TEST AND DEMONSTRATION OF A NEW-TECHNOLOGY 50KW WIND TURBINE BLADE ON A HIGH-WIND SITE

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EXECUTIVE SUMMARY

A new 7.2m wind turbine blade manufactured using advanced production technology has been tested on a high wind site on the West Coast of Scotland. The glass-epoxy blade is made by NOI Scotland using resin infusion moulding (otherwise known as RIM, a vacuum resin transfer process that dispenses with traditional 'wetting out' of glass cloth), and features 'keyed' root studs and an infused unidirectional glass girder, both integrally moulded with the primary blade structure.

A test set of blades was installed on an AOC15/50 wind turbine of 50kW rating. The wind turbine is a fixed-speed, stall-regulated machine with downwind rotor and free yaw operation. One of the blades was equipped with strain gauges to measure flapwise (out-of-plane) and edgewise (in-plane) loading at a location corresponding to 12.9% of blade tip radius, for comparison with results from prior static and fatigue tests at the US National Wind Test Centre (operated by NREL).

The test facility on the Island of Luing, Argyll, was completed in September 2002 with the installation of the AOC machine. Prior to commissioning, essential electrical work was carried out to complete the grid connection, and a data logger and power supply were attached to the rotor hub to take signals from the blade strain gauges. Wind speed measurements were made using an external 10m met mast; a further data logger was subsequently installed to measure the electrical power curve.

The wind turbine has completed over three months of continuous operation, and a large amount of high-quality strain data has been obtained in wind speeds averaging up to 21.4m/s. The data consist of 10-minute mean, max, min and SD values for each of the four strain gauges, plus mean wind speed. The strain gauges are oriented to measure strain on the blade high-pressure (HP) and low-pressure (LP) surfaces, and the leading and trailing edge.

Measured strain levels are well within design values, albeit the wind turbine has not yet experienced the design driver conditions for either flapwise or edgewise loading, namely the extreme gust on a stationary rotor, and a generator short-circuit, respectively. Based on the above maximum wind speed, however, and taking account of the 10-minute logging period, the machine has run in wind speeds close to its shut-down limit of 25m/s averaged over 3 minutes.

The peak flapwise strain recorded to date is 1400$\mu\varepsilon$[*], in both compressive (LP) and tensile (HP) senses. This compares with design values of +3400$\mu\varepsilon$ (tensile) and –3200$\mu\varepsilon$ (compressive) respectively, and cracking limit of 5000$\mu\varepsilon$. The maximum recorded edgewise strain is +1000$\mu\varepsilon$ on the trailing edge; the corresponding value for the leading edge is +750$\mu\varepsilon$. Design values are +2900$\mu\varepsilon$ and –2065$\mu\varepsilon$, respectively.

Strain records were converted to equivalent flap and edgewise bending moments using calibration data from the NREL prototype tests. Peak bending moments have then been compared with data previously measured on an AOC15/50 turbine in the US, equipped with the original wood-laminate blade design. The Luing data indicate broadly comparable loading to the earlier measurements, but extend to higher wind speeds, where loads are seen to increase significantly.

The highest flapwise load seen to date on Luing (41kNm) is equivalent to 64% of the design load, or 32% of the structural capacity of the blade, with the latter established in a static destruction test at NREL. The highest measured edgewise moment (25kNm) is 56% of the design load, or 42% of

[*] $\mu\varepsilon$ = microstrain (1$\mu\varepsilon$ = 0.0001% units of strain)

its proven structural capacity, where the latter is based on a non-destructive proof load test at NREL.

Although the edgewise loading is apparently quite high in relation to design, strain levels have not exceeded 1000με on either the leading or trailing edge gauge locations, and there is no evidence that overspeed or normal air braking induce significant edgewise loading. Strain levels are slightly higher at the trailing edge gauge location, as expected from design.

Detailed analysis of fatigue loading is not possible, as the Luing data logger does not collect rainflow matrix entries. The highest flapwise cyclic strain to date, however (as peak-to-peak range in a 10-minute record), is 1908me: this compares with the 1600με range used in the NREL flap fatigue tests, where the prototype blade survived 4.4 million cycles. The average flapwise strain range on Luing is 342me, and 10-minute strain ranges exceed the NREL test values only in wind speeds above 15m/s.

