68.2  ALFA= -16.6  CL=-.60  CD= .30
TORQUE=-2.96
RADIAL STATION= .75   BETA=36.0   THETA=70.9  ALFA= -16.9  CL=-.60  CD= .30
TORQUE=-4.20
RADIAL STATION= .85   BETA=33.6   THETA=73.0  ALFA= -16.6  CL=-.60  CD= .30
TORQUE=-5.75
RADIAL STATION= .95   BETA=31.2   THETA=74.7  ALFA= -15.9  CL=-.30  CD= .30
TORQUE=-6.29
COEFF TORQUE AT RS=21*83  COEFF TQ CORRECTED= -1.25   LAMBDA=2.75  F/L= .05
 COEFFICIENT OF PERF  =  -3.44
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      PROGRAM RRR
C     THIS PROGRAM CALCULATES COEFF OF TORQUE AND PERF
C     ///////////////  ENTERING  1.4 SWIRL FACTOR ////////////  -------> LESO II
      BASED ON CL AND CD OF BLADE SECTIONS
C     DATA ENTRY IF FOR F/L  0.05 AND 0.10 ONLY
C     CURVED PLATES ONLY
C     MUST ENTER LAMBDA AND RADIUS, MODIFY BLADE CORRECTION
C     AND BETA ANGLE OF BLADES TO RUN OTHER CONFIGURATIONS
C     ANGLES USED ARE:
C     BETAB    ANGLE OF BLADE TO ROTOR PLANE, DEGREES
C     BETA    BETAB IN RADIANS
C     THETAB   ANGLE OF INCIDENT WIND IN DEGREES
C     THETA   THETAB IN RADIANS
C     ALFAB    ANGLE OF ATTACK IN DEGREES
C     ALFA    ALFAB IN RADIANS
C     ALFA = BETA - THETA
C     KK IS RADIAL STATION COUNTER, WATCH INNER LIMIT
C     WHEN LAMBDA IS ZERO, CD  GOES TO ZERO FOR STARTING TORQUE
C
C     NO CORRECTION IS MADE FOR VELOCITY REDUCTION ACROSS BLADES
C     (1-A)
C     PROGRAMME SHOULD BE USED FOR COMPARATIVE PURPOSES ONLY
C     ********************
C     THIS PROGRAMME HAS  CL= 50% @ RS .95 TO  MODEL TIP LOSSES
C     ******************B
C     SEE ALSO PROGRAM ROTOR.FOR FOR 12PU500 DATA
C
C     !!!!!!!!!!!!!!!!!!
C     THIS PROGRAM HAS TIP ANGLE AT 30 DEGREES
C     !!!!!!!!!!!!!!!!!!!!!
C     SEE ALSO PROGRAM ROLL.FOR
      REAL PI,RR,THETAB,ALFAB,ALFA,THETA,BETA,BETAB
      AREA=.2*.2
      BLADES=18
      FBYL =.05
      RR=2.0
6     DO 25 I=1,12
      ALAMB=(I*.25)-.25
      CT=0.0
      PI=3.1415
2     DO 30  KK=45,95,10
      RS=KK/100.0
      BC =(((RS-.375)*2.0*.120)+.200)/.200
      THETA=ATAN(RS*ALAMB*1.4)
C     SWIRL FACTOR ENTERED    .... 1.4 ////
      THETAB=THETA*180./PI
      BETA=(45.0-((RS-.375)*RR*12))*PI/180
C     BETA IS BLADE ANGLE INITIATIZATION, CHANGE FOR NEW CONFIGUR'N
      BETAB=BETA*180/PI
      ALFAB=90-BETAB-THETAB
      ALFA=ALFAB*PI/180.
111   FORMAT('    ALFA,BETA,THETA',3F6.2,' RS & LAMBDA',2F6.3)
      IF(ALFAB.GT.90)GOTO99
      IF(FBYL.EQ.0.10)GOTO71
      IF(FBYL.EQ..05)GOTO 41
      WRITE(2,31)
31    FORMAT('    /// CL.CD NOT TABULATED  PROG ABORTED !!!')
      GOTO 101
C     F BY L EQUAL 5%
41    IF(ALFAB.LT.85)GOTO42
      CL=0.0
      CD=1.2
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      CD=1.13
      GOTO91
43    IF(ALFAB.LT.65)GOTO44
      CL=.48
      CD=1.14
      GOTO91
44    IF(ALFAB.LT.55)GOTO45
      CL=.62
      CD=.95
      GOTO91
45    IF(ALFAB.LT.45)GOTO46
      CL=.75
      CD=.80
      GOTO91
46    IF(ALFAB.LT.35)GOTO47
      CL=.88
      CD=.65
      GOTO91
47    IF(ALFAB.LT.25.5)GOTO48
      CL=1.0
      CD=.50
      GOTO91
48    IF(ALFAB.LT.17.6)GOTO49
      CL=1.12
      CD=.35
      GOTO91
49    IF(ALFAB.LT.12.4)GOTO50
      CL=1.13
      CD=.25
      GOTO91
J     IF(ALFAB.LT.10.8)GOTO51
      CL=1.15
      CD=.15
      GOTO91
51    IF(ALFAB.LT.7.3)GOTO52
      CL=1.0
      CD=.10
      GOTO91
52    IF(ALFAB.LT.2.5)GOTO53
      CL=.68
      CD=.04
      GOTO91
53    IF(ALFAB.LT.-2.5)GOTO54
      CL=.30
      CD=.03
      GOTO91
54    IF(ALFAB.LT.-7.5)GOTO55
      CL=-.20
      CD=.08
      GOTO91
55    IF(ALFAB.LT.-15)GOTO56
      CL=-.4
      CD=.10
      GOTO91
56    IF(ALFAB.LT.-19.8)GOTO100
      CL=-.6
      CD=.3
      GOTO91
C     F BY L EQUAL TO 10%
71    IF(ALFAB.LT.85)GOTO72
      CL=0.0
      CD=1.22
      GOTO91
72    IF(ALFAB.LT.75)GOTO73
```

```
      CD=1.2
      GOTO91
73    IF(ALFAB.LT.65)GOTO74
      CL=.5
      CD=1.1
      GOTO91
74    IF(ALFAB.LT.55)GOTO75
      CL=.68
      CD=1.0
      GOTO91
75    IF(ALFAB.LT.45)GOTO76
      CL=.80
      CD=.85
      GOTO91
76    IF(ALFAB.LT.37)GOTO77
      CL=.96
      CD=.70
      GOTO91
77    IF(ALFAB.LT.32)GOTO78
      CL=1.05
      CD=.65
      GOTO91
78    IF(ALFAB.LT.27)GOTO79
      CL=1.18
      CD=.58
      GOTO91
79    IF(ALFAB.LT.22)GOTO80
      CL=1.2
      CD=.48
      GOTO91
      IF(ALFAB.LT.18)GOTO81
      CL=1.2
      CD=.35
      GOTO91
81    IF(ALFAB.LT.15.5)GOTO82
      CL=1.45
      CD=.30
      GOTO91
82    IF(ALFAB.LT.13.5)GOTO83
      CL=1.50
      CD=.25
      GOTO91
83    IF(ALFAB.LT.11)GOTO84
      CL=1.454
      CD=.2
      GOTO91
84    IF(ALFAB.LT.7)GOTO85
      CL=1.3
      CD=.15
      GOTO91
85    IF(ALFAB.LT.2.2)GOTO86
      CL=1.05
      CD=.15
      GOTO91
86    IF(ALFAB.LT.-2.5)GOTO87
      CL=.6
      CD=.08
      GOTO91
87    IF(ALFAB.LT.-7.5)GOTO88
      CL=.10
      CD=.07
      GOTO91
88    IF(ALFAB.LT.-15)GOTO89
      CL=-.12
```

```
      CL=-.35
      CD=.35
      GOTO 91
91    CONTINUE
      IF (RS.EQ..95)CL=CL*.5
      T=(CL*COS(THETA)-CD*SIN(THETA))*RS*BC
     *  *1.0/(COS(THETA))*1.0/(COS(THETA))
      CT=CT+T
      WRITE(2,33)RS,BETAB,THETAB,ALFAB,CL,CD,T
33    FORMAT('  RADIAL STATION=',F4.2,'   BETA=',F4.1,'   THETA='
     *  ,F4.1,'  ALFA=',F6.1,'  CL=',F4.2,'  CD=',F4.2,'    TORQUE=',
     *  F5.2)
30    CONTINUE
      CTA=CT*BLADES*AREA/(RR*RR*PI)
      WRITE(2,35)CT,CTA,ALAMB,FBYL
35    FORMAT('  COEFF TORQUE AT RS=',F5.2,'  COEFF TQ CORRECTED=',
     *  F6.2,'   LAMBDA=',F4.2,'  F/L=',F4.2)
      CP=CTA*ALAMB
      WRITE(2,103)CP
103   FORMAT('   COEFFICIENT OF PERF  = ',F6.2)
25    CONTINUE
      GOTO101
99    WRITE(2,37)
37    FORMAT('     **** ALFA .GT.  90 !!!!!!')
      GOTO101
100   WRITE(2,39)ALFAB
39    FORMAT('  **** ALFA LESS THAN -19.6, NO VALUES GIVEN
     *    PROGRAMME ABORTED !!!!!',F8.3)
101   STOP
      END
```

```
RADIAL STATION= .45   BETA=43.2   THETA= 0.0  ALFA=  46.8  CL= .75  CD= .80
TORQUE=  .37
RADIAL STATION= .55   BETA=40.8   THETA= 0.0  ALFA=  49.2  CL= .75  CD= .80
TORQUE=  .50
RADIAL STATION= .65   BETA=38.4   THETA= 0.0  ALFA=  51.6  CL= .75  CD= .80
TORQUE=  .65
RADIAL STATION= .75   BETA=36.0   THETA= 0.0  ALFA=  54.0  CL= .75  CD= .80
TORQUE=  .82
RADIAL STATION= .85   BETA=33.6   THETA= 0.0  ALFA=  56.4  CL= .62  CD= .95
TORQUE=  .83
RADIAL STATION= .95   BETA=31.2   THETA= 0.0  ALFA=  58.8  CL= .31  CD= .95
TORQUE=  .50
COEFF TORQUE AT RS= 3.66  COEFF TQ CORRECTED=   .21   LAMBDA=0.00  F/L= .05
 COEFFICIENT OF PERF  =   0.00
 DIAL STATION= .45   BETA=43.2   THETA= 9.0  ALFA=  37.8  CL= .88  CD= .65
TORQUE=  .39
RADIAL STATION= .55   BETA=40.8   THETA=10.9  ALFA=  38.3  CL= .88  CD= .65
TORQUE=  .51
RADIAL STATION= .65   BETA=38.4   THETA=12.8  ALFA=  38.8  CL= .88  CD= .65
TORQUE=  .65
RADIAL STATION= .75   BETA=36.0   THETA=14.7  ALFA=  39.3  CL= .88  CD= .65
TORQUE=  .80
RADIAL STATION=  85   BETA=
```

```
RADIAL STATION= .75    BETA=31.2    THETA=18.4    ALFA=  40.4   CL= .44   CD= .65
 TORQUE=  .38
 COEFF TORQUE AT RS= 3.66   COEFF TQ CORRECTED=    .21    LAMBDA= .25   F/L= .05
  COEFFICIENT OF PERF  =     .05
 RADIAL STATION= .45    BETA=43.2    THETA=17.5    ALFA=  29.3   CL=1.00   CD= .50
 TORQUE=  .43
 RADIAL STATION= .55    BETA=40.8    THETA=21.1    ALFA=  28.1   CL=1.00   CD= .50
 TORQUE=  .58
 RADIAL STATION= .65    BETA=38.4    THETA=24.5    ALFA=  27.1   CL=1.00   CD= .50
 TORQUE=  .73
 RADIAL STATION= .75    BETA=36.0    THETA=27.7    ALFA=  26.3   CL=1.00   CD= .50
 TORQUE=  .91
 RADIAL STATION= .85    BETA=33.6    THETA=30.8    ALFA=  25.6   CL=1.00   CD= .50
 TORQUE= 1.09
 RADIAL STATION= .95    BETA=31.2    THETA=33.6    ALFA=  25.2   CL= .56   CD= .35
 TORQUE=  .63
 COEFF TORQUE AT RS= 4.37   COEFF TQ CORRECTED=    .25    LAMBDA= .50   F/L= .05
  COEFFICIENT OF PERF  =     .13
 RADIAL STATION= .45    BETA=43.2    THETA=25.3    ALFA=  21.5   CL=1.12   CD= .35
 TORQUE=  .52
 RADIAL STATION= .55    BETA=40.8    THETA=30.0    ALFA=  19.2   CL=1.12   CD= .35
 TORQUE=  .71
 RADIAL STATION= .65    BETA=38.4    THETA=34.3    ALFA=  17.3   CL=1.13   CD= .25
 TORQUE= 1.00
 RADIAL STATION= .75    BETA=36.0    THETA=38.2    ALFA=  15.8   CL=1.13   CD= .25
 TORQUE= 1.29
 RADIAL STATION= .85    BETA=33.6    THETA=41.8    ALFA=  14.6   CL=1.13   CD= .25
 TORQUE= 1.62
 RADIAL STATION= .95    BETA=31.2    THETA=44.9    ALFA=  13.9   CL= .56   CD= .25
 TORQUE=  .72
 COEFF TORQUE AT RS= 5.86   COEFF TQ CORRECTED=    .34    LAMBDA= .75   F/L= .05
  COEFFICIENT OF PERF  =     .25
 RADIAL STATION= .45    BETA=43.2    THETA=32.2    ALFA=  14.6   CL=1.13   CD= .25
 TORQUE=  .56
 RADIAL STATION= .55    BETA=40.8    THETA=37.6    ALFA=  11.6   CL=1.15   CD= .15
 TORQUE=  .87
 RADIAL STATION= .65    BETA=38.4    THETA=42.3    ALFA=   9.3   CL=1.00   CD= .10
 TORQUE= 1.06
 RADIAL STATION= .75    BETA=36.0    THETA=46.4    ALFA=   7.6   CL=1.00   CD= .10
 TORQUE= 1.41
 RADIAL STATION= .85    BETA=33.6    THETA=50.0    ALFA=   6.4   CL= .68   CD= .04
 TORQUE= 1.31
 RADIAL STATION= .95    BETA=31.2    THETA=53.1    ALFA=   5.7   CL= .34   CD= .04
 TORQUE=  .77
 COEFF TORQUE AT RS= 5.98   COEFF TQ CORRECTED=    .34    LAMBDA=1.00   F/L= .05
  COEFFICIENT OF PERF  =     .34
 RADIAL STATION= .45    BETA=43.2    THETA=38.2    ALFA=   8.6   CL=1.00   CD= .10
 TORQUE=  .58
 RADIAL STATION= .55    BETA=40.8    THETA=43.9    ALFA=   5.3   CL= .68   CD= .04
 TORQUE=  .59
 RADIAL STATION= .65    BETA=38.4    THETA=48.7    ALFA=   2.9   CL= .68   CD= .04
 TORQUE=  .83
 RADIAL STATION= .75    BETA=36.0    THETA=52.7    ALFA=   1.3   CL= .30   CD= .03
 TORQUE=  .47
 RADIAL STATION= .85    BETA=33.6    THETA=56.1    ALFA=    .3   CL= .30   CD= .03
 TORQUE=  .61
  DIAL STATION= .95    BETA=31.2    THETA=59.0    ALFA=   -.2   CL= .15   CD= .03
 TORQUE=  .31
 COEFF TORQUE AT RS= 3.39   COEFF TQ CORRECTED=    .19    LAMBDA=1.25   F/L= .05
  COEFFICIENT OF PERF  =     .24
 RADIAL STATION= .45    BETA=43.2    THETA=43.4    ALFA=   3.4   CL= .68   CD= .04
 TORQUE=  .43
 RADIAL STATION= .55    BETA=40.8    THETA=49.1    ALFA=    .1   CL= .30   CD= .03
 TORQUE=  .27
 RADIAL STATION= .65
```

```
TORQUE= -.66                                                                  ALFA=  -3.6  CL=-.20  CD= .08
RADIAL STATION= .85   BETA=33.6   THETA=60.7   ALFA=  -4.3  CL=-.20  CD= .08
TORQUE= -.94
RADIAL STATION= .95   BETA=31.2   THETA=63.4   ALFA=  -4.6  CL=-.10  CD= .08
TORQUE= -.93
COEFF TORQUE AT RS=-1.45  COEFF TQ CORRECTED=  -.08   LAMBDA=1.50  F/L= .05
 COEFFICIENT OF PERF  =   -.12
RADIAL STATION= .45   BETA=43.2   THETA=47.8   ALFA=  -1.0  CL= .30  CD= .03
TORQUE=  .19
RADIAL STATION= .55   BETA=40.8   THETA=53.4   ALFA=  -4.2  CL=-.20  CD= .08
TORQUE= -.34
RADIAL STATION= .65   BETA=38.4   THETA=57.9   ALFA=  -6.3  CL=-.20  CD= .08
TORQUE= -.53
RADIAL STATION= .75   BETA=36.0   THETA=61.4   ALFA=  -7.4  CL=-.20  CD= .08
TORQUE= -.79
RADIAL STATION= .85   BETA=33.6   THETA=64.4   ALFA=  -8.0  CL=-.40  CD= .10
TORQUE=-1.88
RADIAL STATION= .95   BETA=31.2   THETA=66.8   ALFA=  -8.0  CL=-.20  CD= .10
TORQUE=-1.76
COEFF TORQUE AT RS=-5.11  COEFF TQ CORRECTED=  -.29   LAMBDA=1.75  F/L= .05
 COEFFICIENT OF PERF  =   -.51
RADIAL STATION= .45   BETA=43.2   THETA=51.6   ALFA=  -4.8  CL=-.20  CD= .08
TORQUE= -.24
RADIAL STATION= .55   BETA=40.8   THETA=57.0   ALFA=  -7.8  CL=-.40  CD= .10
TORQUE= -.68
RADIAL STATION= .65   BETA=38.4   THETA=61.2   ALFA=  -9.6  CL=-.40  CD= .10
TORQUE=-1.04
RADIAL STATION= .75   BETA=36.0   THETA=64.5   ALFA= -10.5  CL=-.40  CD= .10
TORQUE=-1.54
RADIAL STATION= .85   BETA=33.6   THETA=67.2   ALFA= -10.8  CL=-.40  CD= .10
 ORQUE=-2.20
RADIAL STATION= .95   BETA=31.2   THETA=69.4   ALFA= -10.6  CL=-.20  CD= .10
TORQUE=-2.13
COEFF TORQUE AT RS=-7.83  COEFF TQ CORRECTED=  -.45   LAMBDA=2.00  F/L= .05
 COEFFICIENT OF PERF  =   -.90
RADIAL STATION= .45   BETA=43.2   THETA=54.8   ALFA=  -8.0  CL=-.40  CD= .10
TORQUE= -.46
RADIAL STATION= .55   BETA=40.8   THETA=60.0   ALFA= -10.8  CL=-.40  CD= .10
TORQUE= -.76
RADIAL STATION= .65   BETA=38.4   THETA=64.0   ALFA= -12.4  CL=-.40  CD= .10
TORQUE=-1.19
RADIAL STATION= .75   BETA=36.0   THETA=67.1   ALFA= -13.1  CL=-.40  CD= .10
TORQUE=-1.78
RADIAL STATION= .85   BETA=33.6   THETA=69.5   ALFA= -13.1  CL=-.40  CD= .10
TORQUE=-2.55
RADIAL STATION= .95   BETA=31.2   THETA=71.5   ALFA= -12.7  CL=-.20  CD= .10
TORQUE=-2.53
COEFF TORQUE AT RS=-9.27  COEFF TQ CORRECTED=  -.53   LAMBDA=2.25  F/L= .05
 COEFFICIENT OF PERF  =  -1.19
RADIAL STATION= .45   BETA=43.2   THETA=57.6   ALFA= -10.8  CL=-.40  CD= .10
TORQUE= -.51
RADIAL STATION= .55   BETA=40.8   THETA=62.6   ALFA= -13.4  CL=-.40  CD= .10
TORQUE= -.86
RADIAL STATION= .65   BETA=38.4   THETA=66.3   ALFA= -14.7  CL=-.40  CD= .10
TORQUE=-1.35
)DIAL STATION= .75   BETA=36.0   THETA=69.1   ALFA= -15.1  CL=-.60  CD= .30
,ORQUE=-4.24
RADIAL STATION= .85   BETA=33.6   THETA=71.4   ALFA= -15.0  CL=-.60  CD= .30
TORQUE=-6.25
RADIAL STATION= .95   BETA=31.2   THETA=73.3   ALFA= -14.5  CL=-.20  CD= .10
TORQUE=-2.97
COEFF TORQUE AT RS=16*17  COEFF TQ CORRECTED=  -.93   LAMBDA=2.50  F/L= .05
 COEFFICIENT OF PERF  =  -2.32
RADIAL STATION=  45   BETA=43.2   THETA=[illegible]
```