One significant difference between the design fatigue load spectrum and the data from Luing is that measured flapwise loads show a significant reversing component. Whereas the NREL fatigue tests were based on an R-ratio (ratio of minimum to maximum stress) of 0.1, the Luing measurements indicate an actual value of –0.6. The reason for the load reversal is not entirely explained, and may be due to gyroscopic flapwise loads induced by yaw motion.

Flapwise strain ranges from stationary rotor measurements indicate a V2 dependency on wind speed, as expected. Extrapolation of the results to extreme wind speeds (60m/s) indicates sensible maximum strain values, although a more thorough analysis would require the use of peak or mean strain values; this has not been done here due to the difficulty in allowing for zero-offset errors in the strain readings.

The measured electrical power curve shows a healthy characteristic, albeit peak stalled power is approximately 60kW rather than the nominal 50kW. This initially led to the controller shutting the turbine down on over-power in high winds, although changes to the controller settings have now overcome this problem. Blade pitch adjustment at the hub may ultimately be indicated. Notwithstanding the above, energy capture to date has averaged around a 38% capacity factor.

The Luing tests have satisfactorily demonstrated operation of the new glass-epoxy blade in the conditions experienced to date, including high winds. Performance monitoring will, however, continue beyond the formal end of this project. It is recommended that the fatigue design of the GRE blade might be reviewed in future on the basis of the Luing strain data, and that the influence of yaw activity on blade flapwise cyclic loading be further investigated.

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1 OBJECTIVES OF THE PROJECT

The principal objective of the project was to carry out field tests on a 7.2m wind turbine blade incorporating innovative design features, which are intended to facilitate manufacture of this and future blade types by speeding the moulding and finishing cycles, while simultaneously improving the laminate quality.

The tests were also planned as the final stage in verification of the particular blade prior to commercial production, by comparing actual loading (particularly in high winds) with design values and the results of prior laboratory tests on two prototypes.

In addition, the project was intended as a realistic demonstration of a small-scale wind turbine designed for remote and rural applications, but designed using modern techniques and structural materials. In this way the project should contribute to the ongoing reduction in cost of wind energy at this scale.

2 BACKGROUND

This project concludes a blade technology development programme originally begun by Aerpac UK Ltd in 1998, but threatened with termination when that company ceased trading in February 2001. The blade was developed as a technology demonstrator for use on the Atlantic Orient 50kW wind turbine, under an R & D programme supported by the Scottish Office Industry Department SPUR programme [1].

The 7.2m glass-epoxy blade is manufactured by resin-infusion moulding (RIM), and introduces a number of structural innovations. These include infusion-bonded root studs that are moulded into place with the laminate (Figure 1), and in-mould infusion of the load-bearing unidirectional (UD) glass 'girder' (Figure 2). In addition, the blade is a commercial product in its own right, supplanting the wood-laminate design previously used by the AOC15/50.

By early 2001 the blade development programme had proceeded as far as full-scale static and fatigue tests [2,3] at the NREL National Wind Test Centre in Colorado, with highly promising results. A further project to test a set of blades on a wind turbine on a high wind site – the island of Luing in Argyll – was also under way, with funding support from Scottish Enterprise Fife. This was curtailed, however, by the insolvency of Aerpac UK.

In June 2001 NOI Immobilien GmbH, parent of the present blade manufacturing company NOI Scotland, acquired the design and tooling for the new 7m blade. A decision was then made by NOI Scotland to complete the Luing field test project, in order that the blade could progress into commercial production. Funds were then sought from DTI in support of this objective, and the present project was supported under Contract Agreement W/45/00622/00/00.

The project began formally in December 2001, and was originally due to be completed in July 2002. Delays affecting the delivery of the wind turbine, however, led to a late start to the experimental monitoring programme and an agreed extension to the contract to February 2003. The present report concludes the contract.

3 PROJECT DESCRIPTION

The original blade development programme comprised three phases, namely (1) design and prototype manufacture, (2) laboratory testing of components and complete blades, and (3) full-scale field trials on a high-wind site. When Aerpac UK went into Administration (see above), the first two phases were complete and construction of the test project under (3) was well advanced.

The present project was therefore concerned with the completion of the field tests, and comprised the following tasks:

Construction and commissioning: Completion of essential electrical works, commissioning the wind turbine, and installation of test instrumentation. *Note*: the design and build of the wind turbine foundations and winch system used to erect the turbine are the subject of a separate DTI-supported project: see Ref. [4].