```
TORQUE=-1.93
RADIAL STATION= .65    BETA=38.4    THETA=68.2    ALFA= -16.6    CL=-.60    CD= .30
TORQUE=-3.15
RADIAL STATION= .75    BETA=36.0    THETA=70.9    ALFA= -16.9    CL=-.60    CD= .30
TORQUE=-4.87
RADIAL STATION= .85    BETA=33.6    THETA=73.0    ALFA= -16.6    CL=-.60    CD= .30
TORQUE=-7.22
RADIAL STATION= .95    BETA=31.2    THETA=74.7    ALFA= -15.9    CL=-.30    CD= .30
TORQUE=-8.51
COEFF TORQUE AT RS=26*24  COEFF TQ CORRECTED= -1.50    LAMBDA=2.75    F/L= .05
 COEFFICIENT OF PERF  =  -4.13
```

# APPENDIX 4

## WINDMILL CONTROL AND BRAKING SYSTEMS

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## WINDMILL CONTROL AND BRAKING SYSTEMS

Controls and brakes are safety systems used on windmills for one main reason: to prevent damage from being done, either by high winds to the rotor or tower, or by moving parts to personnel working on the machine. Control systems control or limit the maximum speed of the rotor, saving it from destructive centrifugal and gyroscopic forces. These systems can also limit the tower loads to keep them below the design maximums during high winds or storms. Typical control systems allow the windmill to operate up to 15 - 20 m/s, activating gradually to protect the windmill beyond the maximum design speed.

There are many types of control systems. A very good summary by CWD. (SWD) is available. (reference no. 1)

Note that the control systems, such as the hinged tail, do not apply braking forces to the windmill. Control systems will only reduce the power absorbed by the rotor, often to levels where the rotor is stopped by the load.

BRAKES: it is often necessary to have additional braking and locking mechanisms. These brakes or locks are required when performing maintenance, putting the machine out of service or keeping it stopped during stormy weather. They can be as simple as a bolt, pin or chain fastening the wheel when it is stopped. Brakes that slow the rotor, stop it and lock it are generally drum or disc type. These can be easily incorporated into a wind system through good mechanical design. Automotive or truck components are often more than adequate and a readily available source of supply.

For windpumping systems, the hinged tail working on gravity or spring tension principle is quite adequate. The gravity system is somewhat more reliable - gravity never breaks, gets stolen or tampered with, rusts or required spare parts. The hinged tail system controls the windmill by allowing the rotor to swing out of the wind gradually as the wind force increases. It requires the rotor to be offset from the main yaws axis, or an auxillary side vane to be provided so that a moment will develop about the main axis. The tail will also bring the rotor back into the wind as the wind speed decreases back into the working range. (Some hinged tails use a latching mechanism to prevent this return when it is desired to inspect the rotor for possible damage prior to using it following high winds.)

## Description of Hinged-Tail System with Offset Rotor

The hinged tail system has two axes. The first is the main vertical axis about which the entire windmill rotates or "yaws". The other axis is the tail hinge, about which the tail swings relative to the rest of the rotor head and chassis of the windmill. For the entire windmill rotor, tail, chassis etc. to be in an equilibrium state, and not rotating about either of these axes, the sum of the moments around these individual axes must be equal to zero.

The axes and the motions relative to them are illustrated:

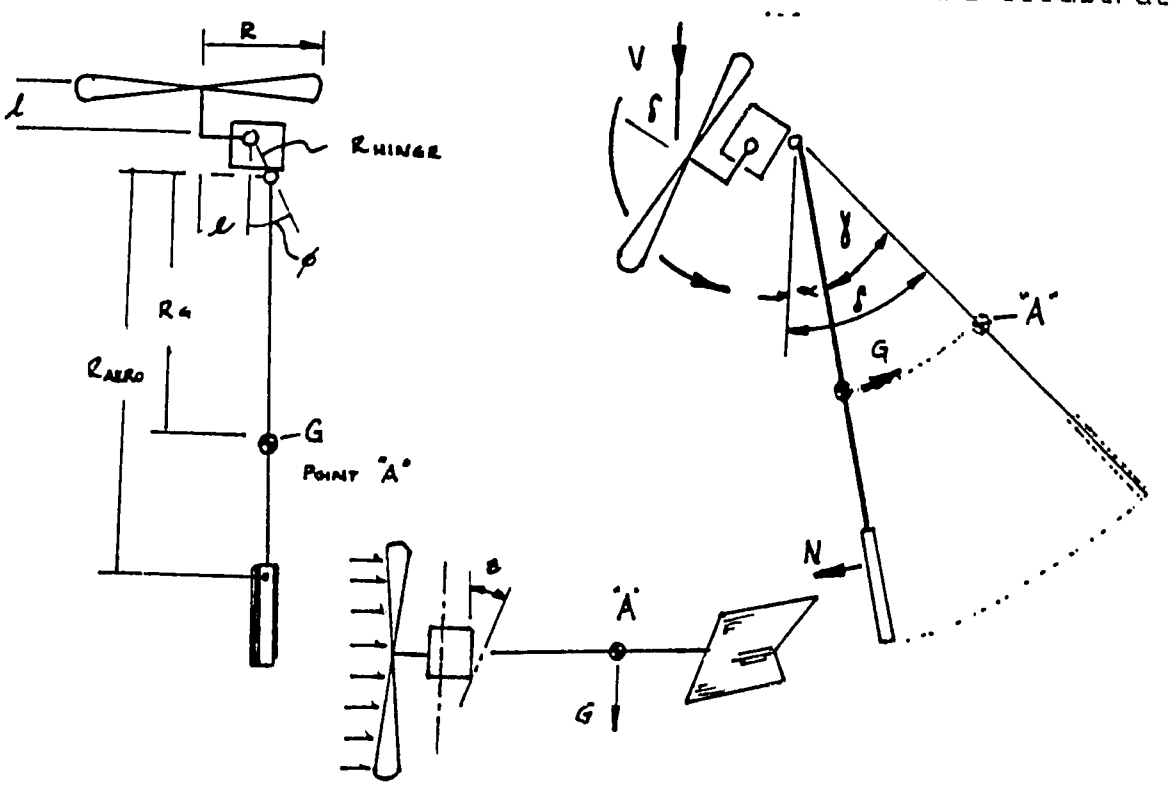


Figure 1 : Main axes and geometry of hinged tail system

To conceptualize how the hinged tail system works, there is little "trick" that must be appreciated. The hinged tail system i much like a rigid tail system. With the rigid tail system, when th wind changes direction, the tail sees a side wind, albeit one reduce from the atmospheric wind velocity as the tail is in the wake of th rotor. There is a normal force generated by the tail which moves th rotor back towards the wind. As the tail comes parallel with the win direction, the force diminishes and the rotor stabilizes facing int the wind. (note: the tail surface and its moment arm must produce large enough moment around the yaw axis to balance the forces trying to bring the rotor out of the wind. If this is not the case, th system is unstable, and will likely turn backwards.)

With an offset rotor and a rigid tail, the rotor will bring the entire windmill around until the moment generated by the offset rotor is balanced by the side aerodynamic forces on the tail as it come out into the windstream. The resulting angle is constant for all winc speeds.

The hinged tail system works similarly. When the rotor comes out of the wind - as it designed to do when the wind is too strong - the tail is brought into the wind to counteract this movement. However, rather than turn the rotor completely back into the wind, as with the non-offset rotor, the tail takes up an angle of less than 90 degrees with the rotor plane, allows the rotor to stabilize angled to the wind, as with the offset rotor. However, in this case the angle of the rotor to the wind increases as the wind velocity increases.

How the tail does this is as follows. The tail is hinged so



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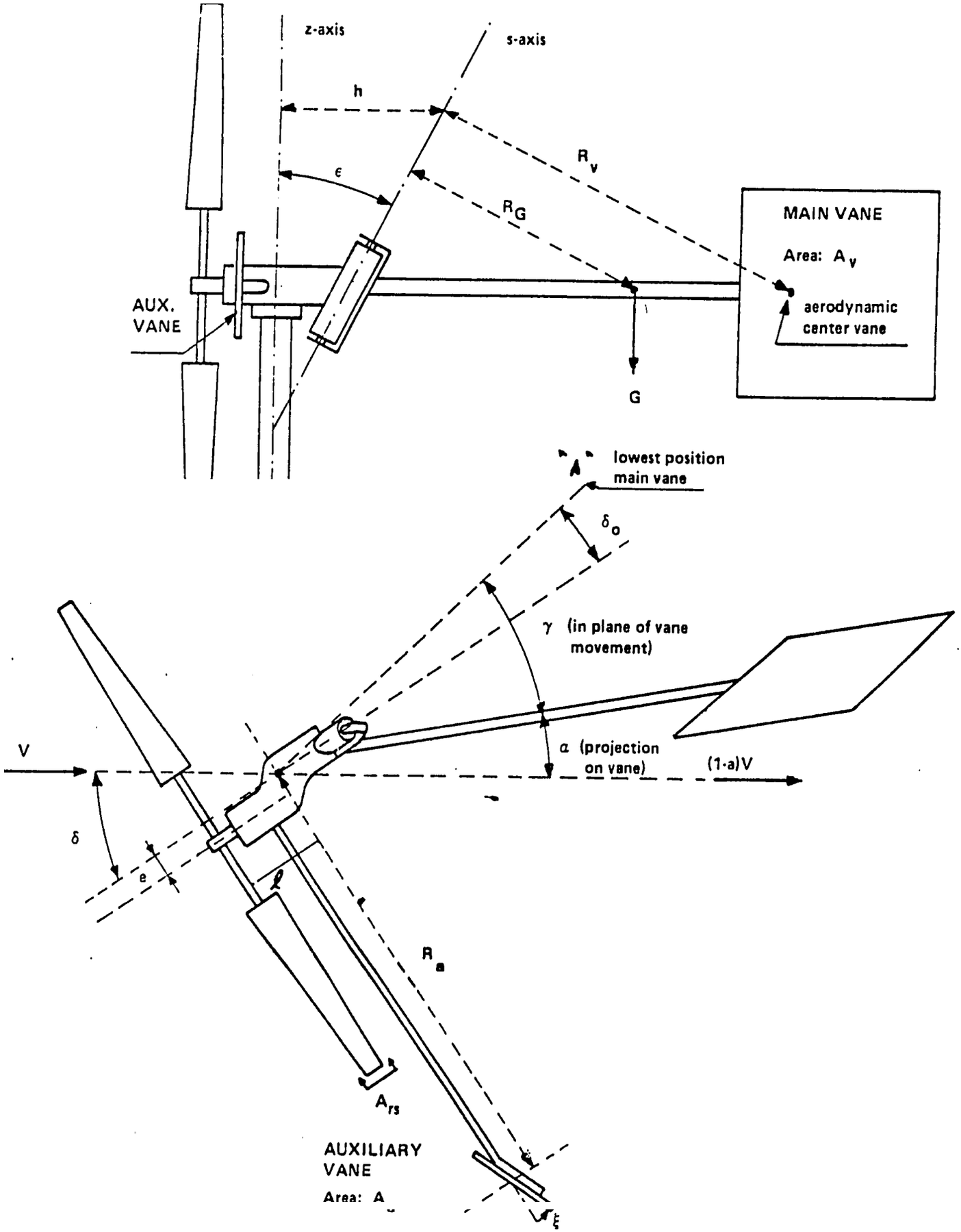


Fig. 1 Schematic drawings of the different parameters involved in the analysis of the inclined hinged vane safety system. (SOURCE SWD B2-1)

that it can vary its angle with respect to the rotor axis. Remember that the tail always wants to be parallel with the wind, as that is the path of least wind resistance. Now, if the rotor and tail were not 'locked' together in someway, if the tail were free on the hinge, the tail would just trail in the wind, and the rotor would swing right back perpendicular to the wind, along side the tail, at the slightest breeze.

Here is the "trick".. Gravity 'locks' the tail relative to the rotor, and the aerodynamic force on the offset rotor is counter-balanced by the tail (the moments about the main yaw axis are in equilibrium). What makes this interesting is that the position at which the tail is 'locked' is different for each wind speed, allowing the rotor to come progressively further out of the wind as the velocity increases.

The way this 'locking' action occurs is by balancing the moments around the hinge axis so that they are equal to zero. When this happens, the tail will not move relative to the chassis or the rotor, i.e. it is in equilibrium at the hinge. To achieve this, there must be another force creating an opposite moment about the hinge axis to counterbalance the aerodynamic force on the tail which is required to hold the rotor in position, at angle d to the wind. This is where gravity comes into play.

The hinge of the tail is angled back (and sometimes sideways) so that the centre of gravity of the tail no longer moves in a horizontal plane. It moves in an oblique plane with its lowest point, point "A" behind the main yaw axis and the hinge axis. This point stays fixed with respect to the hinge at all times, as well as to the rotor, so when the rotor and hinge joint turn about the yaw axis, the point "A" moves correspondingly. However, the tail moves away from this spot under the influence of the wind, as the tail tries to stay parallel with the wind. As the tail moves from this lowest point, it climbs up the sloping plane, and gravity tries to bring it back down again. The higher it goes, the greater the gravity force. At the same time as the wind forces the tail to climb up this plane, the angle of the tail to the wind is reducing so the aerodynamic forces also diminish. This goes on until the moments created by the gravity and the aerodynamic forces are balanced, and the hinge joint is in equilibrium.

Now at the same time, the aerodynamic forces on the rotor and the aerodynamic forces from the tail seek their equilibrium about the main yaw axis, and finally the entire system comes to a static state.

To briefly re-iterate, the drag forces on the rotor create a moment about the main yaw axis. As the system starts to rotate under this offset force, the tail following the low spot in its' plane of rotation, moves out into the windstream. The rotor continues to angle out of the wind until the tail, chasing the low point, comes out into the wind enough to provide the opposite, counterbalancing moment about the yaw axis. The tail is held at this attitude by the gravity force which provides a balancing moment around the hinge axis, 'locking' it up so that it will transmit the aerodynamically derived moment from the tail to the yaw axis. When equilibrium is achieved the sum of the moments about the main yaw axis <u>and</u> the sum of the moments about the hinge axis are simulataniously all <u>zero</u>.



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## The Mathematical MODEL

These actions of the tail about its axis, gravity effect and the yawing of the rotor about the main axis can all be described by a mathematical model. This is desirable so that a reasonable attempt can be made to design a system that will be functional, as well as predicting before hand the result of any changes carried out on a field system to try and modify its characteristics. To reduce the amount of computations required, the smaller second and third order terms are dropped for simplicity. The model may be solved algebraically by manual calculations, however numerical iteration using a hand calculator or small computer can simplify the process.

A fortran programme is provided to assist with the solution of the equations by iteration.

Main Axis Equation:

The force on the rotor is the aerodynamic drag on the rotor surface is, noting that it is by definition parallel to the wind direction, and hence cannot be broken to components:

$$F_r = C_d \tfrac{1}{2} \rho A_{rotor} V^2 \qquad (1)$$

the value Cd = 8/9 is the theoretical value when max. power is taken from the wind. (see later note on changing this value to .50 x 8/9)

As the rotor yaws with the wind by angle $\delta$, the projected area of the rotor providing the drag surface changes by cos $\delta$.:

$$F_r = C_d \tfrac{1}{2} \rho (A_{rotor} \cos\delta) V^2 \qquad (2)$$

Now, the effective moment arm also changes with yaw angle $\delta$:

$$e' = e \cos\delta \qquad (3)$$

This is more complex when there is an offset to the side and the rotor is mounted ahead of the yaw axis:

$$\text{moment arm} = e \cos\delta + l \sin\delta \qquad (4)$$



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Therefore, the moment generated by the rotor is

$$M_r = C_d \tfrac{1}{2}\rho (A_{rotor} \cos\delta) V^2 \times (e \cos\delta + \ell \sin\delta) \tag{5}$$

and when '$\ell$' is small:

$$M_r = C_d \tfrac{1}{2}\rho (A_{rotor} \cos\delta) V^2 \times (e \cos\delta) \tag{6}$$

Note: when the rotor is offset, and '$\ell$' is not small, it must still be included. This is called the "side" force as it develops when the centre of the rotor moves to the side of the yaw axis creating a moment arm $\sin(\delta) \times \ell$ as a result of '$\ell$'.

The force from the tail is as follows:

A wind blowing on a flat plate generates a force normal to the plate equal to:

$$F_N = C_n \cdot \tfrac{1}{2}\rho A_{TAIL} (V')^2 \tag{7}$$

where $C_n = 2.6\, \alpha_{rad}$ $\alpha \Rightarrow 0° \rightarrow 40°$
as evaluated by SWD (ref 1, fig 11.5)
and $\alpha_{rad}$ is in radians.

Now, as the tail is in the shadow of the rotor, Velocity $V_\infty$ is reduced by a factor (1-a). This has been estimated and will be evaluated as required. (ref no 1, fig. 11.6)

Therefore the effective force due to the aerodynamic load is:

$$F_n = 2.6\, \alpha_{rad} \tfrac{1}{2} \cdot \rho A_{TAIL} ((1-a) V_\infty)^2 \tag{8}$$

The moment arm for the tail about the yaw axis is equal to $[(R_{aero} \cdot \cos(\delta) + R_{hinge} \cdot \cos(\phi+\delta))^2 + (R_{aero} \cdot \sin\delta + R_{hnge} \cdot \sin(\phi+\delta))^2]^{1/2}$

Therefore, the moment due to the tail about the main yaw axis is:

$$M_T = 2.6\, \alpha_{rad} \tfrac{1}{2}\rho A_T (1-a)^2 V^2 \cdot [(R_{aero} \cos\delta + R_{hg} \cdot \cos(\phi+\delta))^2 + (R_{aero} \sin\delta + R_{hg} \sin(\phi+\delta))^2]^{1/2} \tag{9}$$

At equilibrium, the sum of the moments about the yaw axis are: (counterclockwise being +ve)

$$\Sigma M_y = 0 = +M_r - M_T = C_d \tfrac{1}{2}\rho A_{rotor} \cos\delta (1-a)^2 V^2 - 2.6\, \alpha_{rad} \tfrac{1}{2}\rho A_T (1-a)^2 V^2 \cdot [(R_{aero} \cos\delta + R_{hinge} \cos(\phi+\delta))^2 + (R_{aero} \sin\delta + R_{hinge} \sin(\phi+\delta))^2]^{1/2} \tag{10}$$

This is simplified for the computer programme as:

My-axis = CT*EC*cos($\delta$)*cos($\delta$) - CTA*alfa*(Raero + Rhinge) (11)

where $CT = \tfrac{1}{2}\rho A_{rotor} V^2$ (12)

and $CTA = \tfrac{1}{2}\rho A_{TAIL} (1-a)^2 V^2$ (13)

noting that when Raero>>Rhinge, moment arm ≡ Raero + Rhinge



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Hinge Axis Equation

The weight of the tail acts as a pendulum. The forces of gravity acting on the tail are as follows:

$$F = G \sin \epsilon \sin \gamma \tag{14}$$

and: when axis is tipped back by $\epsilon$ only

$$F = G \sin(\epsilon+\beta) \sin \gamma \tag{15}$$

when axis is tipped sideways as well

Noting that $\gamma = \delta - \alpha$ (16)

Therefore:

$$F = G \sin(\epsilon+\beta) \sin(\delta-\alpha) \tag{17}$$

where G is the weight of the tail due to gravity.

As the moment arm is Rg, therefore the moment created by the gravity force on the tail, about the hinge axis is:

$$M_g = + G \sin(\epsilon+\beta) \sin(\delta-\alpha) \times R_g \tag{18}$$

The forces generated by the aero loading on the tail vane is as before:

$$F = C_n \tfrac{1}{2} \rho A_{TAIL} (1-a)^2 V^2$$

and the moment arm of the tail about the hinge axis is Raero. Therefore the moment created by the aerodynamic forces on the tail, about the hinge axis is:

$$M_t = C_n \tfrac{1}{2} \rho A_{TAIL} (1-a)^2 V^2 \times R_{AERO}$$

$$= 2.6\, \alpha_{rad} \tfrac{1}{2} \rho A_{TAIL} (1-a)^2 V^2 \times R_{AERO} \tag{19}$$

At equilibrium the sum of the moments about the hinnge axis are equal to zero:

$$\Sigma M_{HG} = 0 = M_G - M_T$$

$$= G \sin(\epsilon+\beta) \sin(\delta-\alpha) \cdot R_g - 2.6 \tfrac{1}{2} \rho A_T (1-a)^2 V^2 \cdot R_{AERO} \tag{20}$$

simplified as before to:

$$= G \sin(\epsilon+\beta) \sin(\delta-\alpha) \cdot R_g - C_{TA}\, \alpha_{rad} \cdot R_{AERO} \tag{21}$$



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## Solving the Moment Equations:

As the moment equations about the hinge axis (20) and the main yaw axis (10) give two equations and two unknowns, the angles $\delta$ and $\alpha$, and all the other variables are either known or may be evaluated from the reference material, the equations may be solved.

The solution of these equations may be done algebraically, however it is much more straight forward to use an iterative computer programme to do this. A sample programme in fortran is as follows:

Fortran Programme for iteration of angles $\alpha$ and $\delta$ for various wind velocities V.

```
        PROGRAM TAIL SWD                          name of the program
        REAL MYR,MYS,MYT,MTA,MTG
        REAL ALFA,D
71      DO 18 I=9,14
72      DO 19 K=40,60,2                           velocity iteration
73      DO20 J=1,20                               delta iteration
        ALFA=J*2.0*3.1415/360.                    alfa iteration
        D=K*1.0*2.0*3.1415/360.                   alfa to radians
        V=I*1.0                                   delta to radians
        RO=1.229                                  velocity
        RR=.75                                    air density
        AR=RR*RR*3.1415                           rotor radius
        CT=8/9.*V*V*.5*RO*AR*0.5                  area  of rotor
        EC=.178                                   coefficient of perf
        AL=.100                                   eccentricity of rotor
        AT=.41                                    'l' fwd to rotor
        VRED=.7                                   area of tail
        DD = D*360./(2*3.1415)                    (1-a) vel reduction
        IF(DD.GT.45)EC=EC*1.25                    delta to degrees
                                                  modify ecc. to simulate
        IF(DD.GT.45)VRED=.9                       side vane at angles > 45°
        RHG=.10                                   modify  (1-a) for d > 45°
        G=32.4                                    hinge radius
        EPS=15.0*2.0*3.1415/360.                  weight of rotor in N
        RTG=.80                                   hinge angle
        RAERO=1.0                                 tail radius to C of Grav
        CTA=2.6*.5*RO*VRED*VRED*V*V*AT            tail rad. to aero centre
                                                      CTA
        MYR=CT*(EC*COS(D)+AL*SIN(D))*COS(D)          rotor moment
        MYT=CTA*ALFA*(RAERO+RHG)                     tail moment to y-axis
        MTG=G*SIN(EPS)*RTG*SIN(D-ALFA)               gravitymoment to hinge
        MTA=CTA*ALFA*RAERO                           aero moment to hinge
        XX=MYR-MYT                                sum moments about y-axis
        YY=MTG-MTA                                sum of moments hinge-axis
        IF(YY.LT.-2)GOTO 19                       shorten print out
        IF(XX.LT.-1)GOTO 19
        ALFA=ALFA*360.0/(2.*3.1415)               alfa to degrees
        D=D*360.0/(2.*3.1415)                     delta to degrees
        WRITE(2,61)XX,YY,ALFA,D,V
61      FORMAT('  MOM Y AXIS=',F8.5,' MOM TAIL=',F8.5,'  ',      printout
     * 'ALFA =',F4.1,'  DELTA =',F4.1,'  VEL =',F4.1)
20      CONTINUE
```

```
19      CONTINUE
18      CONTINUE
        STOP
        END
                                                end of the programme
```

Parameters used for this model:

| | | |
|---|---|---|
| Radius of rotor | = .75m | |
| air density | = 1.229 | |
| offset ecc | = .178 | see note on calculation |
| $l$ | = .10 | estimated distance from y-axis to rotor |
| area tail | = .41m$^2$ | |
| (1-a) | = .7 | d < 45° |
| | = .9 | d > 45° |
| hinge radius | = .10m | (estimated) |
| weight to tail | G = 32.4N | |
| tail angle | = 15° | (eps) |
| radius to CG | = 0.80m | centre of gravity RG |
| radius to AC | = 1.0m | aerodynamic centre Raero |

Parameters for SWD 2740 rotor
as above except for:

area of side vane = .071 m$^2$
side vane moment arm = 1.26m

Note: In order to use this mathematical model which evaluates an offset rotor rather than a rotor with a side vane, a value must be calculated for the eccentricity of the rotor which would correspond to using a side vane. This is done by solving for the moment arm of a rotor with an equivalent rotor area to the one with the side vane. As the coefficient of normal force on the side vane changes after the angle is greater than 45 degrees, allowance must be made for this too. However, the effect of '$l$' still exists, so this is included.

A modification to the co-efficient of drag for a rotor is made by using a value of 0.5 x 8/9 to compensate for the fact that the rotor Cp is lower than the Betz limit 59.6% and so the drag should also be lower.

Solving for the equivalent eccentricity:

moment due to side vane = area side vane x moment arm x co-eff x f
= .071 x 1.26 x 1.6 (coeff = 2, angle<45°)
x .5 x p x V$^2$

moment due to rotor = rotor arm x force due to drag
= ecc. x 8/9 x .5 x p x .75$^2$ x 3.1415 x V$^2$

Therefore eccentrity, ecc. is equal to: .178 for coeff @ 1.6
.178 x 1.25 for coeff @ 2.0



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## Running the Programme

Once the programme has been run initally, with large changes in the angles as they iterate, it may be necessary to re-run parts of the programme, using smaller changes in the angles. This will give a much more accurate determination of the points when the simultanious equilibrium is obtained.

## Comparing the results:

The fortran programme has been run and the results are plotted on a graph. figure (2). The results from the SWD mathematical model for a hinged tail with a side vane, and the results from wind tunnel tests on an actual rotor are plotted on the same graph. The actual windtunnel data are referred to as those for the SWD 2740 rotor. (ref no 1, figure 11.12, pg 260).

As the results on the graph show, this model gives a very good correlation with the actual wind tunnel measurements on the SWD 2740 rotor.Note how well the shape of the model curve follows the wind tunnel test results. This is an excellent indication that this model should give very good predictions for the hinged tail windmills to be analysed. It is interesting to note that this model shows a much more consistant correlation to the wind tunnel data than the SWD mathematical model. As the two are based on similar premises, this may indicate that there is a small mathematical error in the SWD model.

## SUMMARY

The mathematical model presented here is fairly straight forward and gives good agreement with wind tunnel data. This agreement is within 5-10% when the rotor Cd is adjusted to 50%. This model should prove to be a valuable guide for design work on new windmill hinged tail control systems. It should also prove to be valuable for indicating the trends that various changes in exisiting systems will make, ideal for adjusting or trouble shooting rotors already in the field. In this way, one will have a before hand look at what parameters, such as weight of tail, length of tail arm etc. it will be necessary to adjust and by how much, should it be desirable to raise or lower the furling speed of the rotor.

The model also gives a good prediction of the attitude that the rotor will take to the wind, so that the resulting power available to the rotor may be calculated. This is important so that the matching of the systems may take this variation into account. This is also shown in figure (2). It should be noted that the angle that the tail takes with respect to the rotor is not the angle delta. The correlation of tail to rotor for the SWD 2740 rotor is shown in figure (3), a valuable aid as this is actually the only angle one can visually see change when watching the rotor, tail and wind interact. Unless

there is a wind vane on the site, one does not appreciate the attitude that the rotor is taking to the wind directly. However, by observing the rotor vs. tail angle, one can derive the relationship between the rotor and wind.

Finally, the model will be used to predict the required geometry and operating characteristics for the new LESO II rotor. A summary of the programme used and the results is attached. See Figure 4 and Attachment 3.

Parameters of the LESO II rotor:

| | | |
|---|---|---|
| Rotor diameter | = 4.0 m | |
| rotor offset | = 0.90m | eccentricity |
| rotor forward | = .438 | 'l' |
| Radius hinge | =.254 | |
| $\phi$ hinge angle | = 45° | |
| tail area | = 2.0 $m^2$ | |
| G. tail weight | = 360N | |
| Rg. to c of G | = 1.77m | |
| Raero | =3.25 | to aerocentre of tail |
| tail hinge angle | = 7° | back tilt (eps) $\varepsilon$ |
| tail hinge angle | =5° | side tilt (beta) $\beta$ |

Results:

As Figure 4 shows, a rotor with eps = 7.5 Raero = 3.25 will have good characteristics. The tail will keep the rotor into the wind longer and then bring it up to furling more rapidly than when eps = 10 and Raero= 2.80. Figure 4 also shows how a change to a lower eps = 5 will reduce the gravity effect of the tail, and the rotor will move out of the wind appreciably sooner than when eps is 7.5 or 10.

Summary:

Overall the figure and other curves resulting from re-running the program will assist in showing the trends that any further changes, ie. longer tail, heavier tail more offset etc. will have in changing the actual characteristics of the LESO II and subsequent prototype rotors.



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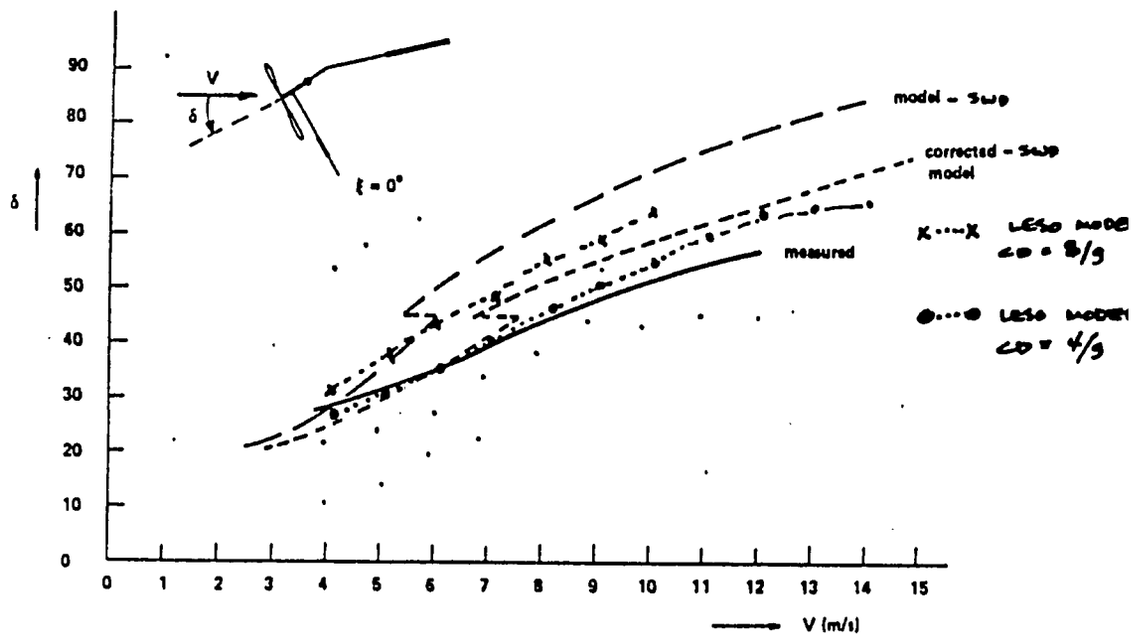



FIGURE 2: ROTOR ANGLE VS. WIND VELOCITY FOR MODEL AND SWD 2740 ROTOR WIND TUNNEL TESTS (SOURCE REF 1, SWD, FIG 11.12 PG 260)

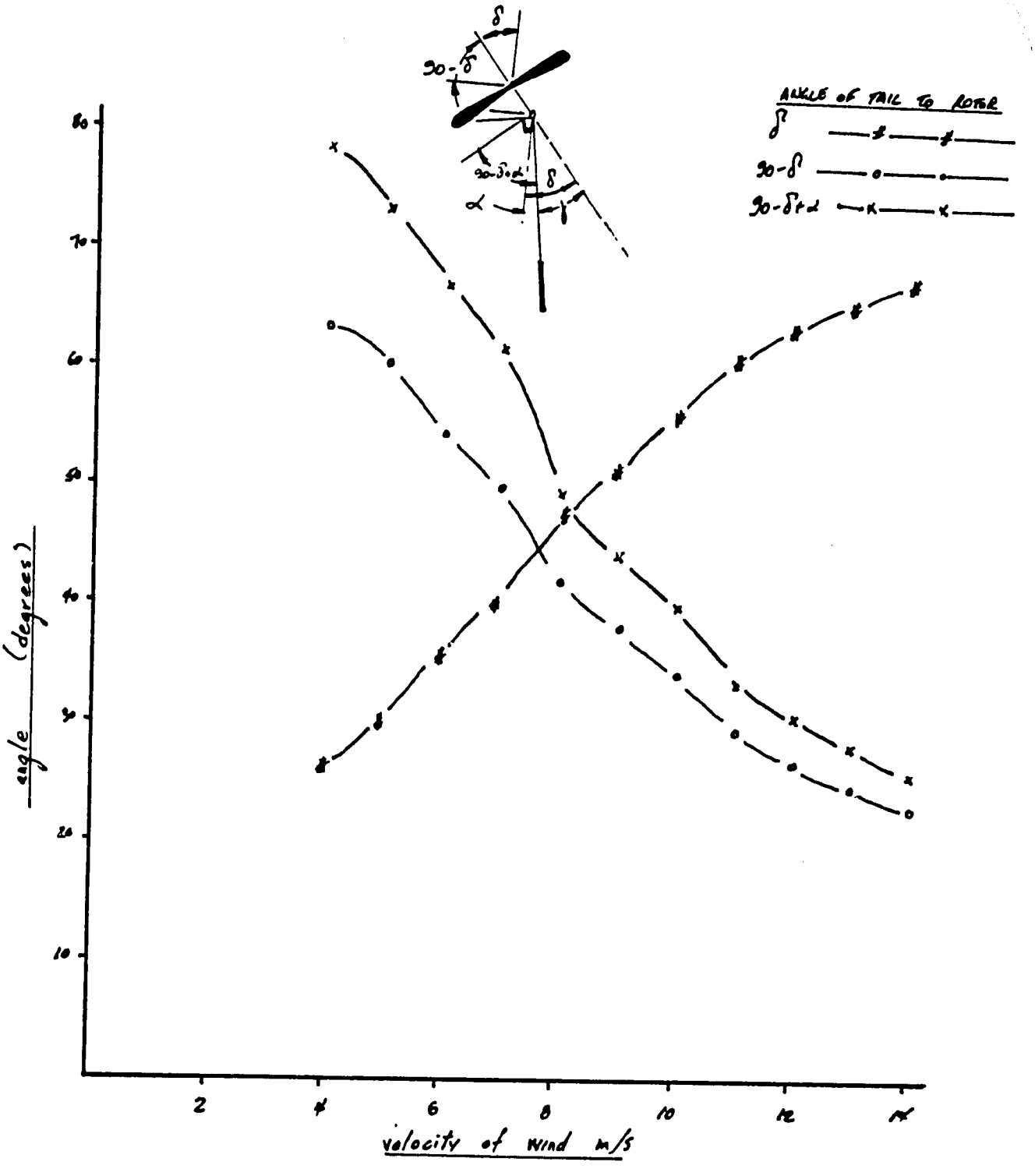



FIGURE 3: ANGLE OF ROTOR VS. TAIL VS. WIND VELOCITY (SWD 24/70 ROTOR)

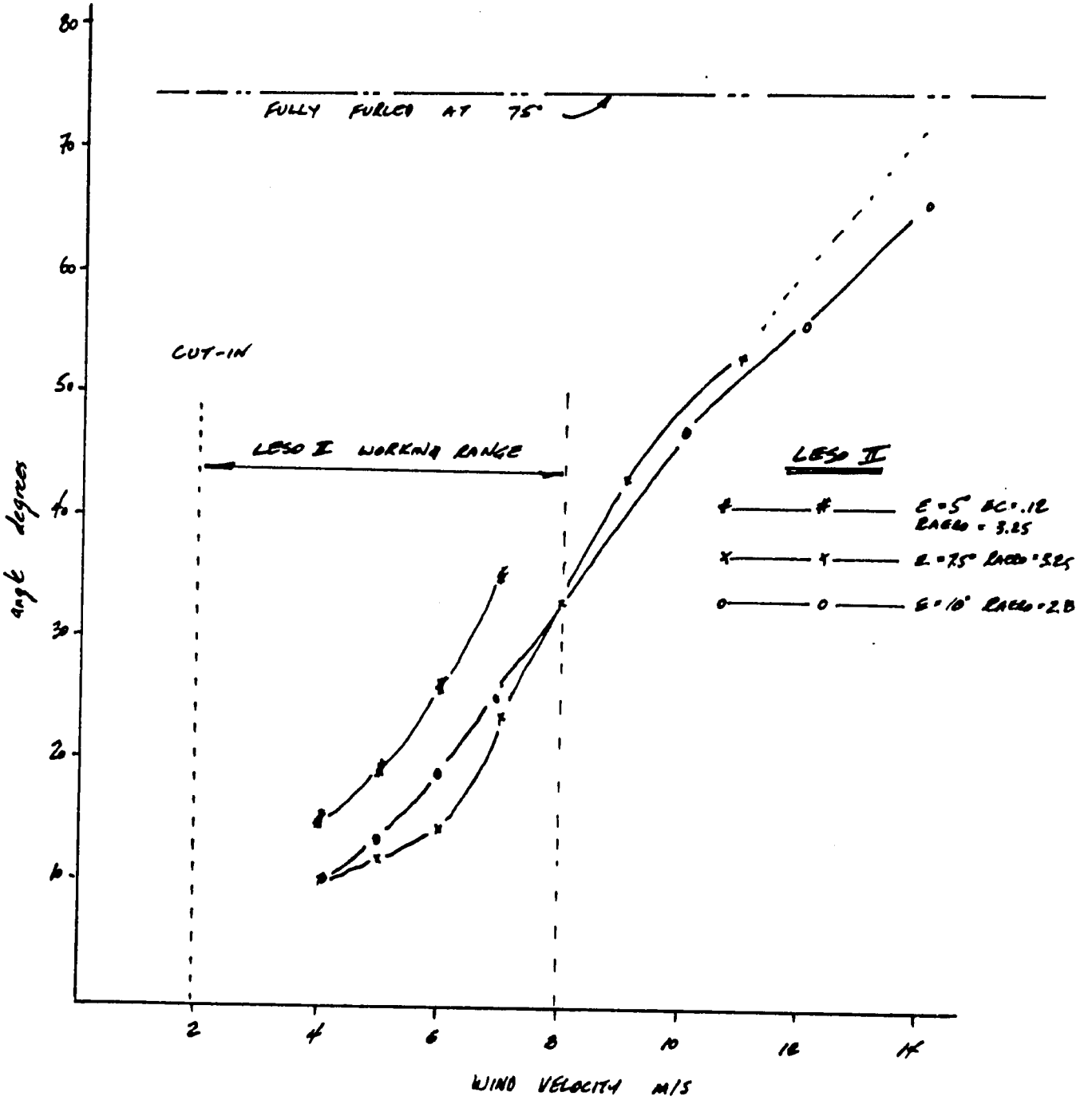
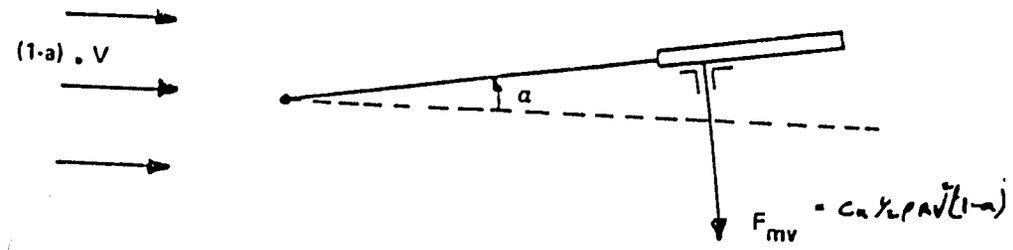



FIGURE 4: MATHEMATICAL MODEL PREDICTIONS FOR LESO II ROTOR & TAIL SYSTEM FURLING PERFORMANCE VS. WIND VELOCITY



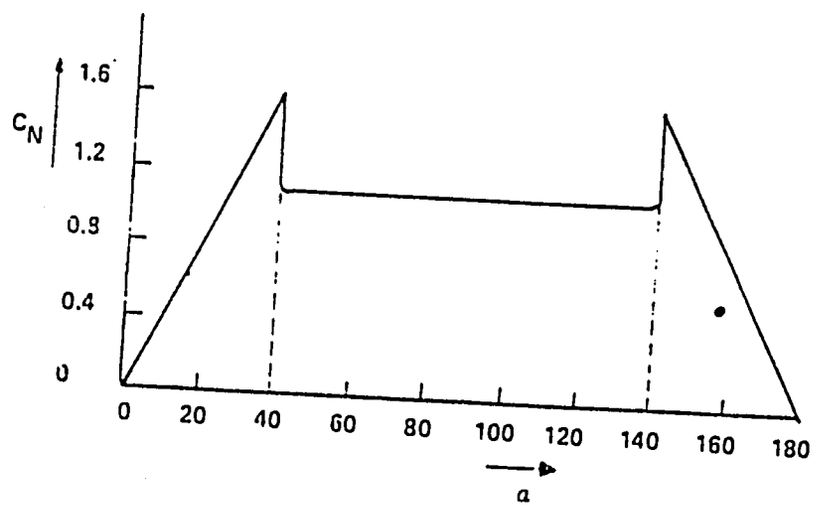




Fig. 11.5 The dimensionless normal force coefficient $C_N$ of a square plate.

REFERENCE FIGURE $\alpha$ VS $C_N$ SOURCE SWD 82-1

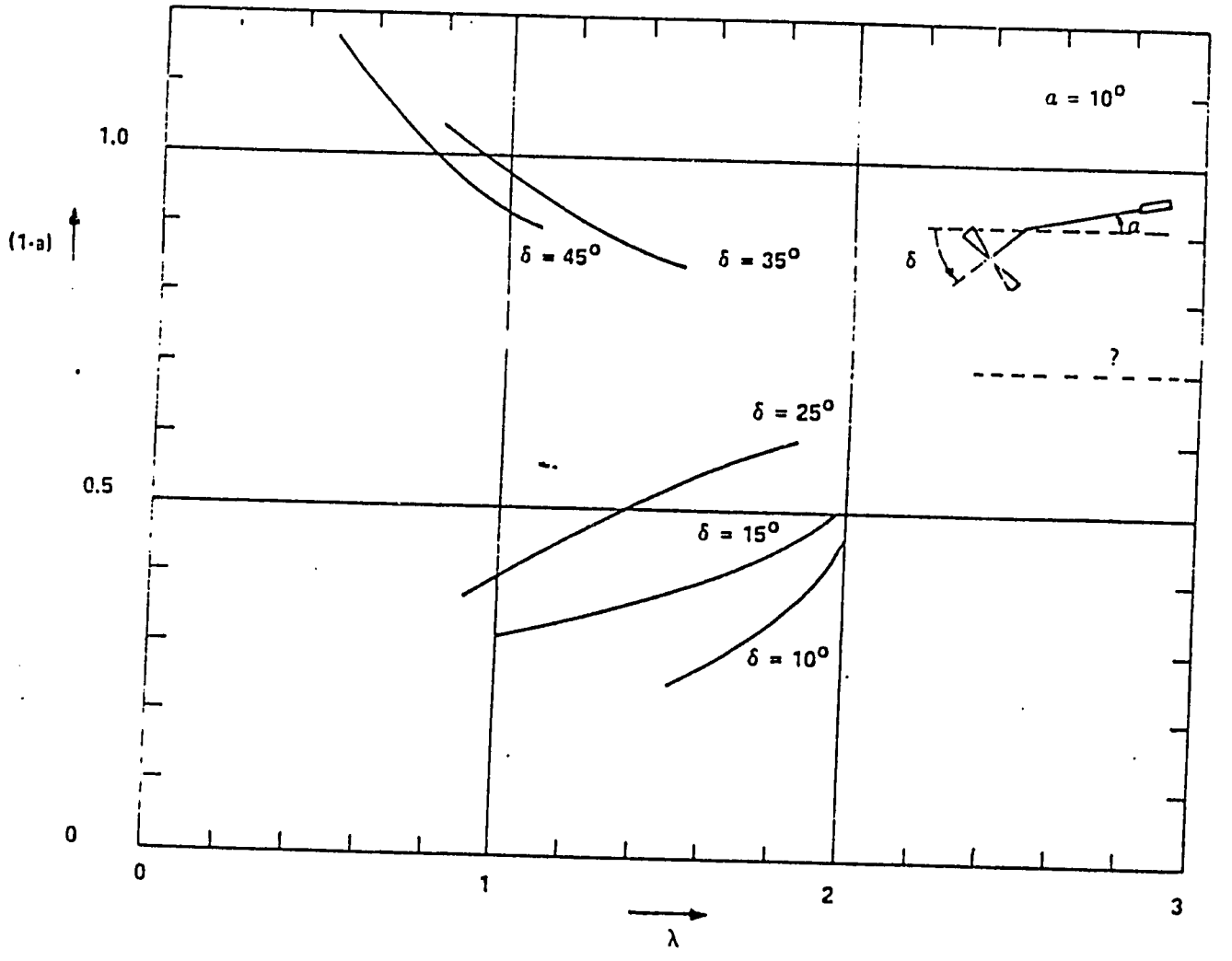



Fig. 11.6 The factor (1-a), indicating the reduced wind speed behind the rotor, as a function of the tip speed ratio of a rotor with a design tip speed ratio of 2. The value of (1-a) is found by taking the square root of the ratio between the moment on the vane <u>with</u> rotor and <u>without</u> rotor. Deflection of the wake, however, causes unrealistic values for high values of δ at low λ.

REFERENCE FIGURE (1-a) vs λ SOURCE SWD 82-1

## ATTACHMENTS

## WINDMILL CONTROL AND BRAKING SYSTEMS

| ATTACH. NO. | TITLE |
|---|---|
| 1 | COMPUTER MODEL OUTPUT PREDICTIONS FOR SWD 2740 ROTOR WITH $C_D = 4/9$ |
| 2 | COMPUTER MODEL OUTPUT PREDICTIONS FOR SWD 2740 ROTOR WITH $C_D = 8/9$ |
| 3 | COMPUTER MODEL OUTPUT PREDICTIONS FOR LESO II ROTOR WITH $C_D = 4/9$ |

## ATTACHMENT NO. 1

COMPUTER MODEL OUTPUT PREDICTIONS FOR

SWD 2740 ROTOR WITH $C_D = 4/9$

# ATTACHMENT NO. 2

## COMPUTER MODEL OUTPUT PREDICTIONS FOR SWD 2740 ROTOR WITH $C_D = 8/9$

# ATTACHMENT NO. 3

## COMPUTER MODEL OUTPUT PREDICTIONS FOR LESO II ROTOR WITH $C_D = 4/9$

LESO II
$\varepsilon_{PO}$ = 7.5