Test and measurement: A minimum two-month measurement and test exercise to establish rotor performance and blade root loading, particularly in high winds. Results to be compared with design values and prior measurement elsewhere (both laboratory and field tests).
Management and reporting: Principally management of subcontracts, and issuing agreed progress reports to ETSU.

The details are described below.

3.1 Construction and Commissioning

The test site on Luing had been identified some time prior to the project, and wind monitoring had established the annual mean wind speed at 10m of 7.0m/s, but with large seasonal variation, and particularly high winds during the winter months. The site is in Argyll, on the west coast of Scotland, and highly exposed to the sea. The maximum 3s gust recorded on the site to date is 44.7m/s (100mph).

The set of 7.2m test blades was manufactured at the NOI Scotland Kirkcaldy factory, and shipped to site on Luing in late 2001. The blades were temporarily stored in a farm building pending delivery of the wind turbine from the manufacturer Atlantic Orient Corporation of Vermont, USA. In the event, the turbine delivery was subject to an extended delay, with all parts eventually arriving on site in August 2002.

A further slippage of approximately 5 weeks occurred due to one of the turbine tower legs being faulty, requiring a replacement to be manufactured and air-freighted from the USA. The erection of the turbine was eventually carried out in early September 2002 (Figure 3). Full details of the construction process, and the innovative infrastructure design, are contained in a separate project report [4].

All LV electrical works were completed, including cabling from the substation to the wind turbine and installation of control and switchgear in the substation, in a subcontract to W T Parker. Energisation of the turbine was on 13th September, with final commissioning by an AOC Canada field engineer the following day. Protection testing of the grid connection was carried out on October 17th, since when the wind turbine has run in unattended operation.

3.2 Test and Measurement

Prior to erection of the wind turbine, one of the rotor blades was strain-gauged to measure root flapwise and edgewise strain (Figure 4). Two gauges were installed per load direction (Figure 5), at a radial location corresponding to that previously used in fatigue tests by NREL on the prototype glass-epoxy blade [3]; this enabled direct comparison of field strain measurements with the laboratory tests.

Element Engineering Ltd. carried out strain gauging and instrumentation under subcontract to NOI Scotland. Strain gauges were Vishay Type CEA-06-250UT-10C, each configured in a full bridge arrangement via the data logger wiring panel (see below). All the gauges were oriented parallel to the blade long axis, to respond to direct strain due to bending.

A Campbell Scientific CR10 data logger, with data storage module and DC power supply, was installed in a hub-mounted enclosure on the wind turbine rotor, drawing power from the on-rotor electrical supply used to energise the blade tip brakes. After a short period of operation it was found that the logger power supply had been damaged by higher than expected voltage levels: a new unit was quickly sourced and fitted.

Originally it was intended to interrogate the data logger remotely using a GSM modem system, also supplied by Campbell Scientific, but this system proved unreliable in practice. Strain data has therefore been downloaded periodically by direct access to the rotor hub: the CR10 storage module is capable of holding several months' data.

An existing 10m met mast at approximately two rotor diameters (30m) distance from the wind turbine was utilised for the tests. Wind speed was measured as 10-minute means, using an NRG-40 pulse anemometer and Isodaq VF1 data logger, the latter chosen for its very low power requirements, and the capability to store up to 55 days' data based on 10-minute averages. The measurement exercise began on 23 November, 2002, during a period of relatively strong winds, and logging has continued since then.

Measurement of the wind turbine electrical power curve was achieved using an additional VF1 data logger installed in the turbine main control panel. This logger was configured to record 10-minute averages, based on a 0-5V analogue signal from the wind turbine's own power transducer. The VF1 clock was first synchronised with those on the external met mast and hub-mounted data loggers.

3.3 Management and Reporting

Management of the project has been carried out by NOI Scotland Limited, as main contractor. Two major subcontracts were placed within the project, to W T Parker of Grantham (£13.5k approx) for completing the LV electrical works for the turbine, and to Element Engineering (£2.6k) for strain gauging and instrumentation work: the details are discussed above. Both subcontracts were completed without any problems, expeditiously, and within budget.

The original reporting schedule called for three interim reports, and one final report. Due to the delays introduced by the late delivery of the wind turbine, however, this was amended to two interim reports only, plus the final report. The project was completed in mid-March 2003, slightly later than the formal deadline of 28th February.