```
C          THIS IS WITH LESO II PARAMETERS
           REAL MYR,MYS,MYT,MTA,MTG
           REAL ALFA,D,INCL
71         DO 18 I=4,7
72         DO 19 K=15,75,3
73         DO 20 J=1,25,2
           ALFA=J*2.0*3.1415/360.
           D=K*1.0*2.0*3.1415/360.
           V=I*1.0
           RO=1.229
           RR=2.0
           AL=.438
           INCL=5.0*2.0*3.1415/360.
           G=360.0
           AR=RR*RR*3.1415
           CT=8/9.*V*V*.5*RO*AR*0.5
           EC=.09
           AT=2.00
           VRED=.7
           DD = D*360./(2*3.1415)
           IF(DD.GT.45)VRED=.9
           RHG=.254
           EPS=7.5*2.0*3.1415/360.
          RTG=1.77
          RAERO=3.25/COS(ESP)
           RAERO2=((RHG*COS(.7853+D)+RAERO*COS(ALFA))**2.0+
     *     (RHG*SIN(.7853+D)+RAERO*SIN(ALFA))**2.0)**0.5
           CTA=2.6*.5*RO*VRED*VRED*V*V*AT
           MYR=CT*(EC*COS(D)+AL*SIN(D))*COS(D)
           MYT=CTA*ALFA*RAERO2
           MTG=G*SIN(EPS+INCL)*RTG*SIN(D-ALFA)
           MTA=CTA*ALFA*RAERO
           XX=MYR-MYT
           YY=MTG-MTA
           IF(YY.LT.-10)GOTO19
           IF(XX.LT.-10)GOTO19
           IF(YY.GT.5)GOTO20
           IF(XX.GT.10)GOTO20
          ALFA=ALFA*360.0/(2.*3.1415)
          D=D*360.0/(2.*3.1415)
          WRITE(2,61)XX,YY,ALFA,D,V
61        FORMAT('  MOM Y AXIS=',F8.5,' MOM TAIL=',F8.5,'   ',
     * 'ALFA =',F4.1,'  DELTA =',F4.1,'  VEL =',F4.1)
20        CONTINUE
19        CONTINUE
18        CONTINUE
          STOP
          END
```

MOM Y AXIS=-2.81694 MOM TAIL= 1.62678 ALFA = [illegible] DELTA [illegible]

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| | | | | | |
|---|---|---|---|---|---|
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| MOM Y AXIS=-8.20674 | MOM TAIL=-8.85286 | ALFA =13.0 | DELTA =17.0 | VEL = 4.0 |
| MOM Y AXIS=-3.36645 | MOM TAIL= 4.98315 | ALFA =10.0 | DELTA =18.0 | VEL = 4.0 |
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| MOM Y AXIS=-7.89417 | MOM TAIL=-6.45338 | ALFA =13.0 | DELTA =18.0 | VEL = 4.0 |
| MOM Y AXIS=-4.57361 | MOM TAIL= 3.56216 | ALFA =11.0 | DELTA =19.0 | VEL = 4.0 |
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| MOM Y AXIS=-3.88841 | MOM TAIL=-3.17592 | ALFA = 9.0 | DELTA =16.0 | VEL = 5.0 |
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| MOM Y AXIS=-3.39116 | MOM TAIL= -.78960 | ALFA = 9.0 | DELTA =17.0 | VEL = 5.0 |
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| MOM Y AXIS=-2.91034 | MOM TAIL= 1.59087 | ALFA = 9.0 | DELTA =18.0 | VEL = 5.0 |
| MOM Y AXIS=-5.26008 | MOM TAIL=-3.00989 | ALFA =10.0 | DELTA =18.0 | VEL = 5.0 |
| MOM Y AXIS=-7.61414 | MOM TAIL=-7.61649 | ALFA =11.0 | DELTA =18.0 | VEL = 5.0 |
| MOM Y AXIS=-2.44648 | MOM TAIL= 3.96477 | ALFA = 9.0 | DELTA =19.0 | VEL = 5.0 |
| MOM Y AXIS=-4.79420 | MOM TAIL= -.62942 | ALFA =10.0 | DELTA =19.0 | VEL = 5.0 |
| MOM Y AXIS=-7.14626 | MOM TAIL=-5.23018 | ALFA =11.0 | DELTA =19.0 | VEL = 5.0 |
| MOM Y AXIS=-9.50264 | MOM TAIL=-9.83678 | ALFA =12.0 | DELTA =19.0 | VEL = 5.0 |
| MOM Y AXIS=-4.34579 | MOM TAIL= 1.74448 | ALFA =10.0 | DELTA =20.0 | VEL = 5.0 |
| MOM Y AXIS=-6.69585 | MOM TAIL=-2.84971 | ALFA =11.0 | DELTA =20.0 | VEL = 5.0 |
| M Y AXIS=-9.05031 | MOM TAIL=-7.45046 | ALFA =12.0 | DELTA =20.0 | VEL = 5.0 |
| MOM Y AXIS=-3.91533 | MOM TAIL= 4.11108 | ALFA =10.0 | DELTA =21.0 | VEL = 5.0 |
| MOM Y AXIS=-6.26342 | MOM TAIL= -.47581 | ALFA =11.0 | DELTA =21.0 | VEL = 5.0 |
| MOM Y AXIS=-8.61584 | MOM TAIL=-5.07000 | ALFA =12.0 | DELTA =21.0 | VEL = 5.0 |
| MOM Y AXIS=-5.84942 | MOM TAIL= 1.89079 | ALFA =11.0 | DELTA =22.0 | VEL = 5.0 |
| MOM Y AXIS=-8.19983 | MOM TAIL=-2.69610 | ALFA =12.0 | DELTA =22.0 | VEL = 5.0 |
| MOM Y AXIS=-5.45435 | MOM TAIL= 4.24938 | ALFA =11.0 | DELTA =23.0 | VEL = 5.0 |
| MOM Y AXIS=-7.80270 | MOM TAIL= -.32950 | ALFA =12.0 | DELTA =23.0 | VEL = 5.0 |

3 5/12
α = 6

| | | | | |
|---|---|---|---|---|
| MOM Y AXIS=-7.08710 | MOM TAIL= 4.37895 | ALFA =12.0 | DELTA =25.0 | VEL = 5.0 |
| MOM Y AXIS=-9.41586 | MOM TAIL= -.19119 | ALFA =13.0 | DELTA =25.0 | VEL = 5.0 |
| MOM Y AXIS=-9.07602 | MOM TAIL= 2.15866 | ALFA =13.0 | DELTA =26.0 | VEL = 5.0 |
| MOM Y AXIS=-8.75673 | MOM TAIL= 4.49907 | ALFA =13.0 | DELTA =27.0 | VEL = 5.0 |
| MOM Y AXIS= -.16077 | MOM TAIL=-9.56336 | ALFA = 6.0 | DELTA =10.0 | VEL = 6.0 |
| MOM Y AXIS= .67027 | MOM TAIL=-7.16387 | ALFA = 6.0 | DELTA =11.0 | VEL = 6.0 |
| MOM Y AXIS= 1.48297 | MOM TAIL=-4.76805 | ALFA = 6.0 | DELTA =12.0 | VEL = 6.0 |
| MOM Y AXIS= 2.27640 | MOM TAIL=-2.37662 | ALFA = 6.0 | DELTA =13.0 | VEL = 6.0 |
| MOM Y AXIS=-1.10323 | MOM TAIL=-7.96526 | ALFA = 7.0 | DELTA =13.0 | VEL = 6.0 |
| MOM Y AXIS= 3.04954 | MOM TAIL= .00970 | ALFA = 6.0 | DELTA =14.0 | VEL = 6.0 |
| MOM Y AXIS= -.32711 | MOM TAIL=-5.57383 | ALFA = 7.0 | DELTA =14.0 | VEL = 6.0 |
| MOM Y AXIS= 3.80150 | MOM TAIL= 2.39017 | ALFA = 6.0 | DELTA =15.0 | VEL = 6.0 |
| MOM Y AXIS= .42789 | MOM TAIL=-3.18751 | ALFA = 7.0 | DELTA =15.0 | VEL = 6.0 |
| MOM Y AXIS=-2.95202 | MOM TAIL=-8.77104 | ALFA = 8.0 | DELTA =15.0 | VEL = 6.0 |
| MOM Y AXIS= 4.53144 | MOM TAIL= 4.76407 | ALFA = 6.0 | DELTA =16.0 | VEL = 6.0 |
| MOM Y AXIS= 1.16067 | MOM TAIL= -.80704 | ALFA = 7.0 | DELTA =16.0 | VEL = 6.0 |
| MOM Y AXIS=-2.21607 | MOM TAIL=-6.38473 | ALFA = 8.0 | DELTA =16.0 | VEL = 6.0 |
| MOM Y AXIS= 1.87095 | MOM TAIL= 1.56685 | ALFA = 7.0 | DELTA =17.0 | VEL = 6.0 |
| MOM Y AXIS=-1.50299 | MOM TAIL=-4.00426 | ALFA = 8.0 | DELTA =17.0 | VEL = 6.0 |
| MOM Y AXIS=-4.88327 | MOM TAIL=-9.58194 | ALFA = 9.0 | DELTA =17.0 | VEL = 6.0 |
| MOM Y AXIS= 2.55733 | MOM TAIL= 3.93346 | ALFA = 7.0 | DELTA =18.0 | VEL = 6.0 |
| MOM Y AXIS= -.81356 | MOM TAIL=-1.63036 | ALFA = 8.0 | DELTA =18.0 | VEL = 6.0 |
| MOM Y AXIS=-4.19089 | MOM TAIL=-7.20147 | ALFA = 9.0 | DELTA =18.0 | VEL = 6.0 |
| MOM Y AXIS= -.14857 | MOM TAIL= .73624 | ALFA = 8.0 | DELTA =19.0 | VEL = 6.0 |
| MOM Y AXIS=-3.52293 | MOM TAIL=-4.82757 | ALFA = 9.0 | DELTA =19.0 | VEL = 6.0 |
| MOM Y AXIS= .49107 | MOM TAIL= 3.09483 | ALFA = 8.0 | DELTA =20.0 | VEL = 6.0 |
| MOM Y AXIS=-2.88013 | MOM TAIL=-2.46097 | ALFA = 9.0 | DELTA =20.0 | VEL = 6.0 |
| MOM Y AXIS=-6.25794 | MOM TAIL=-8.02479 | ALFA =10.0 | DELTA =20.0 | VEL = 6.0 |
| MOM Y AXIS=-2.26340 | MOM TAIL= -.10238 | ALFA = 9.0 | DELTA =21.0 | VEL = 6.0 |
| MOM Y AXIS=-5.63808 | MOM TAIL=-5.65818 | ALFA =10.0 | DELTA =21.0 | VEL = 6.0 |
| MOM Y AXIS=-1.67338 | MOM TAIL= 2.24747 | ALFA = 9.0 | DELTA =22.0 | VEL = 6.0 |
| MOM Y AXIS=-5.04494 | MOM TAIL=-3.29959 | ALFA =10.0 | DELTA =22.0 | VEL = 6.0 |
| MOM Y AXIS=-8.42317 | MOM TAIL=-8.85540 | ALFA =11.0 | DELTA =22.0 | VEL = 6.0 |
| MOM Y AXIS=-1.11068 | MOM TAIL= 4.58788 | ALFA = 9.0 | DELTA =23.0 | VEL = 6.0 |
| MOM Y AXIS=-4.47911 | MOM TAIL= -.94974 | ALFA =10.0 | DELTA =23.0 | VEL = 6.0 |
| MOM Y AXIS=-7.85427 | MOM TAIL=-6.49681 | ALFA =11.0 | DELTA =23.0 | VEL = 6.0 |
| MOM Y AXIS=-3.94132 | MOM TAIL= 1.39067 | ALFA =10.0 | DELTA =24.0 | VEL = 6.0 |
| MOM Y AXIS=-7.31338 | MOM TAIL=-4.14695 | ALFA =11.0 | DELTA =24.0 | VEL = 6.0 |
| MOM Y AXIS=-3.43207 | MOM TAIL= 3.72091 | ALFA =10.0 | DELTA =25.0 | VEL = 6.0 |
| MOM Y AXIS=-6.80099 | MOM TAIL=-1.80655 | ALFA =11.0 | DELTA =25.0 | VEL = 6.0 |
| MOM Y AXIS=-6.31779 | MOM TAIL= .52370 | ALFA =11.0 | DELTA =26.0 | VEL = 6.0 |
| MOM Y AXIS=-9.69028 | MOM TAIL=-5.00376 | ALFA =12.0 | DELTA =26.0 | VEL = 6.0 |
| MOM Y AXIS=-5.26434 | MOM TAIL= 2.84307 | ALFA =11.0 | DELTA =27.0 | VEL = 6.0 |
| MOM Y AXIS=-9.23364 | MOM TAIL=-2.67352 | ALFA =12.0 | DELTA =27.0 | VEL = 6.0 |
| MOM Y AXIS= 3.09843 | MOM TAIL=-9.30391 | ALFA = 6.0 | DELTA =13.0 | VEL = 7.0 |
| MOM Y AXIS= 4.15077 | MOM TAIL=-6.91759 | ALFA = 6.0 | DELTA =14.0 | VEL = 7.0 |
| MOM Y AXIS= 5.17426 | MOM TAIL=-4.53713 | ALFA = 6.0 | DELTA =15.0 | VEL = 7.0 |
| MOM Y AXIS= 6.16780 | MOM TAIL=-2.16323 | ALFA = 6.0 | DELTA =16.0 | VEL = 7.0 |
| MOM Y AXIS= 1.58008 | MOM TAIL=-8.88889 | ALFA = 7.0 | DELTA =16.0 | VEL = 7.0 |
| MOM Y AXIS= 7.13002 | MOM TAIL= .20337 | ALFA = 6.0 | DELTA =17.0 | VEL = 7.0 |
| MOM Y AXIS= 2.54657 | MOM TAIL=-6.51499 | ALFA = 7.0 | DELTA =17.0 | VEL = 7.0 |
| MOM Y AXIS= 8.05989 | MOM TAIL= 2.56196 | ALFA = 6.0 | DELTA =18.0 | VEL = 7.0 |
| MOM Y AXIS= 3.48082 | MOM TAIL=-4.14839 | ALFA = 7.0 | DELTA =18.0 | VEL = 7.0 |
| MOM Y AXIS= 8.95636 | MOM TAIL= 4.91182 | ALFA = 6.0 | DELTA =19.0 | VEL = 7.0 |
| MOM Y AXIS= 4.38163 | MOM TAIL=-1.78980 | ALFA = 7.0 | DELTA =19.0 | VEL = 7.0 |
| MOM Y AXIS= -.20221 | MOM TAIL=-8.50015 | ALFA = 8.0 | DELTA =19.0 | VEL = 7.0 |
| M Y AXIS= 5.24793 | MOM TAIL= .56006 | ALFA = 7.0 | DELTA =20.0 | VEL = 7.0 |
| MOM Y AXIS= .66840 | MOM TAIL=-6.14157 | ALFA = 8.0 | DELTA =20.0 | VEL = 7.0 |
| MOM Y AXIS= 6.07877 | MOM TAIL= 2.90047 | ALFA = 7.0 | DELTA =21.0 | VEL = 7.0 |
| MOM Y AXIS= 1.50362 | MOM TAIL=-3.79171 | ALFA = 8.0 | DELTA =21.0 | VEL = 7.0 |
| MOM Y AXIS= 2.30246 | MOM TAIL=-1.45130 | ALFA = 8.0 | DELTA =22.0 | VEL = 7.0 |
| MOM Y AXIS=-2.27766 | MOM TAIL=-8.14347 | ALFA = 9.0 | DELTA =22.0 | VEL = 7.0 |
| MOM Y AXIS= 3.06387 | MOM TAIL= .87894 | ALFA = 8.0 | DELTA =23.0 | VEL = 7.0 |
| MOM Y AXIS=-1.51176 | MOM TAIL=-5.80306 | ALFA = 9.0 | DELTA =23.0 | VEL = 7.0 |

6/14 α=1

7

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|---|---|---|---|---|
| MOM Y AXIS= -.07541 | MOM TAIL=-1.15345 | ALFA = 9.0 | DELTA =25.0 | VEL = 7.0 |
| MOM Y AXIS=-4.67142 | MOM TAIL=-7.82458 | ALFA =10.0 | DELTA =25.0 | VEL = 7.0 |
| MOM Y AXIS= .55348 | MOM TAIL= 1.15435 | ALFA = 9.0 | DELTA =26.0 | VEL = 7.0 |
| MOM Y AXIS=-4.01813 | MOM TAIL=-5.50521 | ALFA =10.0 | DELTA =26.0 | VEL = 7.0 |
| MOM Y AXIS= 1.16184 | MOM TAIL= 3.44985 | ALFA = 9.0 | DELTA =27.0 | VEL = 7.0 |
| MOM Y AXIS=-3.40524 | MOM TAIL=-3.19741 | ALFA =10.0 | DELTA =27.0 | VEL = 7.0 |

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|---|---|---|---|---|
| MOM Y AXIS=-7.98201 | MOM TAIL=-9.85698 | ALFA =11.0 | DELTA =27.0 | VEL = 7.0 |

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|---|---|---|---|---|
| MOM Y AXIS= 5.84009 | MOM TAIL=-5.15127 | ALFA = 8.0 | DELTA =25.0 | VEL = 8.0 |
| MOM Y AXIS= 7.46990 | MOM TAIL= -.57323 | ALFA = 8.0 | DELTA =27.0 | VEL = 8.0 |
| MOM Y AXIS= 1.51751 | MOM TAIL=-8.53970 | ALFA = 9.0 | DELTA =27.0 | VEL = 8.0 |
| MOM Y AXIS= 8.88403 | MOM TAIL= 3.95012 | ALFA = 8.0 | DELTA =29.0 | VEL = 8.0 |
| MOM Y AXIS= 2.94403 | MOM TAIL=-3.98831 | ALFA = 9.0 | DELTA =29.0 | VEL = 8.0 |
| MOM Y AXIS= 4.14859 | MOM TAIL= .50563 | ALFA = 9.0 | DELTA =31.0 | VEL = 8.0 |
| MOM Y AXIS=-1.79198 | MOM TAIL=-7.41775 | ALFA =10.0 | DELTA =31.0 | VEL = 8.0 |
| MOM Y AXIS= 5.12590 | MOM TAIL= 4.93661 | ALFA = 9.0 | DELTA =33.0 | VEL = 8.0 |
| MOM Y AXIS= -.80200 | MOM TAIL=-2.95461 | ALFA =10.0 | DELTA =33.0 | VEL = 8.0 |

8/33 α=10

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|---|---|---|---|---|
| MOM Y AXIS= -.04343 | MOM TAIL= 1.44288 | ALFA =10.0 | DELTA =35.0 | VEL = 8.0 |
| MOM Y AXIS= 6.48746 | MOM TAIL=-8.65155 | ALFA = 9.0 | DELTA =33.0 | VEL = 9.0 |
| MOM Y AXIS= 7.43094 | MOM TAIL=-4.28889 | ALFA = 9.0 | DELTA =35.0 | VEL = 9.0 |
| MOM Y AXIS= 8.07740 | MOM TAIL= .00011 | ALFA = 9.0 | DELTA =37.0 | VEL = 9.0 |
| MOM Y AXIS= .60841 | MOM TAIL=-9.32859 | ALFA =10.0 | DELTA =37.0 | VEL = 9.0 |
| MOM Y AXIS= 8.42408 | MOM TAIL= 4.21024 | ALFA = 9.0 | DELTA =39.0 | VEL = 9.0 |
| MOM Y AXIS= .97232 | MOM TAIL=-5.07838 | ALFA =10.0 | DELTA =39.0 | VEL = 9.0 |
| MOM Y AXIS= 1.03579 | MOM TAIL= -.90961 | ALFA =10.0 | DELTA =41.0 | VEL = 9.0 |

9/45

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|---|---|---|---|---|
| MOM Y AXIS= .79927 | MOM TAIL= 3.17262 | ALFA =10.0 | DELTA =43.0 | VEL = 9.0 |
| MOM Y AXIS= 9.45980 | MOM TAIL= 1.12982 | ALFA = 9.0 | DELTA =45.0 | VEL =10.0 |
| MOM Y AXIS= .32635 | MOM TAIL=-9.71085 | ALFA =10.0 | DELTA =45.0 | VEL =10.0 |
| MOM Y AXIS= .50964 | MOM TAIL= 2.38927 | ALFA = 6.0 | DELTA =47.0 | VEL =10.0 |
| MOM Y AXIS=-3.15237 | MOM TAIL=-9.06888 | ALFA = 6.0 | DELTA =51.0 | VEL =11.0 |
| MOM Y AXIS=-5.66301 | MOM TAIL=-5.72499 | ALFA = 6.0 | DELTA =53.0 | VEL =11.0 |

α=1

10/47

α=6

11/

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|---|---|---|---|---|
| MOM Y AXIS=-8.57397 | MOM TAIL=-2.50394 | ALFA = 6.0 | DELTA =55.0 | VEL =11.0 |
| MOM Y AXIS= 7.05051 | MOM TAIL= 2.96954 | ALFA = 5.0 | DELTA =57.0 | VEL =12.0 |

Immediate Fail Eps. Coal. @ 10m/sec δ=60

[illegible]

LESO II
Eps = 10°

```
      PROGRAM TAIL
        THIS IS WITH LESO II PARAMETERS
      REAL MYR,MYS,MYT,MTA,MTG
      REAL ALFA,D,INCL
      DO 18 I=4,12
      DO 19 K=15,75
      DO 20 J=1,30
      ALFA=J*2.0*3.1415/360.
      D=K*1.0*2.0*3.1415/360.
      V=I*1.0
      RO=1.229
      RR=2.0
      AL=.438
      INCL=5.0*2.0*3.1415/360.
      G=360.0
      AR=RR*RR*3.1415
      CT=8/9.*V*V*.5*RO*AR*0.5
      EC=.09
      AT=2.00
      VRED=.7
      DD = D*360./(2*3.1415)
      IF(DD.GT.45)VRED=.9
      RHG=.254
       EPS=10*2.0*3.1415/360.
     RTG=1.77
     RAERO=3.25/COS(ESP)
      RAERO2=((RHG*COS(.7853+D)+RAERO*COS(ALFA))**2.0+
     *  (RHG*SIN(.7853+D)+RAERO*SIN(ALFA))**2.0)**0.5
      CTA=2.6*.5*RO*VRED*VRED*V*V*AT
      MYR=CT*(EC*COS(D)+AL*SIN(D))*COS(D)
      MYT=CTA*ALFA*RAERO2
      MTG=G*SIN(EPS+INCL)*RTG*SIN(D-ALFA)
      MTA=CTA*ALFA*RAERO
      XX=MYR-MYT
      YY=MTG-MTA
      IF(YY.LT.-10)GOTO19
      IF(XX.LT.-10)GOTO19
      IF(YY.GT.5)GOTO20
      IF(XX.GT.10)GOTO20
      ALFA=ALFA*360.0/(2.*3.1415)
      D=D*360.0/(2.*3.1415)
      WRITE(2,61)XX,YY,ALFA,D,V
61    FORMAT('  MOM Y AXIS=',F8.5,' MOM TAIL=',F8.5,'   ',
     * 'ALFA =',F4.1,'  DELTA =',F4.1,'  VEL =',F4.1)
20    CONTINUE
19    CONTINUE
18    CONTINUE
      STOP
      END
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|---|---|---|---|---|
| MOM Y AXIS=-2.81694 | MOM TAIL= 4.44892 | ALFA = 9.0 | DELTA =15.0 | VEL = 4.0 |
| MOM Y AXIS=-4.32455 | MOM TAIL= .16301 | ALFA =10.0 | DELTA =15.0 | VEL = 4.0 |
| MOM Y AXIS=-5.83475 | MOM TAIL=-4.12729 | ALFA =11.0 | DELTA =15.0 | VEL = 4.0 |
| MOM Y AXIS=-7.34751 | MOM TAIL=-8.42109 | ALFA =12.0 | DELTA =15.0 | VEL = 4.0 |
| MOM Y AXIS=-3.99495 | MOM TAIL= 3.02794 | ALFA =10.0 | DELTA =16.0 | VEL = 4.0 |
| MOM Y AXIS=-5.50401 | MOM TAIL=-1.25798 | ALFA =11.0 | DELTA =16.0 | VEL = 4.0 |
| MOM Y AXIS=-7.01561 | MOM TAIL=-5.54827 | ALFA =12.0 | DELTA =16.0 | VEL = 4.0 |
| MOM Y AXIS=-8.52972 | MOM TAIL=-9.84207 | ALFA =13.0 | DELTA =16.0 | VEL = 4.0 |
| MOM Y AXIS=-5.18329 | MOM TAIL= 1.60696 | ALFA =11.0 | DELTA =17.0 | VEL = 4.0 |
| MOM Y AXIS=-6.69374 | MOM TAIL=-2.67896 | ALFA =12.0 | DELTA =17.0 | VEL = 4.0 |
| MOM Y AXIS=-8.20674 | MOM TAIL=-6.96926 | ALFA =13.0 | DELTA =17.0 | VEL = 4.0 |
| MOM Y AXIS=-4.87305 | MOM TAIL= 4.46664 | ALFA =11.0 | DELTA =18.0 | VEL = 4.0 |
| MOM Y AXIS=-6.38235 | MOM TAIL= .18597 | ALFA =12.0 | DELTA =18.0 | VEL = 4.0 |
| MOM Y AXIS=-7.89417 | MOM TAIL=-4.09995 | ALFA =13.0 | DELTA =18.0 | VEL = 4.0 |
| MOM Y AXIS=-9.40860 | MOM TAIL=-8.39024 | ALFA =14.0 | DELTA =18.0 | VEL = 4.0 |
| MOM Y AXIS=-6.08169 | MOM TAIL= 3.04565 | ALFA =12.0 | DELTA =19.0 | VEL = 4.0 |
| MOM Y AXIS=-7.59239 | MOM TAIL=-1.23501 | ALFA =13.0 | DELTA =19.0 | VEL = 4.0 |
| MOM Y AXIS=-9.10566 | MOM TAIL=-5.52093 | ALFA =14.0 | DELTA =19.0 | VEL = 4.0 |
| MOM Y AXIS=-7.30169 | MOM TAIL= 1.62467 | ALFA =13.0 | DELTA =20.0 | VEL = 4.0 |
| MOM Y AXIS=-8.81382 | MOM TAIL=-2.65600 | ALFA =14.0 | DELTA =20.0 | VEL = 4.0 |
| MOM Y AXIS=-7.02242 | MOM TAIL= 4.47823 | ALFA =13.0 | DELTA =21.0 | VEL = 4.0 |
| MOM Y AXIS=-8.53340 | MOM TAIL= .20369 | ALFA =14.0 | DELTA =21.0 | VEL = 4.0 |
| MOM Y AXIS=-8.26472 | MOM TAIL= 3.05725 | ALFA =14.0 | DELTA =22.0 | VEL = 4.0 |
| MOM Y AXIS=-9.77719 | MOM TAIL=-1.21730 | ALFA =15.0 | DELTA =22.0 | VEL = 4.0 |
| MOM Y AXIS=-9.51938 | MOM TAIL= 1.63626 | ALFA =15.0 | DELTA =23.0 | VEL = 4.0 |

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|---|---|---|---|---|
| MOM Y AXIS=-9.27391 | MOM TAIL= 4.48283 | ALFA =15.0 | DELTA =24.0 | VEL = 4.0 |
| MOM Y AXIS= 1.78736 | MOM TAIL= 2.94678 | ALFA = 4.0 | DELTA = 7.0 | VEL = 4.0 |
| MOM Y AXIS= .28300 | MOM TAIL=-1.34965 | ALFA = 5.0 | DELTA = 7.0 | VEL = 4.0 |
| MOM Y AXIS=-1.22393 | MOM TAIL=-5.64783 | ALFA = 6.0 | DELTA = 7.0 | VEL = 4.0 |
| MOM Y AXIS=-2.73336 | MOM TAIL=-9.94689 | ALFA = 7.0 | DELTA = 7.0 | VEL = 4.0 |
| MOM Y AXIS= .67289 | MOM TAIL= 1.52580 | ALFA = 5.0 | DELTA = 8.0 | VEL = 4.0 |
| MOM Y AXIS= -.83282 | MOM TAIL=-2.77063 | ALFA = 6.0 | DELTA = 8.0 | VEL = 4.0 |
| MOM Y AXIS=-2.34107 | MOM TAIL=-7.06881 | ALFA = 7.0 | DELTA = 8.0 | VEL = 4.0 |
| MOM Y AXIS= 1.05596 | MOM TAIL= 4.39861 | ALFA = 5.0 | DELTA = 9.0 | VEL = 4.0 |
| MOM Y AXIS= -.44851 | MOM TAIL= .10481 | ALFA = 6.0 | DELTA = 9.0 | VEL = 4.0 |
| MOM Y AXIS=-1.95557 | MOM TAIL=-4.19162 | ALFA = 7.0 | DELTA = 9.0 | VEL = 4.0 |
| MOM Y AXIS=-3.46517 | MOM TAIL=-8.48980 | ALFA = 8.0 | DELTA = 9.0 | VEL = 4.0 |
| MOM Y AXIS= -.07145 | MOM TAIL= 2.97763 | ALFA = 6.0 | DELTA =10.0 | VEL = 4.0 |
| MOM Y AXIS=-1.57731 | MOM TAIL=-1.31617 | ALFA = 7.0 | DELTA =10.0 | VEL = 4.0 |
| MOM Y AXIS=-3.08574 | MOM TAIL=-5.61260 | ALFA = 8.0 | DELTA =10.0 | VEL = 4.0 |
| MOM Y AXIS=-4.59664 | MOM TAIL=-9.91078 | ALFA = 9.0 | DELTA =10.0 | VEL = 4.0 |
| MOM Y AXIS=-1.20671 | MOM TAIL= 1.55664 | ALFA = 7.0 | DELTA =11.0 | VEL = 4.0 |
| MOM Y AXIS=-2.71393 | MOM TAIL=-2.73715 | ALFA = 8.0 | DELTA =11.0 | VEL = 4.0 |
| MOM Y AXIS=-4.22371 | MOM TAIL=-7.03358 | ALFA = 9.0 | DELTA =11.0 | VEL = 4.0 |
| MOM Y AXIS= -.84423 | MOM TAIL= 4.42596 | ALFA = 7.0 | DELTA =12.0 | VEL = 4.0 |
| MOM Y AXIS=-2.35025 | MOM TAIL= .13566 | ALFA = 8.0 | DELTA =12.0 | VEL = 4.0 |
| MOM Y AXIS=-3.85884 | MOM TAIL=-4.15814 | ALFA = 9.0 | DELTA =12.0 | VEL = 4.0 |
| M Y AXIS=-5.36996 | MOM TAIL=-8.45437 | ALFA =10.0 | DELTA =12.0 | VEL = 4.0 |
| OM Y AXIS=-1.99509 | MOM TAIL= 3.00497 | ALFA = 8.0 | DELTA =13.0 | VEL = 4.0 |
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# APPENDIX 5

## ESTIMATED TOWER COSTS VS. HEIGHTS FOR WIND PUMPING SYSTEMS

W. SCHMIDT
GEE/LESO
JULY 1984

# ESTIMATED TOWER COSTS VERSUS HEIGHTS

Note on the correlation of estimated tower costs vs. heights for windmill-waterpumping systems.

It is of interest to correlate the costs for towers vs. height for windmills pumping water so that the initial establishment of system parameters, tower height, rotor dia etc. may be optimized to maximize the cost benefits of the system's water output.

In order to establish some basis for an estimate of tower costs, it was assumed that the manufacturers published weights for existing towers would be representative of the costs. This is felt to be a reasonable estimate as fabricated steel components generally have a total cost of $1.50 to $2.00 US per pound ($3.30 to $4.40 US/kg) provided that no extensive machining work is required.

The weights of towers from Aermotor, Comet and Dempster were tabulated and the weights were divided by the height of the tower to obtain a weight/foot or weight/meter equipment. This was then plotted on a graph, see Figure 1. This weight/foot was then divided by the diameter of the rotor to obtain a specific weight/(foot-diameter), see Figure 1.

## Summary of Results:

The general trend shows that as the diameters increase and heights get higher, there is a slight increase in the specific tower costs. However, for a general size range, the specific costs are fairly consistent. Thus, they may be assumed to be linear over a small range. This will aid in the optimization by allowing one to say that, generally, if one increases the diameter by 10-20% or the height by 10-20%, or vice versa, the costs will increase or decrease 10-20% respectively.

Now, if tower height vs. output is correlated, it is found that for boundary layer roughness giving a corresponding power law coefficient of 1/7, the power increases as (H /Ho) 3/7, approximately the square root of the change in height. If the coefficient is 1/3, then the relationship is linear, a change in height giving a direct change in power input.

Figure 2 shows these relationships graphically.

This means that as costs for the tower are linear with height or diameter, and power is linear with area ($d^2$) but influenced by the power law coefficient, it may be generally said that if n is less than 1/3, it is better to increase power by increasing rotor diameter, and if n is greater than 1/3, by increasing tower height.

This assumes a 50:50 split in rotor to tower costs for the total system. If the tower costs are more than 50% of total costs, the break point on power law coefficient increases and unless the boundary layer is very rough (ie. n greater than 1/2, which is likely unsuited to wind generation in the first place) it is generally more cost effective to increase power output with a larger rotor.

Of course, there are limits to this as rotor diameters greater than 10 m are not normally necessary for wind pumping needs. Standard rules of thumb such as having rotor at least 5 meters above and clear from local obstructions to keep it free from turbulence must also be observed.

TOWER WEIGHT VS. HEIGHT FROM PUBLISHED MANUFACTURERS DATA

(TOTAL WT LBS) / (WT / FT HEIGHT) / (WT / FT. HT. / FT DIA)

## AERMOTOR

| TOWER HEIGHT FT. | ROTOR DIA FT. | | | | |
|---|---|---|---|---|---|
| | 6, 8 | 10 | 12 | 14 | 16 |
| 21' | 390/18.5/2.3 | 590/24.2/2.4 | — | — | — |
| 27' | 490/18.1/2.2 | 639/23.7/2.3 | 780/29/2.4 | 900/33.3/2.37 | 1600/59.3/3.7 |
| 33' | 590/17.8/2.2 | 768/23.3/2.3 | 960/29/2.4 | 1090/33/2.35 | 1915/58/3.6 |
| 40' | 695/17.4/2.2 | 912/22.8/2.3 | 1140/28.5/2.4 | 1300/32.5/2.32 | 2295/57.4/3. |
| 47' | 840/17.8/2.2 | 1075/22.9/2.3 | 1440/30.6/2.5 | — | |

## DEMPSTER

| | | | | | |
|---|---|---|---|---|---|
| 22' | 340/15.4/2.0 | 533/24.2/2.4 | — | — | — |
| 28' | 430/15.3/1.9 | 657/23.5/2.3 | — | — | — |
| 33' | 516/15.6/1.95 | 780/23.6/2.4 | — | — | — |
| 39' | 616/15.7/1.96 | 914/23.5/2.4 | — | — | — |
| 30' | — | — | 935/31.2/2.5 | 1000/33.3/2.3 | — |
| 40' | — | — | 1230/31/2.6 | 1296/32.4/2.3 | — |

## COMET

ROTOR DIA.

| TOWER HEIGHT FT. | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 27 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | 390/19.5/ 3.3 | 650/22.5 3.4 | 550/22.5 2.7 | 700/35 2.9 | 700/35 2.5 | — | — | — | — | — | — | — |
| 25 | 500/20/ 3.3 | 690/27.6 3.4 | 690/27.6 27 | 840/33.6 2.8 | 890/35.6 2.4 | — | — | — | — | — | — | — |
| 30 | 590/19.6/ 3.3 | 800/26.6 3.4 | 800/26.6 26.6 | 1000/33.3 2.8 | 1010/33.6 2.4 | 1620/54 3.4 | 1620/54 2.9 | 2100/70 3.5 | 2100/70 3.2 | — | — | — |
| 35 | 710/20.3/ 3.3 | 950/27.1 3.4 | 950/27 2.7 | 1180/33.7 2.8 | 1230/35 2.5 | 1820/52 3.3 | 1820/52 2.9 | 2400/68.5 3.4 | 2400/68 3.1 | — | — | — |
| 40 | — | 1080/27 3.4 | 1080/27 2.7 | 1360/34 2.8 | 1400/35 2.5 | 2150/54 3.4 | 2150/54 2.9 | 2900/72.5 3.6 | 2900/72 3.2 | 3200/82 3.4 | 3900/100 3.7 | — |
| 44 | — | — | — | — | — | — | — | — | — | 3500/80 3.3 | 4700/106 3.9 | 5600/125 4.2 |
| 45 | — | 1250/27.7 3.4 | 1250/27.7 27 | 1560/34.7 2.9 | 1630/36 2.6 | 2400/53 3.4 | 2400/53 2.9 | 3200/71 3.5 | 3200/71 3.2 | — | — | — |
| 49 | — | — | — | — | — | — | — | — | — | 4000/82 3.4 | 5200/106 3.9 | 6200/126 4.2 |
| 50 | — | 1400/28 3.4 | 1400/28 2.8 | 1750/35 2.9 | 1830/36.6 2.6 | 2900/58 3.6 | 2900/58 3.2 | 3900/78 3.9 | 3900/78 3.5 | — | — | — |
| 54 | — | — | — | — | — | — | — | — | — | 4500/83 3.4 | 6400/118 4.3 | 7400/137 4.4 |
| 55 | — | — | — | 2200/36.4 3.0 | 2300/42 3 | 3200/58 3.6 | 3200/58 3.2 | 4300/78 3.9 | 4300/78 3.5 | — | — | — |
| 59 | — | — | — | — | — | — | — | — | — | 5100/86.4 3.6 | 7000/119 4.4 | 8000/145 4.6 |
| 60 | — | — | — | 2200/36.7 3.0 | 2400/40 2.8 | 3800/63 3.9 | 3800/63 3.5 | 4900/82 4.1 | 4900/82 3.7 | — | — | — |

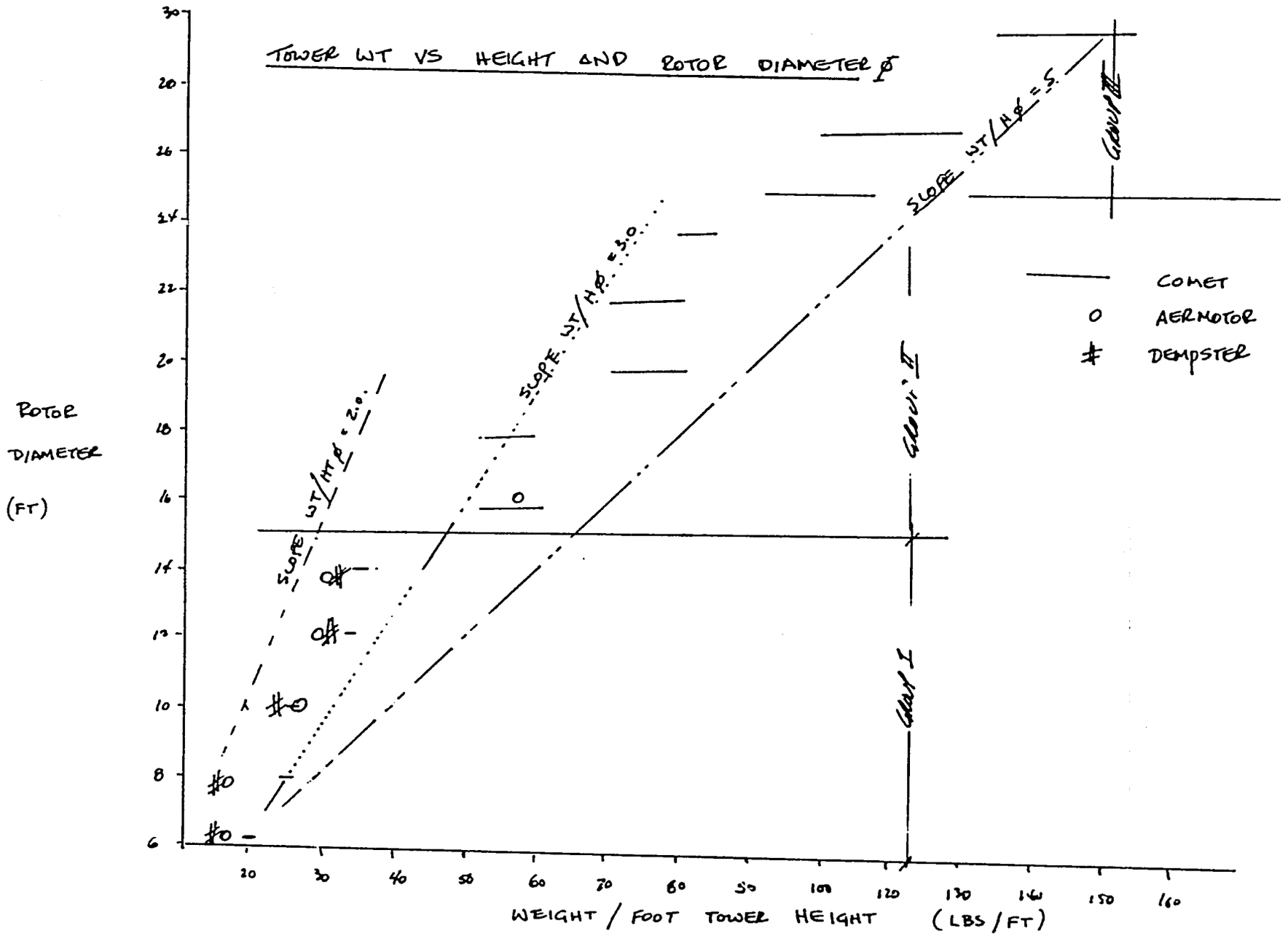


Figure 1: TOWER WT VS HT & ø

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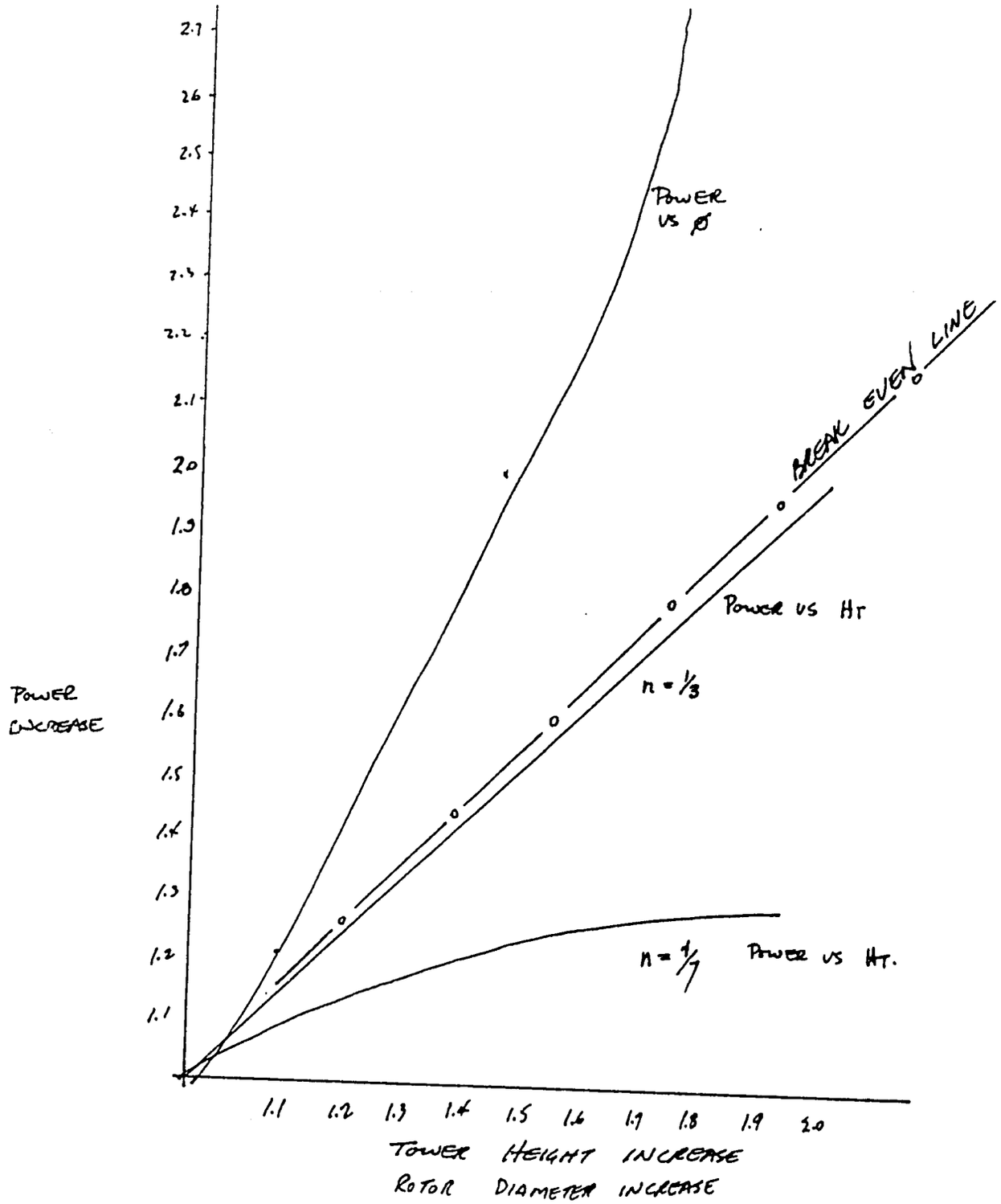


figure 2: POWER INCREASE VS TOWER HEIGHT AT VARIOUS POWER LAW COEFFICIENTS.

# APPENDIX 6

## EVALUATION OF WIND POWERED SYSTEMS PERFORMANCE

W. SCHMIDT
GEE/LESO
AUGUST 1984

# EVALUATION OF WIND POWERED SYSTEM PERFORMANCE

This report has been prepared in response to Scope of Work Item No. 4, review or propose wind energy system monitoring procedures and recommend instrumentation for system performance data acquisition.

There are two sets of circumstances for which it is desirable to evaluate the performance of wind powered systems, in this case those used for water pumping. They are:

1. Overall field performance of demonstration units by monitoring the flow rate of water delivered vs. the wind regime. By measuring these two parameters, it will be possible to evaluate the output of the system and to recommend any changes in design parameters, diameter of rotor, cut-in velocity, cut-out velocity, stroke or matching with the pump etc. which may enhance the overall system characteristics.

2. Performance evaluation of a wind rotor to determine its coefficient of performance vs. tip speed ratio and starting torque. This done by measuring wind speed, (when stable of a period of time greater than the response time of the system) rpm and torque output of the rotor. This will enable a baseline performance curve to be established for a given rotor configuration. This will then permit the assessment of any changes to the rotor configuration to be compared against this baseline.

By evaluating these performance parameters, it is possible to assess the efficiency of a wind powered system, determine the sizing required for given applications, and the predict the overall potential and suitability for delivering water (or power) at a selected site.

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## OVERALL FIELD PERFORMANCE EVALUATION

The overall field performance evaluation is the final assessment of the entire wind powered system. It determines how much water is being delivered at a site (or power being generated) over a period of time, leading to the efficiency and ultimately the cost effectiveness of the system. It is assumed that the wind rotor characteristics are known, or can be evaluated as described later in this discussion. The measuring of the wind regime on a spectral basis (ie. number of hours vs. wind velocity) will give the power input into the system. When this is compared to the effective power output, measured for water pumping systems as the flow vs. the discharge head, this will give the overall system efficiency. In turn, this indicates how suitable the system is for the installed application, if it is large enough, or if the rotor is well matched to the pump and so on.

## TECHNIQUES & INSTRUMENTATION REQUIREMENTS

### Wind Velocity Measurements

The wind velocity measurements, as mentioned, indicate the power input into the system, as well as the suitability of the wind regime for power production, ie. whether or not there is enough power available in the wind to produce significant water outputs at the site.

As the power level developed by the machine is a function of the velocity to the third power, $V^3$, the accuracy of the measurements of the wind speeds and the width of the ranges chosen has the greatest influence on predicting this input into the system. Ideally, one would prefer to measure the entire wind spectrum concentrating on the ranges between the cut-in velocity of the wind system, Vcut-in, around 2 m/s for water pumping, up to 7-10 m/s, beyond which there is little overall energy available when the wind averages are in the 3-5 m/s range (as is typical for the non-coastal near equatorial locations). It is important to use ranges that are small enough, preferably only 1 m/s wide. This will minimize errors introduced when the energy distribution is showed in a measurement range.

This measurement can be done by:

1. wind spectrum analyzer
2. wind speed chart recorder

The wind spectrum analyzer has the advantage that the wind speed-frequency information may be read out directly from the instrument. It has the disadvantage that it does not retain the wind history so that short term cycles, such as diurnal variatons may be analyzed.

The chart recorder has the advantage of presenting a fuller picture of the wind history, and makes it easier to correlate any diurnal variations that may be important.

It also makes it quite easy to determine when periods of steady wind occur during performance evaluation testing.

This system has the disadvantage that the data retrieval can be very time consuming, and subject to large averaging errors or loss of information.

## Location of Anemometers

Anemometers should be located, as general rules of thumb dictate, within 15-20 rotor diameters of the windmill, but not closer than 2-3 diameters. It should also be located at the same height as the rotor hub centre, and not in turbulent wake from rotor or other local obstructions. Further details may be found in anemometer suppliers literature.

## Water Flow Measurement

Water flow measurement in the field can be broken down into two categories:

1. short term
2. long term

The short term measurements may be carried out by timing the delivery into a known volume, ie. a 200 litre drum or 2 $m^3$ steel container. The container should be large enough to take 2-3 minutes to fill to avoid introducing excessive measuring errors, which would occur with shorter filling times.

Short term measurements may also be taken by constructing a weir in the out flow channel, and calculating the flow using handbook valves for the shape of the weir. Attention must be paid to the response time of the weir and channel for the entire range of flows expected. See Attachment No. 1 for further details.

Long term measurements require the use of totalizing flow meters such as those used for metering domestic water consumption. However, more complex recording instrumentation could be used if it is important to keep records for comparison with wind data. Alternatively long term data could be collected by very detailed record keeping of storage reservoir volumes.

The value of these measurements, when used in conjunction with windmill information is to evaluate the performance of the pump, ie. to see if it is leaking etc.

## RPM Measurements

It may also be of use to measure the rotational speed of the windmill rotor. As most rotors turn at less than 100 rpm it should be possible to count this rate while using a watch to give the elapsed time. Counting should be done for approximate 1-1½ minutes to minimize interval errors. When the rpm vs. wind speed for the rotor is determined while the wind is constant and the rotor not indergoing a transient response, a good estimate of rotor tip speed may be made. This will assist in verifying the matching of the rotor to the pump.

## Preparation for Evaluation

Prior to visiting the site for field evaluation studies, the predicted performance charts for the windmill rotor and pump combination should be known, charted and on hand. This will make it possible to make field changes if necessary to correct any obvious mismatching in the system that may have inadvertently occurred.

It will also be necessary to know the design pumping head for the system, pumping losses and be able to measure the static head difference while in the field.

## Measurement of Field Performance

Using the instrumentation prescribed, the data is collected in the field and preliminary evaluations made. In this way field modifications can be made and evaluated immediately. The field tests may be quite time consuming if the winds are irregular.

## INTERPRETATION OF RESULTS FROM FIELD PERFORMANCE MEASUREMENTS

| Results | Other Measurements | Causes |
|---|---|---|
| 1. windmill not starting | - wind speed Vcut-in | 1. pump too large<br>2. pump jammed or broken<br>3. transmission jammed<br>4. tail locked out<br>5. blade angles off |
| | - low wind speed | 1. pump dia or stroke too large<br>2. poor wind regime |
| 2. windmill running too fast, high rpm | - flow okay | 1. head lower than expected<br>2. blade angles too shallow (will be hard starting) |
| | - low flow | 1. pump leaking or unhooked<br>2. well dry |
| | - wind high | 1. tail vane not furling |
| 3. windmill running okay | - performance as charted | 1. good system in operation (evaluate total cost effectiveness) |

Other projects carrying out field performance evaluations are BHEL in Kenya with the Kijito system and VITA with the V-8B system in Thailand. (Ref. 1)

## EVALUATION OF ROTOR CP AND STARTING TORQUE

The measurements required for evaluating the performance of a rotor vs. rpm are best carried out under controlled conditions. Even well instrumented field trials, under atmospheric wind conditions are susceptible to the measurement erors and uncertainties. The variability of the wind speed and its power input as a cubic function, $V^3$, the dynamic yawing of the wind rotor and the response characteristic of the rotor will all affect the accuracy of output data. However, with a great deal of patience and ingenuity these errors can be kept to a minimum.

One technique that may be useful is to arrange to carry out tests with artificially induced "wind". This may be done by mounting the test rotor on a vehicle or river barge, locating it out of any local turbulence from the vehicle itself. During periods of wind calm, the vehicle may be motored at the desired speed held constant while rpm and torque measurements are made.

When the natural wind is to be used, patience is the key work. The evaluation reading of rpm and torque are only valid when the wind has been constant, ie. ± 10% for 1½-2 minutes, and then does not drop off until at least the same amount of time has elapsed after the reading is taken. Even then, error ranges may be calculated and shown to be in the 20% range.

It is also time consuming to evaluate the full range of tip speed ratios, as for lower values, any changes in wind speed will cause drastic changes in rpm or even cause the rotor to stop. Then the whole system will have to be reset and prepared for another long steady wind.

While some research organizations such as N.A. Rockwell have been able to evaluate the performance curves for rotors on a dynamic basis using extremely sophisticated and expensive computerized instrumentation, this level of evaluation will not be reliable or cost effective under present conditions at LESO.

It is always important to keep in mind that the optimization of the rotor configuration through extensive evaluation testing is not the only way to increase windmill output. Optimizations of blade angles, shapes etc. may improve a rotors output by ± 10%. However, a 50% net increase in power may be gained for example by changing the diameter of a 4 m Ø rotor to 5 m Ø, without any other configuration modifications.

## INSTRUMENTATION FOR PERFORMANCE EVALUATION

### Wind Measurement

A chart recorder is essential to give the record of wind history, and to identify when the wind speed is constant enough to take rpm and torque readings. The chart recorder may be backed up by a real time data logger for easier data reduction. The location of the anemometer is important, as previously discussed.

## RPM Measurements

Rotor speed may be timed manually as discussed in the previous section, or recorded by a chart recorder or data logger using a suitable rpm sensor. A straight forward technique which could be used would be to drive an anemometer head from the rotor shaft and use a similar instrument chain as for wind speed readings.

## Torque Measurements

Torque measurements are taken as the reaction force of a loaded rotor shaft against a moment arm. The key to good accuracy is to absorb the power smoothly from the shaft and to keep the torque arm length constant.

Attachment No. 2 shows a standard prony brake arrangement, and similar devices may be made up from suitable automotive braking components. Force readings may be taken as the deflection of a known spring or torsion bar or from a fully instrumented strain gauge, depending on accuracy of readings desired.

## Angle of Rotor to Wind Measurements

The angle of the rotor to the wind must be monitored so the output values may be corrected for any velocity reductions if necessary.

## Results

The data from the measurements can be analyzed and presented in the standard CP or CT vs tip speed ratio graphs. Comparisons between rotors are then easily carried out. These techniques for performance evaluation have been used successfully by most research organizations, and are the source of all empirical performance figures for wind rotors.

## Attachments

1. Standard Handbook Weir Data for Water Measurements
2. Standard Handbook Data for Power Measurement

## References

1. Performance Testing of a Windmill - Pump System
W. Nijhoff, Renewable Energy Review Journal, Vol. 6, No. 1, Jan. 1984.

Attachment No. 1 - Standard Handbook Weir Data for Water Measurement

## ASME WEIRS

**Definitions** A weir is a dam over which liquids are forced to flow. Weirs are used to measure the flow of liquids in open channels or in conduits which do not flow full; i.e., there is a free liquid surface. Weirs are almost exclusively used for measuring water flow, although small ones have been used for metering other liquids. Weirs are classified according to their notch or opening as follows: (1) **rectangular notch** (original form); (2) V or **triangular notch**; (3) **trapezoidal notch**, which when designed with end slopes one horizontal to four vertical is called the **Cipolletti weir**; (4) the **hyperbolic weir** designed to give a constant coefficient of discharge; and (5) the **parabolic weir** designed to give a linear relationship of head to flow. As shown in Fig. 30, the top of the weir is the **crest** and the distance from the liquid surface to the crest $b$ is called the **head**.

The sheet of liquid flowing over the weir crest is called the **nappe**. When the nappe falls downstream of the weir plate, it is said to be free, or **aerated**. When the width of the approach channel $L_c$ is greater than the crest length $L_w$, the nappe will contract so that it will have a minimum width less than the crest length. For this reason, the weir is known as a **contracted weir**. For the special case where $L_w = L_c$, the contractions do not take place, and such weirs are known as **suppressed weirs**.

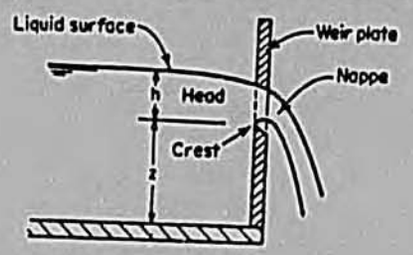


Fig. 30 Notation for weir study.

**Parameters** The forces acting on a liquid flowing over a weir are inertia, viscous, surface tension, and gravity. If the weir head produced by the flow is $b$, the characteristic length of the weir is $L_w$, and the channel width is $L_c$, either similarity or dimensional analysis leads to $f(F, W, R, L_w/L_c) = 0$, which may be written as $V = K\sqrt{2gb}$, where $K$ is the **weir coefficient** and $K = f(W, R, L_w/L_c)$. Since the weir has been almost exclusively used for metering water flow over limited temperature ranges, the effects of surface tension and viscosity have not been adequately established by experiment.

**Caution** The numerical values of coefficients for weirs are based on experimental data obtained from calibration of weirs with long approaches of straight channels. Head measurement should be made at a distance at least three to four times the expected maximum head $b$. Screens and baffles should be used as necessary to ensure steady uniform flow without waves or local eddy currents. The approach channel should be relatively wide and deep.