4 RESULTS AND ANALYSIS

4.1 Strain histories

The time histories of two of the strain gauges during the month beginning 24 November are shown in Figure 6, together with the corresponding mean wind speed. The upper chart shows strain from flapwise gauge A, on the high-pressure (upwind) blade surface; the lower chart shows the simultaneous data for edgewise gauge C on the blade leading edge. Each data point refers to a 10-minute sample, with the mean, maximum and minimum strains recorded; the wind speed is the 10-minute average.

The correspondence between peak flapwise strain and wind speed is clearly seen in Figure 6; the edgewise strain data show a similar, though less pronounced, relationship to wind speed. Both strain records indicate a high degree of reversed loading which, in the flapwise case (gauge A) is slightly unexpected, and likely to be significant in regard to fatigue performance; in the edgewise case reversed loading is due to the strong influence of blade self-weight.

Strain histories for gauges B (flapwise, LP surface) and D (edgewise, trailing edge) are not shown here. The former is, however, almost a mirror image of the data from gauge A as they are positioned on opposite sides of the flapwise neutral axis (see Figure 5). Strain on gauge A is predominantly tensile and B compressive, but as noted above, a significant amount of reversed loading is apparent on both. The gauge D signal suffered from an intermittent fault that limited (though not to zero) the amount of useful data.

During the period shown the maximum 10-minute wind speed was 21.4m/s. The peak gust is unknown, but based on typical wind statistics a value of around 24m/s is likely. Note the periods of wind speed below 5m/s when the turbine goes off-line, and the extreme strain values converge on the mean. At the time of writing the wind turbine was also experiencing some control problems, evidenced by shutdown on over-power: an instance of this is seen in Figure 6 in late November, in a wind speed of 15-20m/s.

4.2 Comparison with design values

Mean and extreme strain values for gauges A, B, and C are shown as a function of average wind speed in Figure 7. Data from gauge D are omitted, for reasons noted above. From the given plots it is seen that strain extremes increase with wind speed, at first gradually, but above around 12m/s more markedly. The change in characteristic may be due to the onset of blade stall. The high degree of reversed loading on all three gauges is also clearly seen.

A summary of peak strain measurements is contained in Table 1, together with design values: note that the latter are actually referred to Station 43, approximately 130mm further outboard of the present gauge location, but the locations are sufficiently close for valid comparison. Note also that the design load case for flapwise loading is the maximum gust on the stationary rotor, and for edgewise loading the transient torque due to a generator short-circuit.

Table 1 - Peak strain values: comparison of measurements made to date (10-minute mean wind speeds up to 21.4m/s) with design values.

Gauge	Location	Primary Loading	Microstrain $\mu\varepsilon^*$		
			Peak measured	Design value	Strain at NREL 'target' load
A	HP flapwise	Tensile	+1400 -800	+3400	+2750
B	LP flapwise	Compressive	+600 -1400	-3200	-2350
C	LE edgewise	Variable	+700 -750	-2065	-1790
D	TE edgewise	Variable	+1000 -800	+2900	n/a

The measured strain levels shown above are all well within design values, though it should be pointed out that the loading conditions during the test period did not include the design drivers for either flapwise or edgewise bending (see above). Table 1 also contains strain values recorded during proof tests at NREL [2], where the prototype blade was independently subjected to static flapwise and edgewise loading equivalent to the two design cases.

4.3 Peak bending loads

The strain data may be converted to equivalent bending moments using the results of the NREL tests referred to above. Although the prototype blade used for static testing was of slightly different laminate construction to the Luing blades, conversion factors from strain gauge output to applied loading may be based on the NREL tests with reasonable accuracy; the same gauge locations were used in both cases. The following factors are then derived:

Gauge A (flapwise): 30.7 Nm/$\mu\varepsilon$

Gauge B (flapwise): 35.9 Nm/$\mu\varepsilon$

Gauge C (edgewise): 33.8 Nm/$\mu\varepsilon$

Using these factors the peak bending loads for the Luing machine are then as shown in Figure 8. Also shown are historic field data for the original AOC15/50 wood-laminate blade, measured at Bushlands in Texas [5]. The comparison is not exact as (a) the Bushlands machine was US standard with 62 RPM rotor speed as opposed to 60 RPM on Luing, and (b) the loads on the former were measured on the hub, approximately 800mm further inboard than the gauge locations on the Luing blade.

Nonetheless it appears from Figure 8 that the peak bending loads on the new glass-epoxy blade are broadly comparable to those on the original wood-laminate blade. This is not entirely surprising, as the new blade has exactly the same aerodynamic design and geometry as its predecessor [1]. It is

* $\mu\varepsilon$ = microstrain (1$\mu\varepsilon$ = 0.0001% units of strain)

worth noting, however, that no high wind data were collected at Bushlands, and that the Luing machine is testing the blades to significantly higher loads than documented previously.

The design flapwise bending moment for the GRE blade is approximately 64kNm at the Luing strain gauge location, calculated for the case of a gust of 60m/s acting on a stationary blade. The load at which destruction occurred in the NREL flapwise test [2] equated to 127 kNm, or almost double the design load. Thus the highest flapwise load seen to date on Luing (41kNm) is equivalent to 64% of the design load, or 32% of the structural capacity of the blade.

The design edgewise moment is 45kNm, for the case of a generator short circuit, while the (non-destructive) proof load test at NREL involved an edgewise load of 60kNm. These figures compare with the maximum value of approximately 25kNm recorded on Luing; the latter seems relatively high, and may have been exaggerated by an offset drift in the gauge signal. Notwithstanding this possibility, the Luing blade has to date experienced 56% of the design load, or 42% of its proven structural capacity.

The flapwise loads experienced by the blade with the rotor stationary are shown in Figure 9, as strain range against mean wind speed. Peak strain is not plotted, as zero-offset variation tends to obscure the trend at low strain levels (zero offsets are transparent in strain range readings). The data indicate a wind speed-squared dependency, as expected assuming the rotor remains oriented downwind. The equivalent flap bending moment is based on the NREL calibration data (see below).

The extreme strain range shown in Figure 9 is around $200\mu\varepsilon$, corresponding to a flap load of 6kNm. Assuming the V^2 dependency holds good, these figures would rise to $1800\mu\varepsilon$ and 54kNm respectively, in a wind speed on 60m/s. These accord reasonably with design values for the maximum gust case, albeit they are based on strain range (rather than peak) measurements: there is some evidence that peak strain and range are similar in the stationary case, which would go some way to explaining this finding.

4.4 **Fatigue loading**

A complete fatigue evaluation based on the measured data cannot yet be made, as strain records are limited to 10-minute statistical results only: the on-rotor data logger is not programmed to record fatigue loads explicitly, eg. in a rainflow matrix format. Nonetheless some broad comparisons can be made between measured and predicted strain ranges, in regard to blade fatigue life.

Table 2 shows the maximum and mean strain ranges recorded to date on the test turbine, in wind speeds up to 21.4m/s. The data represent the peak-to-peak strain variation in a given 10-minute record; the complete experimental data for gauges A and C are shown as scatter plots in Figure 10. The limitation of this data is that there is no information regarding the frequency of occurrence within the 10-minute sampling period, hence cycle count information is missing.

Table 2 - Strain ranges: comparison of Luing field measurements with design data used in NREL prototype fatigue tests.

Gauge	Location	Primary Loading	Microstrain $\mu\varepsilon$				
			Luing 10-minute range values		NREL fatigue test		
			Highest	Average	Range	Mean	Cycles*
A	HP flapwise	Tensile	1908	342	1580	870	1M
B	LP flapwise	Compressive	1860	344	1440	790	1M
C	LE edgewise	Variable	1162	280	445	118	1M

** Design life is nominal 1M cycles, but flapwise failure occurred in practice at 4M (M = million cycles). Edgewise test was planned but not yet carried out.*

Table 2 also contains strain data from the NREL flapwise fatigue test programme [3], and that planned for a subsequent edgewise test (though not carried out in practice). The strain data are based on the design fatigue spectrum, distilled into a constant-amplitude loading regime for the laboratory tests; the nominal lifetime is represented by 1 million cycles at the given ranges. When the flapwise fatigue test was carried out, the blade in fact survived some 4.4 million cycles (Figure 11).

The NREL test results are therefore equivalent to the blade experiencing a flapwise strain cyclic range of 1600$\mu\varepsilon$, 25 times per hour for the 20-year lifetime of the wind turbine, or over four times per 10-minute period. The Luing data indicate, however, that flapwise strain ranges exceed the NREL test values in wind speeds above 15m/s only (Figure 10), and that the average 10-minute strain range is only 342$\mu\varepsilon$.