**Rectangular Weirs** Figure 31 shows a rectangular weir whose crest width is $L_w$. The volumetric flow rate may be computed from the continuity equation: $Q = AV = (L_w b)(K\sqrt{2gb}) = KL_w\sqrt{2g}\, b^{3/2}$. The ASME "Fluid Meters"

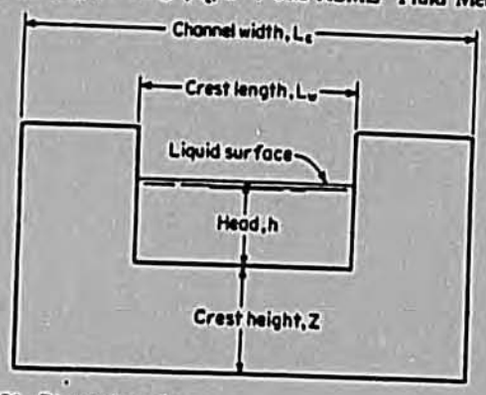


Fig. 31 Rectangular weir.

report recommends the following equation for rectangular weirs: $Q = (2/3)CL_a\sqrt{2g}\, b_a^{3/2}$, where $C$ is the **coefficient of discharge** $C = f(L_w/L_c, b/Z)$, $L_a$ is the adjusted crest length $L_a = L_w + \Delta L$, and $b_a$ is the adjusted weir head $b_a = b + 0.003$ ft. Values of $C$ and $\Delta L$ may be obtained from Table 15. To avoid the possibility that the liquid drag along the sides of the channel will affect side contractions, $L_c - L_w$ should be at least $4b$. The minimum crest length should be 0.5 ft to prevent mutual interference of the end contractions. The minimum head for free flow of the nappe should be 0.1 ft.

**Example.** Water flows in a channel whose width is 40 ft. At the end of the channel is a rectangular weir whose crest width is 10 ft and whose crest height is 4 ft. The water flows over the weir at a height of 3 ft above the crest of the weir. Estimate the volumetric flow rate. $L_w/L_c = 10/40 = 0.25$, $b/Z = 3/4 = 0.75$, from Table 15 (interpolated), $C = 0.589$, $\Delta L = 0.008$, $L_a = L_w + \Delta L = 10 + 0.008 = 10.008$ ft, $b_a = b + 0.003 = 3 + 0.003 = 3.003$ ft, $Q = (2/3)\, CL_a\sqrt{2g}\, b^{3/2}$, $Q = (2/3)(0.589)(10.008)(2 \times 32.17)^{1/2}(3.003)^{3/2}$, $Q = 164.0$ ft³/s (4.644 m³/s).

**Table 15. Values of C and ΔL for Use in Rectangular-Weir Equation**

| h/Z | Crest length/channel width = $L_w/L_c$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0 | 0.2 | 0.4 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| | Coefficient of discharge $C$ | | | | | | | |
| 0 | 0.587 | 0.589 | 0.591 | 0.593 | 0.595 | 0.597 | 0.599 | 0.603 |
| 0.5 | 0.586 | 0.588 | 0.594 | 0.602 | 0.610 | 0.620 | 0.631 | 0.640 |
| 1.0 | 0.586 | 0.587 | 0.597 | 0.611 | 0.625 | 0.642 | 0.663 | 0.676 |
| 1.5 | 0.584 | 0.586 | 0.600 | 0.620 | 0.640 | 0.664 | 0.695 | 0.715 |
| 2.0 | 0.583 | 0.586 | 0.603 | 0.629 | 0.655 | 0.687 | 0.726 | 0.753 |
| 2.5 | 0.582 | 0.585 | 0.608 | 0.637 | 0.671 | 0.710 | 0.760 | 0.790 |
| 3.0 | 0.580 | 0.584 | 0.610 | 0.647 | 0.687 | 0.733 | 0.793 | 0.827 |
| | Adjustment for crest length $\Delta L$, ft | | | | | | | |
| Any | 0.007 | 0.008 | 0.009 | 0.012 | 0.013 | 0.014 | 0.013 | −0.005 |

Compiled from data given in "Fluid Meters," ASME, 1971.

**Triangular Weirs** Figure 12 shows a triangular weir whose notch angle is $\theta$. The volumetric flow rate may be computed from the continuity equation $Q = AV = (b^2 \tan \theta/2)(K\sqrt{2gb}) = K \tan(\theta/2)\sqrt{2g}\, b^{5/2}$. The ASME "Fluid Meters" report recommends the following for triangular weirs: $Q = (8/15)\, C \tan(\theta/2)\sqrt{2g}\,(b + \Delta b)^{5/2}$, where $C$ is the coefficient of discharge $C = f(\theta)$ and $\Delta b$ is the correction for head/crest ratio $\Delta b = f(\theta)$. Values of $C$ and $\Delta b$ may be obtained from Table 16.

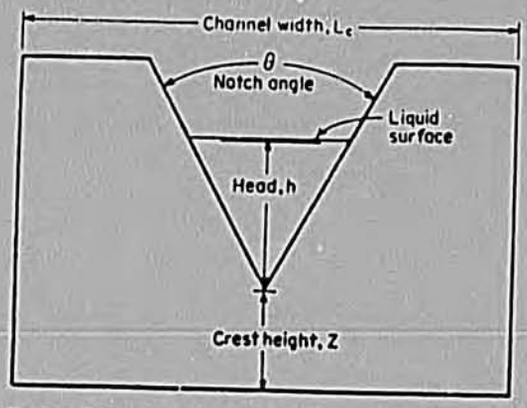


Fig. 32 Triangular weir.

EXAMPLE. It is desired to maintain a flow of 167 ft³/s in an open channel whose width is 20 ft at a height of 7 ft by locating a triangular weir at the end of the channel. The weir has a crest height of 2 ft. What notch angle is required to maintain these conditions? A trial-and-error solution is required. For the first trial assume $\theta = 60°$ (mean value 20 to 100°); then $C = 0.576$ and $\Delta b = 0.004$.

$$b + Z = 7 = b + 2 \therefore b = 5$$

$$Q = (8/15)\, C \tan(\theta/2)\sqrt{2g}\,(b + \Delta b)^{5/2}$$

$167 = (8/15)(0.576) \tan(\theta/2)\sqrt{2 \times 32.17}\,(5 + 0.004)^{5/2}$, $\tan^{-1}(\theta/2) = 1.20993$, $\theta = 100°51'$.

Second trial, using $\theta = 100$, $C = 0.581$, $\Delta b = 0.003$, $167 = (8/15)(0.581) \tan(\theta/2)\sqrt{2 \times 32.17}\,(5 + 0.003)^{5/2}$, $\tan^{-1}(\theta/2) = 1.20012$, $\theta = 100°39'$ (close check).

**Table 16. Values of $C$ and $\Delta h$ for Use in Triangular-Weir Equation**

| Item | Weir notch angle $\theta$, deg | | | | | | |
|---|---|---|---|---|---|---|---|
| | 20 | 30 | 45 | 60 | 75 | 90 | 100 |
| $C$ | 0.592 | 0.586 | 0.580 | 0.576 | 0.576 | 0.579 | 0.581 |
| $\Delta b$, ft | 0.010 | 0.007 | 0.005 | 0.004 | 0.003 | 0.003 | 0.003 |

Compiled from data given in "Fluid Meters," ASME, 1971.

## Attachment No. 2 - Standard Handbook Data for Power Measurements

### POWER MEASUREMENT

Power is defined as the rate of doing work. Common units are the horsepower and the kilowatt: 1 hp = 33,000 ft·lb/min = 0.746 kW. The power input to a rotating machine in hp (W) = $2\pi nT/k$, where $n$ = r/min of the shaft where the torque $T$ is measured in lbf·ft (N·m), and $k$ = 33,000 ft·lbf/hp·min [60 N·m/(W)(min)]. The same equation applies to the power output of an engine or motor, where $n$ and $T$ refer to the output shaft. Mechanical power-measuring devices (**dynamometers**) are of two types: (1) those absorbing the power and dissipating it as heat and (2) those transmitting the measured power. As indicated by the above equation, two measurements are involved: shaft speed and torque. The speed is measured directly by means of a tachometer. Torque is usually measured by balancing against weights applied to a fixed lever arm; however, other force measuring methods are also used. In the **transmission dynamometer**, the torque is measured by means of strain-gage elements bonded to the transmission shaft.

There are several kinds of **absorption dynamometers**. The **Prony brake** applies a friction load to the output shaft by means of wood blocks, flexible band, or other friction surface. The **fan brake** absorbs power by "fan" action of rotating plates on surrounding air. The **water brake** acts as an inefficient centrifugal pump to convert mechanical energy into heat. The pump casing is mounted on antifriction bearings so that the developed turning moment can be measured. In the **magnetic-drag** or **eddy-current brake**, rotation of a metal disk in a magnetic field induces eddy currents in the disk which dissipate as heat. The field assembly is mounted in bearings in order to measure the torque.

One type of **Prony brake** is illustrated in Fig. 35. The torque developed is given by $L(W - W_0)$, where $L$ is the length of the brake arm, ft; $W$ and $W_0$ are the scale loads with the brake

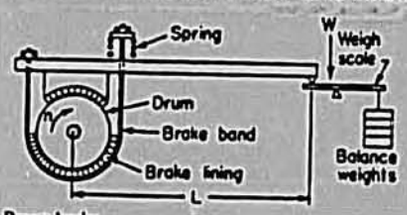


Fig. 35 Prony brake.

operating and with the brake free, respectively. The brake horsepower then equals $2\pi nL(W - W_0)/33{,}000$, where $n$ is shaft speed, r/min.

In addition to eddy-current brakes, **electric dynamometers** include calibrated generators and motors and cradle-mounted generators and motors. In calibrated machines, the efficiency is determined over a range of operating conditions and plotted. Mechanical power measurements can then be made by measuring the electrical power input (or output) to the machine. In the electric-cradle dynamometer, the motor or generator stator is mounted in trunnion bearings so that the torque can be measured by suitable scales.

# APPENDIX 7

## EXISTING PROGRAMS FOR APPLE COMPUTER ON HAND AT LESO, JUNE 1984

LESO/GEE
PROGRAMS ON-HAND

```
JLIST

100  REM  INTEGRATION OF MULTIBLADE
105  REM  WINDMILL MODEL AND WEIBULL
110  REM  WIND MODEL TO GET OVERALL
115  REM  WATER OUTPUT
120  REM
130  REM
200  REM  PROMPT USER,READ DATA
201  REM
202  HOME
205  PRINT "INTEGRATION OF MULTIBLADE WINDMILL WITH WEIBULL WIND DISTRIBU
     TION"
206  PRINT
207  PRINT
210  PRINT "INPUT ROTOR DIAMETER IN METERS": INPUT RDIAM
212  PRINT "INPUT WINDMILL GEAR RATIO": INPUT GBR
213  PRINT "INPUT TOTAL PUMPING HEAD IN METERS": INPUT HEAD
214  PRINT "INPUT CYLINDER DIAMETER IN METERS": INPUT CDIAM
215  PRINT "INPUT WINDMILL STROKE IN METERS": INPUT STROKE
216  PRINT "INPUT WIND PUMP RATED SPEED IN M/S": INPUT VR
217  PRINT "INPUT PUMP AND LINKAGE MECH EFFICIENCY": INPUT NPT
218  PRINT "INPUT AIR DENSITY IN KG/M3": INPUT RHOAIR
219  PRINT "INPUT WINDMILL SHUTDOWN SPEED IN M/S": INPUT VF
220  PRINT "INPUT INTEGRATION INTERVAL IN M/S": INPUT DV
222  PRINT "INPUT MEAN VELOCITY IN M/S": INPUT VBAR
224  PRINT "INPUT WEIBULL SHAPE FACTOR": INPUT K
226  PRINT "INPUT TIME PERIOD(IN HOURS) OVER WHICH THE INTEGRAL IS TO BE
     CALCULATED": INPUT PERIOD
230  PRINT "INPUT THE MAXIMUM ALLOWED PUMP STROKE IN METERS": INPUT MAXST
     R
231  REM
232  REM
233  REM =TO CHANGE WINDMILLS CHANGE 313,330,336
239  REM
240  REM
241  DIM TSR(500),PRPM(500),WF(500),FLOW(500),HOURS(500),PV(500),PSTROKE(
     500),VPS(500),QA(500)
242  REM
249  REM  INITIALIZE
250 Y% = (1 / DV) * VR + 1
251 Z% = (1 / DV) * VF + 2
259  REM
267  REM
268  GOSUB 1000
269  REM
270  REM
271  PRINT "DO YOU WANT A FULL OUTPUT(INPUT 1) OR JUST THE FINAL WATER OU
     TPUT(INPUT 0)": INPUT SIGN
280  IF SIGN = 1 THEN  PRINT "V"; TAB( 15);"PUMP STROKE"; TAB( 30);"VOL/S
     TROKE"
299  REM  SET CONSTANTS
300 WQA = (STROKE * 1000.0 * 9.81 * HEAD * (CDIAM ^ 2)) / (8.0 * NPT * GB
     R)
305 QP = WQA * 3.141592654
310 K1 = 2 / (RHOAIR * 3.141592654 * ((RDIAM / 2) ^ 3))
312 NVP = 0.9
313 CQD = 0.333
```

```
316 V = 0.0
318  FOR I = 1 TO Z%
319 PSTROKE(I) = STROKE * ((V / VD) ^ 2)
320  IF PSTROKE(I) > MAXSTR THEN PSTROKE(I) = MAXSTR
321 QA(I) = (PSTROKE(I) * 1000.0 * 9.81 * HEAD * (CDIAM ^ 2)) / (8.0 * NF
     T * GBR)
322 VPS(I) = 3.1415926 * (CDIAM ^ 2) * PSTROKE(I) * 250 * NVP
323  IF SIGN = 1 THEN  PRINT V; TAB( 15);PSTROKE(I); TAB( 30);VPS(I)
324 V = V + DV
325  NEXT I
326 TSR(1) = 0.0:PRPM(1) = 0.0:WF(1) = 0.0
327 V = DV
328  FOR I = 2 TO Y%
330 TSR(I) = 2 - ((3.003003 * K1 * QA(I)) / (V ^ 2))
335  IF TSR(I) < 0.0 THEN TSR(I) = 0.0
336  IF TSR(I) > 2 THEN TSR(I) = 2
340 PRPM(I) = TSR(I) * K2 * V
345 WF(I) = PRPM(I) * VPS(I) * 60.0
350 V = V + DV
351 LT = TSR(I)
352 LP = PRPM(I)
353 LW = WF(I)
355  NEXT I
356  FOR I = Y% TO Z% - 2
357 TSR(I) = LT:PRPM(I) = LP:WF(I) = L
358  NEXT I
359 TSR(Z%) = 0.0:TSR(Z% - 1) = 0.0
360 PRPM(Z%) = 0.0:PRPM(Z% - 1) = 0.0
361 WF(Z%) = 0.0:WF(Z% - 1) = 0.0
362  REM
391  REM
392  REM
410  REM
415  REM
420 TFLOW = 0.0:V = 0.0
425  FOR I = 1 TO Z%
430 FLOW(I) = WF(I) * HOURS(I) / 1000.0
435 TFLOW = TFLOW + FLOW(I)
440 V = V + DV
445  NEXT I
446  REM
447  REM
448  IF SIGN = 0 THEN  GOTO 470
451  PRINT
452  PRINT "V(M/S)"; TAB( 15)"STRKS/MIN"; TAB( 30)"TSR"; TAB( 45)"LTRS/HR
     "; TAB( 60)"HRS OF WIND"; TAB( 75)"OUTPUT M3"
453  PRINT
454 V = 0.0
455  FOR I = 1 TO Z% - 1
460  PRINT V; TAB( 15)PRPM(I); TAB( 30)TSR(I); TAB( 45)WF(I); TAB( 60)HOU
     RS(I); TAB( 75)FLOW(I)
462 V = V + DV
465  NEXT I
466  PRINT ">"VF; TAB( 15)PRPM(Z%); TAB( 30)TSR(Z%); TAB( 45)WF(Z%); TAB(
     60)HOURS(Z%); TAB( 75)FLOW(Z%)
469  PRINT
470  PRINT
471  PRINT "TOTAL WATER OUTPUT OVER ";PERIOD;" HOURS = ";TFLOW;" CUBIC ME
     TERS"
472  REM
473  REM
481  REM
482  REM
483  PRINT
484  PRINT
```

```
500  PRINT "IF YOU WANT TO RUN AGAIN"
501  PRINT "YOU CAN RESET ANY NUMBER OF"
502  PRINT "VARIABLES YOU WANT FROM THIS LIST:"
505  PRINT  TAB( 10)"1) ROTOR DIAMETER "
510  PRINT  TAB( 10)"2) GEAR RATIO"
515  PRINT  TAB( 10)"3) TOTAL PUMPING HEAD"
520  PRINT  TAB( 10)"4) CYLINDER DIAMETER"
525  PRINT  TAB( 10)"5) STROKE"
530  PRINT  TAB( 10)"6) WINDMILL RATED SPEED"
535  PRINT  TAB( 10)"7) MECH. PUMP EFFICIENCY"
540  PRINT  TAB( 10)"8) AIR DENSITY"
545  PRINT  TAB( 10)"9) WINDMILL SHUTDOWN SPEED"
550  PRINT  TAB( 10)"10) INTEGRATION INTERVAL"
555  PRINT  TAB( 10)"11) MEAN WIND VELOCITY"
560  PRINT  TAB( 10)"12) WEIBULL SHAPE FACTOR"
565  PRINT  TAB( 10)"13) INTEGRAL TIME PERIOD"
567  PRINT  TAB( 10)"14) MAX PUMP STROKE"
570  PRINT "IF YOU WISH TO QUIT TYPE 15,IF NOT,TYPE IN HOW MANY VARIABLES
      YOU WANT TO CHANGE"
575  INPUT CODE
580  IF CODE >  = 15 THEN  GOTO 900
585  FOR I = 1 TO CODE
590  PRINT "INPUT THE NUMBER ASSOCIATED WITH THE VARIABLE TO BE CHANGED":
      INPUT CC
595  IF CC = 1 THEN  GOTO 615
596  IF CC = 2 THEN  GOTO 616
597  IF CC = 3 THEN  GOTO 617
598  IF CC = 4 THEN  GOTO 618
599  IF CC = 5 THEN  GOTO 619
600  IF CC = 6 THEN  GOTO 620
601  IF CC = 7 THEN  GOTO 621
602  IF CC = 8 THEN  GOTO 622
603  IF CC = 9 THEN  GOTO 623
604  IF CC = 10 THEN  GOTO 624
605  IF CC = 11 THEN  GOTO 625
606  IF CC = 12 THEN  GOTO 626
607  IF CC = 13 THEN  GOTO 627
608  IF CC = 14 THEN  GOTO 628
615  PRINT "ROTOR DIAMETER=": INPUT RDIAM: GOTO 630
616  PRINT "GEAR RATIO=": INPUT GBR: GOTO 630
617  PRINT "TOTAL PUMPING HEAD=": INPUT HEAD: GOTO 630
618  PRINT "CYLINDER DIAMETER=": INPUT CDIAM: GOTO 630
619  PRINT "STROKE=": INPUT STROKE: GOTO 630
620  PRINT "WINDPUMP RATED SPEED=": INPUT VR: GOTO 630
621  PRINT "MECH PUMP EFFICIENCY=": INPUT NPT: GOTO 630
622  PRINT "AIR DENSITY=": INPUT RHOAIR: GOTO 630
623  PRINT "WINDMILL SHUTDOWN SPEED=": INPUT VF: GOTO 630
624  PRINT "INTEGRATION INTERVAL=": INPUT DV: GOTO 630
625  PRINT "MEAN WIND VELOCITY=": INPUT VBAR: GOTO 630
626  PRINT "WEIBULL SHAPE FACTOR=": INPUT K: GOTO 630
627  PRINT "INTEGRATION PERIOD=": INPUT PERIOD
628  PRINT "MAX PUMP STROKE = ": INPUT MAXSTR
630  NEXT I
635  GOTO 250
900  END
1000  REM  WEIBULL SUBROUTINE
  30  REM
1082 K4 = (1 + 1 / K)
1085 GK = 3.0867111 - 4.42886996 * K4 + 3.33375693 * (K4 ^ 2) - 1.1629478
     4 * (K4 ^ 3) + 0.171231025 * (K4 ^ 4)
1090 C = VBAR / GK
1095 V = DV
1100 TPV = 0 0 TPV
```

```
1115 PV(I) = ( EXP ( - (((V - D2) / C) ^ K))) - ( EXP ( - (((V + D2) / C)
     ^ K)))
1120 TPV = TPV + PV(I)
1125 HOURS(I) = PERIOD * PV(I)
1130 THR = THR + HOURS(I)
 135 V = V + DV
1140  NEXT I
1145 PV(1) = 1.0 - ( EXP ( - ((D2 / C) ^ K))
1150 PV(T%) =  EXP ( - (((V - D2) / C) ^ K))
1155 TPV = TPV + PV(1) + PV(T%)
1160 HOURS(1) = PERIOD * PV(1)
1165 HOURS(T%) = PERIOD * PV(T%)
1170 THR = THR + HOURS(1) + HOURS(T%)
1175  RETURN
```

```
]LIST

1999  REM   HEIGHT CORRECTION BY JUSTUS
2000  PRINT "INPUT UNITS"
2005  PRINT "      1)METERS/SEC"
2010  PRINT "      2)MILES/HR"
2015  PRINT "      3)KM/HR"
2020  INPUT VUNIT
2025  REM
2030  PRINT "INPUT OBSERVED VELOCITY": INPUT VA
2035  IF VUNIT = 2 THEN VA = VA / 2.23694
2040  IF VUNIT = 3 THEN VA = VA / 3.6
2045  REM
2050  PRINT "INPUT MEASUREMENT HEIGHT(M)": INPUT A
2060 ALPHA = (0.37 - 0.088 * ( LOG (VA))) / (1 - (0.088 * ( LOG (A / 10)))
     ))
2065  PRINT "INPUT DESIRED HEIGHT": INPUT X
2070 VX = VA * ((X / A) ^ ALPHA)
2071  IF VUNIT = 2 THEN VX = VX * 2.23694
2072  IF VUNIT = 3 THEN VX = VX * 3.6
2075  PRINT "V AT DESIRED HEIGHT =  ";VX
2080  PRINT "ALPHA=  ";ALPHA
2085  END
```

```
LIST

100  REM  PROGRAM GENERATES DAY
105  REM  BY DAY WIND SPEED DATA
110  REM  FROM A MONTHLY MEAN
115  REM  AND SIGMA OF DAILY
120  REM  MEANS AND A RANDOM
125  REM  NUMBER ROUTINE
130  REM
135  REM   SAVES DATA INTO DISK
140  REM  FILE FOR USE IN STORAGE
145  REM  PROGRAM
150  REM
155  REM  ASSUMES SIGMA OF DAILY
160  REM  MEANS = CC*MONTHLY MEAN
165  REM
170  REM
180  REM
205  DIM GS(30),VDAY(30)
210  REM
215  REM
220  REM
222  HOME
225  PRINT "ENTER ANY INTEGER(1-10), "
226  PRINT "AS A RANDOM NUMBER SEED "
227  INPUT K
230  PRINT "INPUT MONTHLY MEAN WIND SPEED , IN M/S ": INPUT VM
263  REM
264  REM
265  REM  GENERATE PSEUDO WIND DATA
266  REM
267 CC = 0.45
268 SD = CC * VM
270  REM
272 DT = 0.0:DS = 0.0
275  FOR I = 1 TO 30
285 RK =  RND (K)
290 R1 =  RND (1)
295 GS(I) = ( SQR ( - 2.0 *  LOG (RK))) *  COS (2 * 3.141592654 * R1
305 VDAY(I) = VM + (GS(I) * SD)
306  IF VDAY(I) < 0.0 THEN VDAY(I) = 0.0
307 DT = DT + VDAY(I)
308 DS = DS + (VDAY(I) * VDAY(I))
315  NEXT I
316  REM
317  REM
318 DT = DT / 30
320 SC = ( SQR ((DS - (30 * DT * DT)) / (29)))
325  REM
330  REM
335 X = VM - DT
    XXX = 0.05
339  IF X < 0 THEN X =  - 1 * X
341  IF X > XXX THEN 265
365  REM
366  REM
369  REM  PRINT OUT RESULTS
370  REM
375  REM
```

```
390  PRINT
395  FOR I = 1 TO 30
400  PRINT I,VDAY(I)
405  NEXT I
406  PRINT
407  PRINT "INPUT MEAN = ";VM; TAB( 25);"CALCULATED MEAN = ";DT
408  PRINT "INPUT SIGMA D = ";SD; TAB( 25);"CALCULATED SIGMA D = ";SC
410  REM
420  REM
425  REM . FILE SET UP IN APPLE
427  REM  PLOT FORMAT
430  REM
440 D$ =  CHR$ (4)
442  PRINT "DO YOU WANT TO SAVE THIS INTO A DATA FILE(Y/N) ?": INPUT S$
444  IF S$ = "N" THEN 600
450  PRINT "INPUT NAME OF DATA FILE ": INPUT NAME$
455  PRINT "INSERT PROPER DISKETTE IN D1"
457  PRINT "READY (Y/N) ?"
458  INPUT R$
459  IF R$ = "N" THEN 455
460  REM
462  PRINT D$;"OPEN ";NAME$
464  PRINT D$;"DELETE ";NAME$
465  PRINT D$;"OPEN ";NAME$
466  PRINT D$;"WRITE ";NAME$
467  PRINT 30
468  PRINT 0
470  FOR I = 1 TO 30
475  PRINT I
476  PRINT VDAY(I)
480  NEXT I
0    PRINT D$;"CLOSE ";NAME$
600  PRINT "DO YOU WANT TO RUN AGAIN(Y/N) ?": INPUT C$
610  IF C$ = "Y" THEN 222
790  END
```

# APPENDIX 8

LISTING OF FORTRAN AND WORDSTAR PROGRAMS

PREPARED FOR GEE DURING CONSULTANCY

JUNE 26 - AUGUST 2, 1984

W. SCHMIL
GEE/LESC
JULY 198

# WORDSTAR FILE - NAMES-

This file describes all the files that have been entered on dis
by W. Schmidt during the wind consultancy June 18 - August 13

Sched4 This is the schedule of activities for week no. 4 and a summary of achievements during week no. 3.