The foregoing comparison lends some confidence to the fatigue design of the new blade. Nonetheless a number of points should be made regarding the results, as follows:

(a) The NREL flap fatigue tests were carried out at an R-ratio ($\sigma_{min}/\sigma_{max}$) of 0.1, whereby there is no strain reversal on either the LP or HP surfaces. The Luing data, by contrast show a marked occurrence of strain reversal (see above) and an R-ratio of around –0.6 is more appropriate. The NREL strain ranges therefore correspond to higher peak stress; the difference may be accounted for by a Goodman constant-life diagram [6].

(b) The reason for the flapwise strain reversal is not entirely known. The two obvious possibilities are the once-per-rev tower shadow impulse (the AOC15/50 has a downwind rotor), or gyroscopically induced bending moments due to yaw (the turbine operates in free yaw). The latter seems more logical, as yaw action introduces a 1P reversed flapwise bending load: the marked increase in cyclic strain in winds above 12m/s may then be due to higher turbulence-induced yaw rates. Measurements at a higher sampling rate would be needed to resolve these issues, and also to indicate the occurrence of extreme fatigue loads.

(c) The flapwise load cycles may be reduced by the introduction of a yaw damper, should excessive yaw action turn out to be the cause. It is understood that AOC at one time considered using a yaw damper, and that the tower top is designed to accommodate one.

(d) The lack of load frequency information is a limitation of the Luing strain data, and a complete fatigue assessment would require collection of strain data in a rainflow matrix format. This could be done with the existing data logging equipment, but is not currently planned.

(e) No comparison can yet be made between the measured edgewise strain data and laboratory fatigue tests, for reasons noted above. The magnitude of peak edgewise strain (1000$\mu\varepsilon$) recorded on Luing in relation to the fibre cracking limit (5000$\mu\varepsilon$) gives grounds for confidence, however.

4.5 Power performance

The measured power curve is shown in Figure 12, based on 10-minute average data from the external met mast (with anemometer at 10m a.g.l.) and the wind turbine's own power transducer. The data correspond to just over 2 weeks' operation in mean winds up to 19m/s. The main points of note are:

1. The stall power level is approximately 60kW, rather than the nominal 50kW.
2. There is evidence of the turbine shutting down in wind speeds from 10-16m/s, as seen by the large number of 'drop out' data points between zero and 60kW.

The two phenomena are related: the turbine controller had been temporarily configured to shut down if a mean level of 64kW was exceeded for 2 minutes; the turbine would then auto-restart after a 15-minute period. Due to the higher than predicted stall level this condition was routinely occurring in high winds, however, with the observed results. Intermediate power levels (between zero and 64kW) are an artefact of the 10-minute data sampling period.

To overcome this problem the over-power level was restored to 67kW, as originally configured by AOC. This was done just before a period of calm weather, so not much data is available for comparison. From the small amount there is, however, the controller modification appears to have been successful. Figure 13 shows the power time series (10-minute data points) immediately leading up, then subsequent, to the controller modification.

It may be seen that in the few hours of high wind operation immediately following the controller change, the turbine ran continuously at a mean power level up to 64kW, at which previously it experienced regular shut-downs. In the long term it may be appropriate to re-pitch the rotor blades to a slightly less 'aggressive' setting, to limit peak stalled power: this option is available without modification to the wind turbine, and can in principle be achieved without removing the blades from the hub.

Alternatively, if the major wind turbine components are shown to be capable of continuous operation at the higher power level, the turbine could simply be uprated to 60kW. A review of the drivetrain ratings would be required in this respect. Finally, it may be noted that in the four months since commissioning, the turbine energy output has corresponded to a 38% capacity factor based on the nominal 50kW rating.

5 CONCLUSIONS

The Luing tests have satisfactorily demonstrated operation of the new blade in a range of wind speeds up to 21.4m/s, based on 10-minute means. High quality strain data have been obtained from both flapwise and edgewise gauges, showing clear correlation with wind speed. Higher wind performance will continue to be assessed after the formal end of this project.

In general the loads on the new blade are well within design parameters, although it is clear that the Luing machine (as intended) experiences somewhat higher wind conditions, and correspondingly higher blade loads, than previously instrumented AOC15/50 wind turbines.