Sched5 This is the schedule of activities for week no. 5 and a summary of the achievements during week no. 4.

Sched6 This is the schedule of activities for week no. 6 and a summary of achievements during week no. 5.

Sched7 This is the summary of achievements during week no. 6. (end of contract w schmidt)

STUD This is the Wordstar file containing the comparative analysis of various wind systems prepared for the GEE to present to the director. Its intention is to justify the present direction in wind mill develop-ments.

WEIB This is the Wordstar documentation on the fortran program developed using standard Weibull function to predict wind velocity vs. hourly probabilities for various average V. It also predicts the estimated pumping or electrical outputs that may be expected for that wind regime.
The fortran program is GROG.FOR for the pumping (in strokes for a given dia and tipspeed ratio) and GGELEC.FOR for the electrical outputs (in kilowatt-hours)

KIE This is a Wordstar file which summarizes the findings by the Kenya Industrial Estates Renewable Energy Program during its development of the 12PU500 windmill which may be applicable to the development work being done on LESO I & LESO II wind machines here in Mali.

tt2 This is the Wordstar documentation on the mathematical and computer model for the hinged tail design windmill. The fortran programs are TAIL.FOR. and TSWD.FOR.

FIELD This is the Wordstar file containing the documentation for the field and performance assessment report.

NAMES This is the Wordstar file that lists all the files prepared for the GEE by w. schmidt You are reading output from NAMES

REF This is a wordstar file listing recommended reference material that should be added to G.E.E.'s resource information.

GROG.FOR This is the fortran program to evaluate the Weibull function and tabulate the no. of strokes pumped in a year

GGELEC.FOR This is the fortran program which evaluates the Weibull function and calculates the no. of kilowatt hours that are available at the site during a year.

TAIL.FOR This is the fortran program which calculates the solution to a hinged tail windmill by iterating the two unknown angles. This program contains the input data for LESO II.

TSWD.FOR This is the fortran program which calculates the solution to a hinged tail windmill by iterating the two unknown angles. This program contains the input data for SWD 2740 rotor and provision to change data to that representing an offset rotor model.

ROTOR.FOR This is a fortran programme to estimate the performance of a fan style windmill rotor using curved plate blades. This programme is to be used only for comparative purposes as the model makes several assumptions and neglects several losses. This means that the absolute torque and power levels are not calculated, but the values derived are indications of the efficiencies and potentials for the rotors being compared. This programme uses input parameters from the 12PU500 to verify the model against published curves so that further results may be interpretted and adjusted accordingly.

RRR.FOR This is a fortran programme copy of ROTOR.FOR with the LESO II parameters as inputs.

# APPENDIX 9

## REPORT ON FINDINGS BY KIE ON WORK WITH 12PU500 WINDMILL

W. SCHMIDT
GEE/LESO
JULY 1984

# REPORT ON FINDINGS BY KIE ON WORK WITH 12PU500 WINDMILL

General findings by the Kenya Industrial Estates Renewable Ener Programme on its development and system prototyping which a applicable to other projects doing similar development work. KIE been working with the 12PU500 since it was introduced in 1979 UNIDO project in Kenya.

1. main shaft: should not weld or spot weld to lock bearings shaft as this tends to damage bearings (note: original Ghazipu design had a shaft taper piece not common in other sty bearings so while welding to lock it may work for this style bearing, it does not for the generally available types)

2. main bearing changed to heavy duty oil bath bearing at a cost 20,000/= ($1500 USD$) a pair. (This may not be entirely econom- ically sound as it doubles the cost of the entire system.-ws)

3. cross head frame being reinforced to reduce flexing. Flate plat will be added by welding on sides and top, boxing in structure.

4. pivot for head frame modifications will be required to permit easier orientation, yawing, into the wind. Details of the mod- ifications include axial bearings and roller guides.

5. rod ends, imported at a cost of $7 USD each will be used for connection rod ends rather than fabricate nylon/steel component

6. rocker arm for pump rod: the bearing to be designed using a heavy duty truck universal joint. Several standard sized units are available at low cost, offering good strength, dust resis- tance and fine bearing action.

7. crank arm design changed to stiffen up original design. Two modifications are planned: first, a heavy plate was used for the arm and later the design will incorporate a disc with threaded hole etc. It was identified that this is a critical stress/load transfer zone and efforts to spread the load are very important.

8. modifying the side vane with a larger spring, variable rate and more surface area, some of which will be added at 45' orient- ation to provide for gust pick-up.

9. tower: change to a more 'knock-down' bolted construction to facilitate transportation.

10. tower: details in design added to permit galvanizing of compon- ents, especially for concrete/steel corrosion resistance and for use at coastal locations.

## General Problem Areas

1. Bearings
   - main shaft
   - yaw bearings on tower
   - crank arm

General solution: to replace with heavy duty reliable imported units, generally supplied from automotive/truck sources.

Comment: replacement of the main bearings to increase one-and-a-half to two year observed life by items costing 10x, in fact increasing the total system cost by 50-100%, may not be as cost effective as either reviewing means of increasing the longevity of existing bearings ( ie by sun shading, oversizing, dust protection, regular greasing with clean grease) and if necessary replacement from time to time on a practical maintenance schedule.

2. rigidity of rotor support head and frame:

General solution: additional steel added, especially in sections not completely triangulated in the original design, where it will greatly increase the resistance to twisting.

3. power transmission from rotor shaft to pump rod:

General solution: heavier sections of steel, better bearings and replacement of sliding sections with long swing arms.

4. rotor control system:

General solution: testing and minor modifications to permit fine tuning and long term reliability

## General Comments by KIE

1. machine most suitable for low lift irrigation needs (5 m head) not for pumping to 20m.
2. majority of the system problems is with the pumps, not the wind rotors.
3. will likely redesign for prototype II based on the experience over the past five years.

w.s.27.7.84

## APPENDIX 10

RAPPORT DE STAGE PAR M.B. TOURE AUX U.S.A. ET AU CANADA
DU 1 OCT. AU 12 NOV. 1983

TRIP REPORT BY M.B. TOURE TO USA AND CANADA
OCT. 1 - NOV. 12, 1983

REFERENCE ONLY (IN FRENCH)

DIRECTION NATIONALE DE L'HYDRAULIQUE
ET DE L'ENERGIE

LABORATOIRE DE L'ENERGIE SOLAIRE

UN PEUPLE - UN BUT - UNE FOI

# RAPPORT DE STAGE EFFECTUE PAR M.B. TOURE

## AUX U.S.A. ET AU CANADA DU 1 OCTOBRE AU 12 NOVEMBRE 1983

## I. Introduction.

Dans le cadre du projet "Mali-énergie renouvelable" financé par l'USAID, j'ai effectué un stage aux USA (1-30 Oct.) et au Canada (1-10 Nov.) d'une durée totale d'environ un mois et demi sur l'énergie éolienne.

Cette repartition du stage s'explique par le fait qu'aux USA ce sont les éoliennes à axe horizontal qui sont très développées tandis qu'au Canada les tendances sont surtout axées sur les éoliennes à axe vertical et principalement le type Darrius.

Ce stage a porté sur des cours théoriques et pratique dans des Universités ; une participation à la conférence internationale sur l'énergie éolienne et des visites d'institutions et de personnalités traitant de sujets relatifs à l'exploitation de l'énergie éolienne.

## II. Stage aux USA 1-30 Oct.83

Pendant cette première partie du stage j'ai suivi des cours aux Universités d'état du Nouveau Mexique (pendant deux semaines) et du Massachusett (une semaine) et assiste à la conférence internationale sur l'énergie éolienne, tenue à San Francisco.

### A. Université d'état du Nouveau Mexique : Las Cruces du 3 au 14 Oct.

Le cours dispensé par Mr. Rasmusen, de la faculté d'agriculture ayant pour doyen le Pr. Wragley, a porté sur l'installation, la maintenance et la réparation des éoliennes multipales de pompage de l'eau. Le programme n'était pas conforme à celui qui m'avait été communiqué avant mon départ et qui devait comporté, en plus des aspects pratiques, la théorie des pâles, la conception et la projection des systèmes.

Toutefois il faut reconnaître que ce cours était néanmoins intéressant et surtout très pratique. L'emploi du temps était le suivant :

8ᵉᵃ 11ᵉᵉ - cours théorique
12 - 16³⁰ - séance pratique

Le cours théorique a porté sur l'historique des éoliennes (avec projection de disque), les differentes composantes des machines (Dempster, Aèrometor), la selection de certaines éoliennes, les pompes à piston, le reseau de distribution de l'eau (calcul hydraulique simple), choix des tuyauteries basé sur des critères techniques et économiques.

Quant aux travaux pratiques, ils ont porté sur le montage et de démontage des differentes parties de systèmes de pompage : pylône, roue, système de transmission ; la réparation d'une éolienne Dempter, l'implantation et l'érection d'une éolienne.

En plus des eoliennes de pompage Aerometor et Dempter nous avons travaillé sur les types Samson, Holliday, Baker toutes des multipales avec des diamètres de roue variant entre 1,8 et 2,4 mètres.

Ce cours, qui est dispensé périodiquement au sein de cette université, était suivi par 8 personnes dont 4 Américains, 2 Bostwanais et un Haïtien. Il a été sanctionné par un diplôme : "Diploma of technician of wind technology".

B. <u>Conférence internationale sur l'énergie éolienne</u> :
Sanfrancisco (Californie) 17-19 Oct.

Durant mon stage, il m'a été donné l'opportinuité d'assister à cette grande conférence organisée par AWEA (Americain Wind Energy Association) l'association americaine de l'énergie éolienne aux USA.

Plus de 200 personnes de differents pays (Canada, Etats d'Europe, Japon etc...) ont assisté à cette conférence qui a regroupé fabricants et chercheurs.

Les thèmes discutés, avec apport de projection de diapo et de transparents, ont porté essentiellement sur les aérogénérateurs de moyennes et de grandes puissances : 50 Kw et plus.

Des problèmes relatifs à un développement généralisé de l'utilisation de l'énergie éolienne ont été débattus : conception selection de site, marketing, sécurité, pollution, l'assurance et son impact sur le développement des fermes d'aérogénérateurs.

Il faut signaler que tout le long de cette conférence un accent particulier a été mis sur le développement et l'avenir très prometteur des fermes d'éoliennes surtout dans des régions où la vitesse annuelle moyenne du vent est de l'ordre de 8m/s.

Aux USA, la californie est l'un des états où sont installées le plus des fermes d'éoliennes. Cela a été rendu possible grâce non seulement à un bon régime de vent, mais surtout à cause de la politique incitatrice menée par les organismes d'état, les pouvoirs publics et les particuliers très entreprenants.

Pendant la conférence se déroulait simultanement une exposition d'aérogénérateur, de systèmes de mesures du vent, des machines électriques pouvant être utilisées dans les aérogénérateurs.

En outre une excursion a été organisé à Altamont Pass (situé à quelques miles de San-Francisco) où sont installées des fermes d'aérogénérateurs de differentes firmes : ENERTECH, EST, WIND POWER I Ces aérogénérateurs au nombre de 400 environ et d'une puissance individuelle de 50 à 150 Kw en général produisent de l'électricité directement dans le reseau électrique déjà existant à un coût très competiti 4 cents la KWH. Ils fonctionnent 9 mois l'année et bien que déjà productifs font néanmoins toujours l'objet de R & D.

A Altamontpass, le projet en cours prevoit l'installation de 600 aérogénérateurs en tout et d'une puissance totale de 31 MW

En plus d'Altamont Pass, j'ai pu visité, pendant deux heures, une autre ferme d'aérogénérateurs située à Livermore (à 30 miles de Sans-Francisco)? Mr. Jack Klen, météorologiste de US Wind POWER m'a entretenu des methodes de collecte, d'analyse et de traitement des données du vent par ordinateur.

C. <u>Université d'état du Massachusett</u>. Amherst 24-28 Oc

Cette partie du stage, bien qu'ayant été improvisée par suite d'un changement intervenu dans le programme, a été néanmoins l'une des plus intéressantes surtout sur le plan académique. La firme Dynergy chez laquelle je devais passé un stage d'environ 12 jours sur les "fermes d'éoliennes" aurait quitté la Californie pour l'exécution d'un contrat qu'elle venait d'obtenir ailleurs.

Ainsi j'ai travaillé pendant 5 jours à la faculté de mécanique sur les aspects théoriques de l'énergie éolienne et visité l'atelier de fabrication et des installations.

de durée d'un semestre pour les candidats à la licence et de 2 semestres pour ceux à la maîtrise et au PhD. En plus elle a conçu et fabriqué un aérogénérateur de 25 Kw pour le chauffage d'un bâtiment que j'ai visité en compagnie du Pr.Cromack, doyen adjoint de la faculté de mécanique. Les travaux de R & D sur cette machine qui devaient normalement continuer étaient suspendus previsoirement par manque de financement. Le groupe de recherche en énergie éolienne de l'université s'interesse aussi aux machines à axe verticals ; ainsi la construction d'un Darrius avait débuté dans l'atelier que j'ai pu visiter.

Pendant mon séjour j'étais encadré par 3 professeurs : Pr. Cromack, Dr. McGovan et Dr. J. Manwell. C'est avec ce dernier que j'ai le plus travaillé sous la forme de conférence - question ( ou débat), forme très originale et efficace à raison de 4 à 5 heures par jour. Les sujets traités, en plus de la documentation dont j'ai été pourvu, ont porté sur :

- Methodologie générale de selection de site (Mr.Covan J.Manwell)
- Rotor design (J. Manwell)

En plus de ces cours souvent appuyés par des projections de Diapo, j'ai pu participer avec J. Manwell et Mr.Covan à une séance de calibrage d'un anemomètre (Aeolian MS768) à la soufflerie de l'université et assité au démontage d'un petit aérogénérateur BW 1.000 de chez WindWard (situé à quelques km de l'université) qu'on a ensuite transporté à l'université : il sera utilisé ou plutôt étudié par les étudiants pendant les séances de travaux pratiques.

C'est le lieu de signaler qu'en plus de la permanente disponibilité des professeurs, en particulier du Dr. J.Manwell, j'étais dans de très bonnes conditions de travail.

III. <u>Stage au Canada</u> : 30 Oct. - 9 Nov.

Le stage a été constitué essentiellement sinon surtout de visite de personnes et d'institutions s'occupant d'énergie éolienne.

A. <u>Université Laval</u> : Quebec City (Qebec) 31 Oct.

Pendant deux heures je me suis entretenu avec le Pr. Vinh D. Nguyen du département de génie mécanique. Il m'a parlé de leurs travaux et de leurs activités dans le domaine d'utilisation de l'énergie éolienne et remis quelques documents sur les résultats des tests effdctués sur des prototypes réalisés par eux. Ensuite il m'a fait visité les installations.

Le Pr. V.D. Nguyen est très connu dans le monde éolien pour ses travaux sur les éoliennes à axe vertical notamment sur le type philippini. Par ailleurs il a enseigné aussi pendant quelques années à l'université de Dakar où il avait initié et lancé un programme de R & D sur les éoliennes.

Ma visite des installations a porté sur un Savonius et un philippini installés sur le toit d'un bâtiment de l'université. Ensuite j'ai visité les laboratoires d'aérodynamique et d'electrotechnique où sont conçus des appareils d'instrumentation pour le contrôle et la commande d'aérogénérateurs.

B. Extrawatt St Jean de la lande 1 Nov. $11^{30}$ - $16^{30}$

Extrawatt est une firme Canadienne qui fabrique des aérogénérateurs à l'axe horizontal de 8 et I8 KW. Elle fabrique aussi et seulement sur la base de grande commande (comme ce fût le cas du Pérou), des eoliennes multipales de pompage de l'eau et des pompes à main à des coûts très competitifs.

En compagnie du Président Mr. Cloutier j'ai visité l'atelier de construction mécanique où l'on procède au montage final des aerogénérateurs "EXTRAWATT" avant leur expédition finale. Ainsi j'ai pu voir les 2 aérogénérateurs (sur 50 unités commandées) prêts a être envoyés pour démonstration au Liban, il est prévu un pour la côte d'Ivoire aussi.

Extrawatt est une machine très intéressante non seulement sur le plan financier (c$ 9250 la I8 KW) mais aussi sur le plan technique avec, entre autre, une vitesse de démarrage (avec production d'électricité) très basse : 4 mph

C. Pratt $ Whitney Montreal 2 Nov. $I4^{30}$-$I6^{30}$

C'est une usine qui fabrique essentiellement des turbopropulseurs pour les aviens et les héliceptères.

Mr Jan Vacek m'a fait faire un tour de l'usine où j'ai pu visiter entre autre, le Laboratoire de test aérodynamique, celui de testing des turbopropulseurs et le bureau très sophistiqué d'ingenecring par ordinateur.

Ensuite il m'a entretenu de ses expériences sur les éoliennes axe verticale (éolienne de l'île de Madeleine) sur lesquelles il a eu à travailler d'une manière générale et d'un projet d'éolienne à axe vertical aussi et de 230 KW qu'il avait initié dans le temps et qui finalement n'a pas abouti à cause des difficultés techniques que rencontre sa réalisation.

D. Institut de recherche d'hydro québec IREQ. Montreal 3-4 Nov

Ce très grand institut de renommée mondiale travaille essentiellement sur tous les problèmes relatifs à la distribution de l'énergie

électrique : reseau de moyenne, basse et haute tension, les transformateurs etc... En plus de cela des travaux de R & D y sont menés aussi sur les énergies renouvelables au sein de divisions : énergie éolienne, Biomass, production d'hydrogène (pour stockage de l'énergie), chauffage solaire.

A mon arrivée à l'Ireq j'ai été reçu par Mr Bernard Saulnier, chercheur à la division "énergie éolienne" et qui était le responsable de mon stage. Après ce chaleureux et très cordial accueil j'ai eu droit à une projection de film sur l'Ireq et ses activités. Ensuite j'ai visité certains labo de recherche et d'expérimentation : haute tension, basse tension, transformateurs, simulation de décharche électrique dans les lignes haute tensionetc...)

L'équipe de chercheurs de la division "énergie éolienne" avec laquelle j'ai passé la plupart de mon temps travaille principalement sur les aérogénérateurs à axe vertical et je dirais surtout sur les types Darrieus. Elle a conçu et expérimenté le Darrius de 230 KW de l'Ile de Madeleine et actuellement travaille sur le projet, qui serait une première mondiale d'un Darrius de 3 MW dont les études aérodynamiques étaient terminées ; il restait à finaliser les études de construction mécanique entreprise par une autre firme.

Avec B. Saulnier, I. Paraschivoin, le chef de la division, j'ai eu quelques discussions théoriques sur les Darrius en général et un déjeuner de travail avec toute l'équipe de chercheurs de la division.

J'ai assisté à un essai sur un Darrius de 50 KW. Il était mené par B. Saulnier et Mr. Durieu et a porté sur le démarrage et l'arrêt de la machine, sa production d'électricité, la variation du couple moteur en fonction de la vitesse du vent avec tracé de courbes caractéristiques par l'imprimante de l'ordinateur. Des essais ont porté aussi sur les caractéristiques du couple de freinage et principalement sur sa durée qui est très déterminante pour atténuer l'amplitude des vibrations pouvant causer la rupture des haubans et partant la destruction de la machine.

L'Ireq a effectué aussi des expérimentations sur la production d'hydrogène par l'énergie éolienne. Mr. G. Belanger, chef de cette division a promis d'envoyer au LESO le rapport sur ces essais dès qu'il sera disponible.

Concernant la Biomass, je n'ai vu aucune installation à l'Ireq. Toutefois le chef de cette division m'a affirmé que leurs objectifs portent sur la gazeficatio de la tourpe et la production de méthanol.

.../...

Il n'ya plus de travaux de R & D sur le chauffage Solaire actuellement à l'Ireq. Néanmoins j'ai pu visiter des installations existantes et opérationnelles à titre de démonstration.

E. Bruce research institut. Montreal 7 Nov. $10^{20}$-$13^{00}$

Cet institut de recherche est composé d'un batiment et de 2 Champs d'essais. C'est dans le bâtiment que se trouve, en plus des quelques bureaux, la bibliothèque très fournie. Là j'ai travaillé quelques heures et ai pu obtenir quelques documents.

J'ai visité les 2 champs d'essais. Sur le premier étaient exposés des sechoirs solaires à vapeur pour la cuisson, des fours solaires. Quant au second y étaient exposés un aérogénérateur (1 KW) à axe horizontal un philipini et un savonius et non opérationnel. Le bâtiment qui s'y trouve disposé d'un système de chauffage hybride : aérogénérateur et capteurs solaires. Les digesteurs de biogaz quant à eux étaient déchargés, on devait y débuté incessament des tests avec la betterave comme substrat. Tous ces propotypes ont été réalisés ou expérimentés par des étudiants dans le cadre de leurs mémoires ou thèses.

Le Directeur de l'institut Mr. Lawand m'a invité aussi à une projection de vidéo-cassette très intéressant sur le thème suivant : "Biogaz à Guyana" (Chine) où le biogaz est utilisé pour faire fonctionner groupe électrogène de 25 KWA.

F. SOFATT Montreal 8 Nov. 83 $9^{30}$-$16^{00}$

(Société de formation et d'assistance technique internationale)

C'est dans l'un des bureaux de cette société qu'est installé Dr. Bzrozwki, specialiste en aéronautique qui s'occupe actuellement d'aérogénérateurs à axe vertical.

Notre entretien qui a été très instructif a porté sur les caractéristiques techniques de l'aérogénération (type philippini) WECCAN conçu par lui-même. L'originalité de cette machine se situerai au niveau du profil (Bzrozwki) des pâles, ce qui confère à la machine un coefficient de puissance $C_p$ de 64 % pour des vents faibles. La license serait disponible pour achat.

G. CNRC. OTTAWA 9 Nov. 83 $9^{20}$-$14^{30}$

Canadian National research Council

Cette institution de recherche, comme l'indique son nom.

est principalement axé sur le developpement de tres grosse machine Darr. de
Je citerai le Darrius de 3 MW qui est en cours de conception en collaboration avec l'IREQ.

Mon passage à ce centre a été très très intéressant. Ainsi sous l'aimable direction de J.P. Penna (chercheur) j'ai visité la soufflerie où sont menés les essais aérodynamiques, son système d'instrumentation de collecte, de traitement et de stockage des données par ordinateur. Il m'a été donné l'occasion de voir comment l'on procède pour étudier l'écoulement de l'air (ou fluide) sur différents profils afin de pouvoir ensuite améliorer leurs caractéristiques aérodynamiques et partant leurs performances.

Après la visite j'ai discuté avec J.P. Penna de la théorie des machines Darrius. Les thèmes traités, bien que pas en profondeur vu le temps dont je disposais mais d'une manière très explicite ont portés sur le décrochage statique et dynamique et son influence sur les caractéristiques d'un Darrius ; la différence dans l'étude aérodynamique des machines à axe verticale et celle à axe horizontale.

Ensuite j'ai été reçu par M.S. Chapell, le chef de division, qui m'a parlé des activités du C.N.R.C., de leur option pour les grosses machines à axe vertical uniquement. L'entretien a été bref car je devais prendre l'avion pour Boston (USA) mettant ainsi fin à mon séjour Canadien.

<u>Second WIND</u> Boston (USA) IO Nov. $9^{20}$-$IO^{35}$

"Second wind" est une petite firme, (de 4 à 5 personnes) en pleine expansion, qui fabrique des appareils mesures et d'enregistrement des données du vent. Leur dernier appareil le AL 200 est très impressionnant de par les possibilités qu'il offre à l'utilisateur : les données y peuvent être stockées dans de petits "Chip" électroniques que l'on peut garder aussi longtemps que l'on souhaiterai. Lors de ma visite, la firme démenageait pour des locaux plus grands.

<u>Woods Hole</u> IO-I2 Nov. 83

Woods Hole est une petite ville au bord de la mer et située à quelques milles de Boston. Ici habite Mr. D. Campbell qui m'a très bien accueilli et rendu mon séjour très agréable.

A Woods Hole j'ai rencontré Mr. Rus de"l'association des scientifiques". Il est constructeur de petits aérogénérateurs pour les bateaux. Mr. Rus m'a entretenu de ses projets et entre autre de sa disponibilité pour transmettre sa technologie et son savoir faire dans les pays en voie

.../...

de développement dans des conditions à arrêter de commun accord. Mr. J. Seal m'a remis des documents relatifs à son projet très intéressant de dispositif de fabrication de la glace grâce à l'énergie éolienne.

J'ai pu visiter le "Wind Farm" c'est à dire un parc où sont installés des éoliennes de pompage et de petits aérogénérateurs pour satisfaire la curiosité des visiteurs qui pourraient aussi éventuellement s'ils le désirent s'inscrire à des cours de fabrication d'éolienne rustique à voile. Le bâtiment du propriétaire est alimenté uniquement par 2 aérogénérateurs, de I KW chacun, avec un système de stockage par batteri. Une partie de l'énergie électrique est aussi utilisée pour pomper de l'eau dans un petit château d'eau.
C'est après cette visite quéà pris fin mon stage.

Remarques et Conclusion.

Conformement au programme initial du stage les volets relatifs aux études théoriques n'ont pas été executés comme ce fut le cas de l'université du Nouveau Mexique qui avait un autre programme ou approfondis par manque de temps car comme l'on peut le constater le calendrier était trop serré.

Néanmoins j'ai tiré un grand profil de ce stage que je considère positif. Cela a été possible grâce surtout à l'entière disponibilité des personnes rencontrées. Qu'elles trouvent ici l'expression de ma sincère reconnaissance.

Bamako, le

# APPENDIX 11

## FUTURE DEVELOPMENT OF LESO MK I WIND PUMP

(REFERENCE ONLY)

ITDG
ITP/83067
MAY 1983

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INTERMEDIATE TECHNOLOGY POWER LIMITED

# THE FUTURE DEVELOPMENT OF THE LESO MK I WINDPUMP

SUBMITTED TO

LABORATOIRE DE L'ENERGIE SOLAIRE
MALI

AND

UNITED STATES
AGENCY FOR INTERNATIONAL DEVELOPMENT

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DATE: MAY, 198

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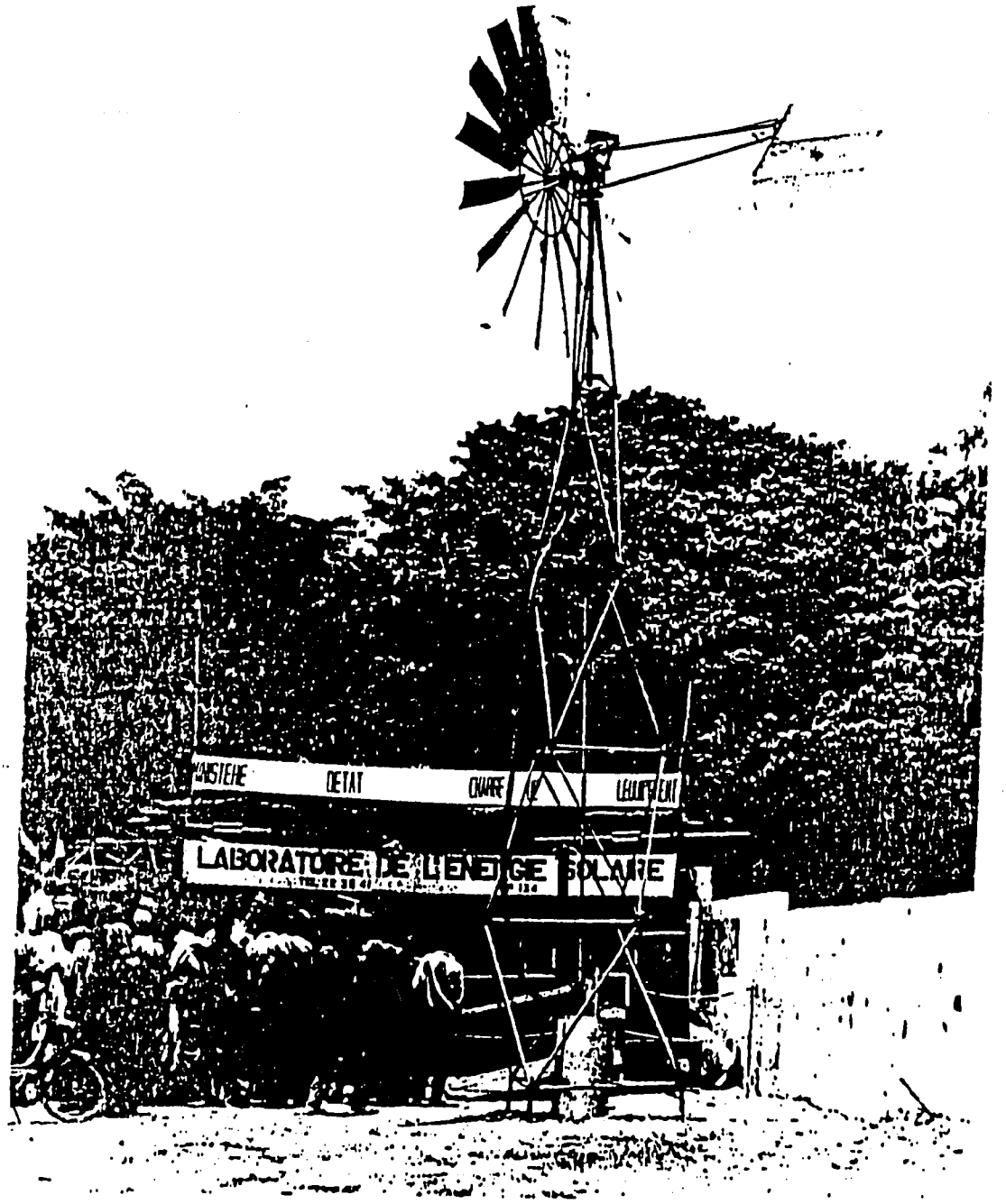


LESO MK 1 WINDPUMP PROTOTYPE ON DISPLAY AT THE TRADE EXHIBITION HELD IN BAMAKO IN APRIL 1983

# THE FUTURE DEVELOPMENT OF THE LESO MK I WINDPUMP

## 1. Introduction

This report has been prepared for the Laboratoire d'Energie Solaire, (LESO), Bamako, Mali, by Peter L Fraenkel of Intermediate Technology Power Ltd., (ITP), following a visit from April 27 through May 2, 1983.

## 2. Background

The LESO Mk I windpump development was initiated by LESO mainly as a workshop training exercise. Assistance with the design and with training was provided by Mr Bill Wright, a UK wind energy expert, while on secondment from ITP, during the period March through May 1982.

The design was intended to be reasonably well engineered, but able to be built entirely with locally available steel stock and components. The cost was also required to be kept as low as possible.

One of the main difficulties related to achieving an adequate power transmission mechanism due to the limited availability of bearings and other good quality machine components in Bamako. Eventually a cam drive mechanism was evolved, which although crude in some respects, does offer some prospect of reliable and effective operation.

The author visited Bamako both in order to deliver a series of lectures on various renewable energy topics, as well as to review the windpump design and this report runs through some of the points discussed and conclusions arrived at in consultation with LESO staff.

Obviously a key element continues to be the training function achieved both for workshop technicians and for the engineers at the laboratory to develop a reasonably complex and demanding item of technology. However, there are also prospects that the design, if perfected, could serve a useful function for farmers in Mali.

A precedent has already been set with the rather cruder and

simpler Sahores windpump introduced by Pere Plasteig with assistance from the US Peace Corps and VITA, for farmers to irrigate small plots of land. Unfortunately this windpump demands rather a lot of repairing and adjustment so the majority are no longer operational (according to the UNIDO/Lavalin Group's UPS Study there are just one or two well maintained exceptions). The LESO windpump involves centralised manufacture, in Bamako, but is intended to overcome some of the reliability problems inherent in designs like the Sahores, and it is therefore hoped it will prove more acceptable to farmers.

Long before that, before independence, more sophisticated windpumps imported from France were installed in the northern desert regions to provide water points for nomads; although most of these no longer function, the failures are thought to be mainly due to minor problems and it is believed many could quite easily be restored. The author of this report happened to visit one or two examples of these between Gao and Tessalit 10 years ago, and at that time, the machines visited were non-operational for minor reasons

About 50 solar photovoltaic pumps are also installed in Mali, but these are very much more expensive than locally made windpumps(or even than imported windpumps) and are totally unsuitable for local manufacture, so offer little prospect for assisting the development of local industry, although they may technically be the best option for pumping water reliably in the less windy south of Mali.

It must be stated that much of Mali is probably not suited for the deployment of windpumps, due to inadequate winds, but on the other hand it is believed that much of the more arid and semi-arid parts of the country are adequately windy. As a rough rule of thumb, it is desirable for the annual mean wind speed to be in excess of 3m/s and the mean monthly windspeed in any month should not be less than 2m/s for windpumps to be economically and technically successful. An important aspect of the work of the LESO is to determine in more detail the wind and solar resource available for use in Mali.

It is believed the main application for the LESO windpump is similar to that of the Sahores, to irrigate plots of land on the banks of the River Niger to the north and east of Bamako. In other words it will generally be continuously supervised by the owner while in use, as irrigation normally demands the presence of the farmer. As a result the LESO windpump will not need the sophisticated storm protection or the capability of running a year or more without attention that is required by commercially manufactured water-supply windpumps, nor will it have to operate on deep boreholes where high pump rod forces would be unavoidable; the possibility for relaxing the requirements compared with a commercially manufactured windpump make it feasible to produce a relatively cheap and simple design. However, it must be stressed that the design will possibly be limited to supervised irrigation applications



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and will not be suitable for unattended duties such as water supply in remote desert locations, in its present form.

## 3. Recommended objectives of future windpump development

Future development should take the design, currently at the prototype stage, to the level where a number of machines can be deployed under controlled field test conditions in order to assess the effectiveness of the concept for irrigation duties. Clearly the field prototypes need not be perfected completely, (indeed this would be impossible as the field experience is a vital element in the development process), but they must be sufficiently well developed to perform reliably and effectively for sufficient periods for farmers to make good use of them.

It is also of considerable psychological importance that no serious failures occur, (such as total self-destruction of a machine), as this could damage the prospects for future dissemination of the technology by giving it a bad name.

It is therefore proposed through the rest of this report to review the technical short-comings of the design as perceived at this stage and to recommend improvements, and then finally, to recommend a basic testing programme (and to suggest some useful measuring and assessment techniques).

## 4. Technical Review

### 4.1 rotor

The main area for concern with the rotor is the blade roots, which consist of standard galvanised water pipe. It is believed these may suffer fatigue failure at the roots and it is recommended that steps be taken to reinforce the blade roots with sleeves formed by splitting a length of the same pipe as is used for the spar and forcing it over the area at risk, or by finding a size of pipe that happens to fit well over the existing spar. A preferred alternative is to find a larger diameter pipe to use as a spar instead, which will not need sleeving.

Attention should be given to avoiding stress concentrations at the point of maximum bending moment due to such things as the U bolt clamps used at present to attach the spars; it would be better to use pipe clamps made from flat bar rather than U bolts. This will require that the rotor ring be changed from pipe construction to angle section construction. It is possible that the LESO may for the time being continue with the existing design, but regular inspection of any windpumps in operation should be carried out to look for early signs of

fatigue cracking at the blade roots.

A minor improvement will be to round the tips of the blade sheets, which at the moment are sharp edged. The main reason is for safety to prevent injury of people working on the machine, but the sharp tips will also generate vortices and turbulence which can cause a small loss of efficiency.

It would be worth experimenting with the use of lighter blade metal, if this can be obtained. This could be thinner steel sheets, which if they prove too flexible, could be reinforced by rolling joggles into it as stiffening (analagous to corrugated sheets); alternatively, if light alloy sheets or finished thin fibre-glass sheets can be found (they are used for roofing in some countries), then these would be even better due to their resistance to corrosion in addition to their light weight.

Some discussions were held on the possibility of cutting the sheets from which the blades are shaped at an angle to their edge to produce trapezoidal blades, (this idea originated from LESO engineers). Typically the blades might be cut so that one end has roughly twice the chord of the other. If the broad end of the trapezium so formed is at the blade roots and the narrow end at the tip, some marginal gain in efficiency will result. Also, because the unsupported part of the tip is narrower, it may be possible to use lighter gauge steel sheet. More important, the average blade root stress will be reduced because of the reduction of both weight and windloading near the tips. Some small reduction in starting torque combined with a small increase in rotor tip-speed ratio is also likely. Therefore this suggestion ought to be tried and is likely to prove a useful one.

## 4.2 transmission unit

The main stub axle which supports the rotor has a serious stress raiser at the point of maximum bending moment and requires modification in order to avoid any risk of fatigue failure. Steps have been already taken to introduce gussets which are welded on to the stub axle where it emerges from the main chassis frame to add to its strength and to move the point of maximum stress outboard from the frame. This should be an adequate improvement.

The rotor hub was attached to the drive shaft by two grub screws, which were inadequate. A larger grub screw held by a welded captive nut is now used and may prove to be sufficient; if this gives trouble, a second grub screw should be used, or possibly screwed keys (i.e. grub screws used like keys which are screwed into axial holes drilled between the shaft and the hub). The front end of the half shaft would need to be solid to cater for this and probably should therefore be a piece of machined bar several cm long inserted into the tubular half shaft, and welded securely to it.

The load on the cam could be reduced slightly by repositioning the position of the ball-bearing cam-follower further from the fulcrum and by increasing the throw of the cam to compensate so as to avoid reducing the pump stroke. The cam throw should be increased as much as possible with the space available, and this will dictate the new position of the cam follower.

It would be desirable to eliminate the intermediate rocker lever which acts as the cam follower, but to do this will require extensive redesign, so this is not recommended at this stage in the development.

## 4.3 Tail and governing system

The existing governing system, in which the tail vane is hinged to the boom, is not recommended as it seems unlikely to provide effective furling under storm conditions. Therefore, the vane requires to be rigidly fitted to the boom, and the boom should in turn be hinged behind the transmission frame.

The force required to hold the tail straight against the wind should if possible be provided by a suitable tensile coil spring, since a system of this kind is much the easiest to design. However, if tensile coil springs cannot be obtained locally, then an inclined hinge is recommended and experiments will be needed to determine the correct hinge angle to obtain the desired furling speed; needless to say, this will be a time-consuming process. Because a coil spring system is so much easier to get right, this is quite strongly recommended, (even if a few springs need to be imported), as it will speed up the development process.

Whichever system is used, suitable bump stops to cushion the tail movement at the ends of its travel are vital. These could be valve springs from an engine acting as buffers by being mounted on suitable brackets. The impacts caused by furling and unfurling can otherwise be considerable and can damage the system.

The existing tail assembly is otherwise attractively light and effective.

## 4.4 Tower and foundations

The existing tower design ought to be completely replaced primarily because it has at present no redundancy (any component failure will cause catastrophic tower collapse) and it involves the flattening of the tubular members at their ends which inherently provides many weak points in the structure. Also the existing tower does not appear stiff enough under strong wind conditions.

Therefore, it is recommended that a three or four cornered



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lattice tower be developed. This should be a welded assembly made up from angle steel sections. If practicable it should be in one, or perhaps two sections. If more than one section is used, then welding jigs will be required to ensure the components assemble together properly after welding.

It is probable that 50mm angle may be used for the corner posts, and 37mm for the horizontal members. 12mm round bar or concrete reinforcement rod may be used for cross bracing, and this normally tensions quite adequately simply by the contraction which occurs after welding.

Where more than one section of tower is used, they may possibly be joined by using bolted fishplates, as with railway tracks.

Concrete foundations, calculated to be stable simply by having adequate weight to prevent up-rooting must be used. Maximum gusts under extreme conditions are unlikely to exceed 40m/s in Mali. The method for calculating gust loadings should be to consider the projected area A of the wind-pump normal to the wind, multiplied by a drag coefficient of about 1.3 in the standard drag calculation:

$$D = Cd.\tfrac{1}{2}\rho AV^2$$

4.5 pumps

Pump sizing can be initially carried out be referring to pumps used with commercial direct drive windpumps of a similar diameter(eg Comet). Obviously allowance must be made for any difference in stroke between the windpumps being compared. Note that most windpumps that size are back-geared and therefore drive a larger pump more slowly.

More scientific sizing may be achieved by determining the starting torque characteristic of the LESO windpump by locking the rotor with a spring-balance (or spring of known stiffness) and measuring the reading (deflection) at different windspeeds. Hence the pump rod pull available for starting at the desired starting windspeed and consequent size of pump may be calculated.

It is recommended that a pump development programme be avoided if possible until the windmill is reasonably satisfactory, since pump development is a considerable project in itself. If possible, commercially available pumps should be used for the time being. However, since only one size of pump is made in Mali, it will eventually be important to develop a pump manufacturing capability. Both IT Power in the UK and the Steering Committee for Wind Energy in the Netherlands are working on pumps for local manufacture and may well have a suitable design that could be adopted or adapted by LESO

This should have several key objectives:

a) to measure the technical performance of the LESO windpump

b) to learn more about the wind regime in Mali

c) to investigate how effective this kind of technology is as used by farmers in Mali

## 5.1 technical performance monitoring

It is recommended that two distinct types of test be carried out, namely:

a) instantaneous tests, and

b) cumulative tests

The former consist of tests which measure the second-by-second output of the windpump in response to variations in the wind, while the latter measures the windpumps output over a lengthy period, (such as 24 hours), in response to the total cumulative wind run in the same period.

Instantaneous testing is important in order to optimise the windpump design, while cumulative testing is more important to determine the practical and economic value of the system.

### 5.1.1 instantaneous testing

A range of options are available to do such tests, ranging from using nothing more than a simple cup-counter anemometer, a 10 gallon (or similar) container (of known capacity) and a stopwatch, to continuously monitoring via electrical transducers feeding either a multi-channel chart recorder or else a micro-processor controlled data-logger (or micro-computer).

The simple option consists of timing the filling of the container, while measuring the wind run in the same period. For success, as steady a windspeed as possible is required, or extraneous results will be obtained. The reason is that this is actually a "cumulative test" over a short time period and the mean wind speed can only be correctly assumed as the wind run divided by the time if the windspeed remains fairly steady. The reason extraneous results will be obtained if the wind varies is because the cube of an average value will be considerably less then the sum of the cubes of its components if these differ very much, (wind energy is proportional to the

wind speed cubed). Extraneous results of this kind had already been obtained by laboratory engineers during some preliminary tests that they had completed before the author's visit; it was recommended that only measurement runs where the wind varies by less than (arbitrarily) plus or minus 15% should be accepted as meaningful. In fact, becuase of this constraint, it is worth limiting the size of the container to be filled so that each test does not last for more than about half a minute or so under typical wind conditions.

More accurate results can be obtained with the aid of electronic monitoring equipment which allows a much shorter sampling time so that the wind speed can be taken as being substantially constant. Even so, if the results are presented as an X-Y "scattergram" considerable scatter will still be found due largely to discrepencies in the wind speed as "seen" at the anemometer head compared with that through the windpump rotor, and due to different response time-constants for the windpump compared with the anemometer head. Again, steady wind conditions (on an open site with little turbulence) will reduce the scatter. However, once a scattergram with a large number of points is derived, a lot of reasonably reliable predictions will be possible from it.

The World Meteorological Office (WMO) has recommended the use of twin anemometers for wind-turbine monitoring, located about one rotor diameter either side of the rotor (roughly in the plane of rotation) at rotor hub height. Since the plane of rotation moves as the wind direction changes, the best tactic is either to set up the anemometers to suit the prevailing wind, (and to log wind direction so allowance for changes can be made), or to use moveable anemometers (which is possible with a small machine), during short term "instantaneous" type tests. For cumulative type tests, it is probably sufficient to use a single anemometer located about 10m from the windpump at hub-height, in a direction chosen so that it is directly downwind of the windmill as seldom as possible.

### 5.1.2 Cumulative testing

Instantaneous testing will normally take place for only a day at the most, and engineers or technicians will be present. Cumulative testing on the other hand requires to be carried out for an extended period, preferably running to two years or more.

The objective is to log average daily output and average daily wind run, usually by arranging for the instruments to be read daily and the result written into a log book. However, automatic equipment that can be read less often can be used, but obviously greatly increases the instrumentation costs.

A useful extra parameter to log cumulatively is the number of strokes completed by the windpump per day, through using a suitable electronic or mechanical totaliser. If a mechanical



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counter is used, it must be borne in mind that it will need to be switched in the region of 25 million times in five years, and therefore needs to be very securely mounted and to be of high mechanical quality - anything crude tends to come to pieces in hours rather than days! For this reason there is a lot to be said for a dry cell powered electronic counter with an optical sensor for this duty. If a clock is added to the electronics, it is then easy to obtain much more useful information such as the hours per day of operation (and hence the mean speed of rotation).

In the end, knowledge of the number of strokes possibly can provide a more reliable indication of water output than the average water meter; in any case it certainly provides a good double-check. However, the pump needs to be calibrated, and it must be borne in mind that the volumetric efficiency may vary significantly in low head pumping applications with pump speed, so a linear relationship with speed should not necessarily be assumed.

A further reason to monitor the number of strokes is to provide some warning if the pump deteriorates due to valve seals or piston leathers wearing or getting damaged. This can happen quite quickly if poor quality materials are used and/or the water contains abrasive silt in suspension.

Finally, a vital requirement with all field tests of this kind is a disciplined approach to calibration and recalibration of transducers, (particularly flow meters). Anemometers cannot be recalibrated in the field, so a good policy is to have several good quality units which can be compared with each other from time to time.

## 5.2 Obtaining improved knowledge of the wind regime in Mali

Every opportunity should be sought to place either cup-counter anemometers (providing someone can be relied on to log their readings preferably two or three times daily) or automatic wind energy prospecters in different regions of the country. There is little doubt that the most important locations to monitor for wind are along the Niger River where it swings north from about Mopti to Gao, as this is the one region likely to have a reasonable wind regime combined with a sizeable static population.

It would also be useful to obtain some data from the arid north of Mali in case windpumps are to be located in future primarily to help the nomads who move around in that area. To that end, wind prospecter units might be placed at such permanently manned locations as the Mali border post with Algeria at Tessalit and perhaps at other centres further south such as Tombouctou and Gao.



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## 5.3 Investigation of the effectiveness of windpumps for irrigation in Mali

This part of the programme is required once the windpumps are sufficiently well proven and understood to be deployed in small numbers with farmers. It is recommended that a suitably qualified investigator spends some time observing the windpumps in use in order to evaluate the effectiveness of the water distribution and application techniques and to gain an insight into any developments needed to assist farmers to make better use of the windpumps. Finally, once it is decided that the system is being used as effectively as is reasonably possible, a proper techno-economic evaluation is required. The objective of this will be to decide what future (if any) the technology might have, and hence the most appropriate next stage for its development.

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# APPENDIX 12

SST PLANNING DES TACHES 1984
GROUP: EOLIENNE
REVISION A

(1984 WORK SCHEDULE FOR WIND POWER TEAM)
(REFERENCE ONLY - IN FRENCH)
DECEMBER 1983

GROUPE : EOLIEN

SST. PLANNING DES TACHES 4

REVISION (A)

Projet : Mois

| | Tache | Oct83 | Nov83 | Dec83 | Jan84 | Fev84 | Mar84 | Avr84 | Mai84 | Jui84 | Jul84 | Aou84 | Sep84 | Oc84 | No |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Etudes des resultats obtenus Projet d'Evaluation des ressources | | | | | X | | | | | | | | | |
| 2 | Rapport interimaire technique sur l'eolienne LESO | | | | | X NARA | | GAO | | | | | | | |
| 3 | Dessin du Systeme de transmission (biellemanivelle) LESO II | | | | | X | X | | | ✓ | | | | | |
| 4 | Essai LESO II (Pales trapezoidales) | | | | | | | | | | * | | | | |
| 5 | Construction et Installation 4 eoliennes LESO I dans les zones | | | | ✓✓ KONATE | | SAN | | | | GAO | NIORO | | GAO | |
| 6 | Etude et Construction d'un Savonius | | | | | | | | | | | | | | |
| 7 | Installation | | | | | | | | | | | | | | |
| 8 | Test Savonius plus rapport | | | | | | | | | | | | | | |
| 9 | Commande aerogenerateur 200 - 400w | | | | | SAI | | | | | | | | | |
| 10 | Montage Test aerogenerateur | | | | | | | | | | | | | | |
| 11 | Installation | | | | | | | | | | | | | | |
| 12 | Rapport Technique Commande KIJITO Install. KIJITO | | | | | | | | | | | (G) | | | |

— PRIORITY TASKS FOR FIELD MISSION JUNE 26 - AUG 2 - 1984.

# APPENDIX 13

## LIST OF ADDITIONAL REFERENCE LITERATURE RECOMMENDED TO SUPPLEMENT EXISTING MATERIAL IN LESO LIBRARY

W. SCHMIDT
GEE/LESO
JULY 1984

# REFERENCE LITERATURE RECOMMENDED FOR LESO LIBRARY

w.schmidt 27.7.84

1. ENGINEERING HANDBOOK ON THE ATMOSPHERIC ENVIRONMENTAL GUIDELINES FOR USE IN WIND TURBINE GENERATOR DEVELOPMENT, W. Frost, B. Long, R. Turner, NASA Technical Paper No. 1359, December 1978, 372 pgs., NASA. Washington D.C., USA, available National Technical Information Service, Alexandria VA., USA.
   - a good reference on interpretting wind history data and for developing design information for wind systems.

2. TECHNICAL REPORT DEALING WITH ORP/TOOL WINDMILL PROJECT (Ghazipur 12PU500), Niek Van de Ven, June 1979. Available WOT/TOOL, T.H. Twente, Postbus 217, Enschede, Holland.
   - history of the development of the 12PU500, providing valuable information for other projects doing similar work

3. STATIC AND DYNAMIC LOADINGS ON THE TOWER OF A WINDMILL, E.C. Klaver, 1977, SWD Publication 77-3, available SWD. P.O. Box 85, Amersfoort, the Netherlands.
   - excellent design information for rotors and towers all in one book. Easy to understand with examples. This is an essential book for anyone working on field projects and needing to do aerodynamic and structural loading calculations.

4. INTRODUCTION TO WIND ENERGY, E.H. Lysen, Aug 1982, 314pgs. SWD Publication 82-1, available SWD. P.O. Box 85, Amersfoort, the Netherlands.
   - a very compresensive summary of wind energy information which is invaluable to the wind energy project staff. Includes much information that is only available otherwise in Dutch technical publications and not published outside of the SWD group. Highly recommended.

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