Further measurements, made at higher sampling frequency and including correlation with yaw motion, are needed to ascertain why flapwise strain shows such a pronounced reversal. While the magnitude of the strain ranges is not necessarily a cause for concern, the design fatigue spectrum should be revisited on the basis of the Luing data.

The rapid growth in flapwise cyclic strain with wind speed above 12m/s may correspond with stalled operation. This can be re-assessed once the rotor power curve is established, and an exercise to do this is now under way; otherwise, measurement of yaw activity may be needed to explain this phenomenon.

The design case for edgewise loading, generator short-circuit, cannot be simply tested in the field. Edgewise strains measured to date are relatively low, however, with no sign that normal or overspeed air-braking is causing unusually high loads.

The measured power curve, and operational behaviour in high winds, indicates that the blade pitch setting may not be optimal and that a small pitch increase is required. This can be accomplished relatively simply. Alternatively, it may be argued that the turbine could be up-rated to 60kW, pending review of the loading implications on the drivetrain and other major components.

Notwithstanding the above questions, the project has succeeded in all its principal objectives. The new blade has to date performed well in aggressive wind conditions, measured loads are within design values, and energy output has been high. The overall operation of the wind turbine is serving as a positive demonstration of a modern, small-scale wind energy plant suitable for remote and rural applications.

6 REFERENCES

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FIGURES

Figure 1 - The ‘keyed’ root studs used on the new blade: the studs are integrally moulded into the blade root laminate during infusion.

Figure 2 - Infusion moulding of the 7.2m blade: the primary structure (unidirectional glass fibre) is moulded integrally with the blade shell.

Figure 3 - The AOC15/50 wind turbine on Luing

Figure 4 - Attaching strain gauges to the test blade.

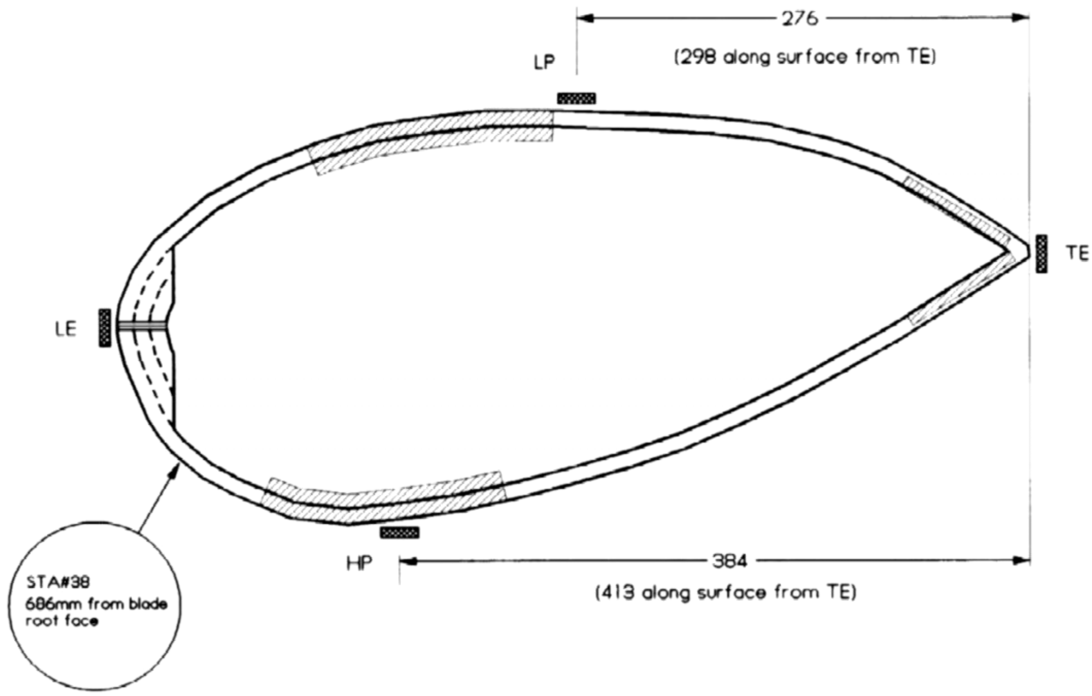


Figure 5 - Strain gauge locations: these were chosen to correspond with those used in the NREL static and fatigue tests [2,3].

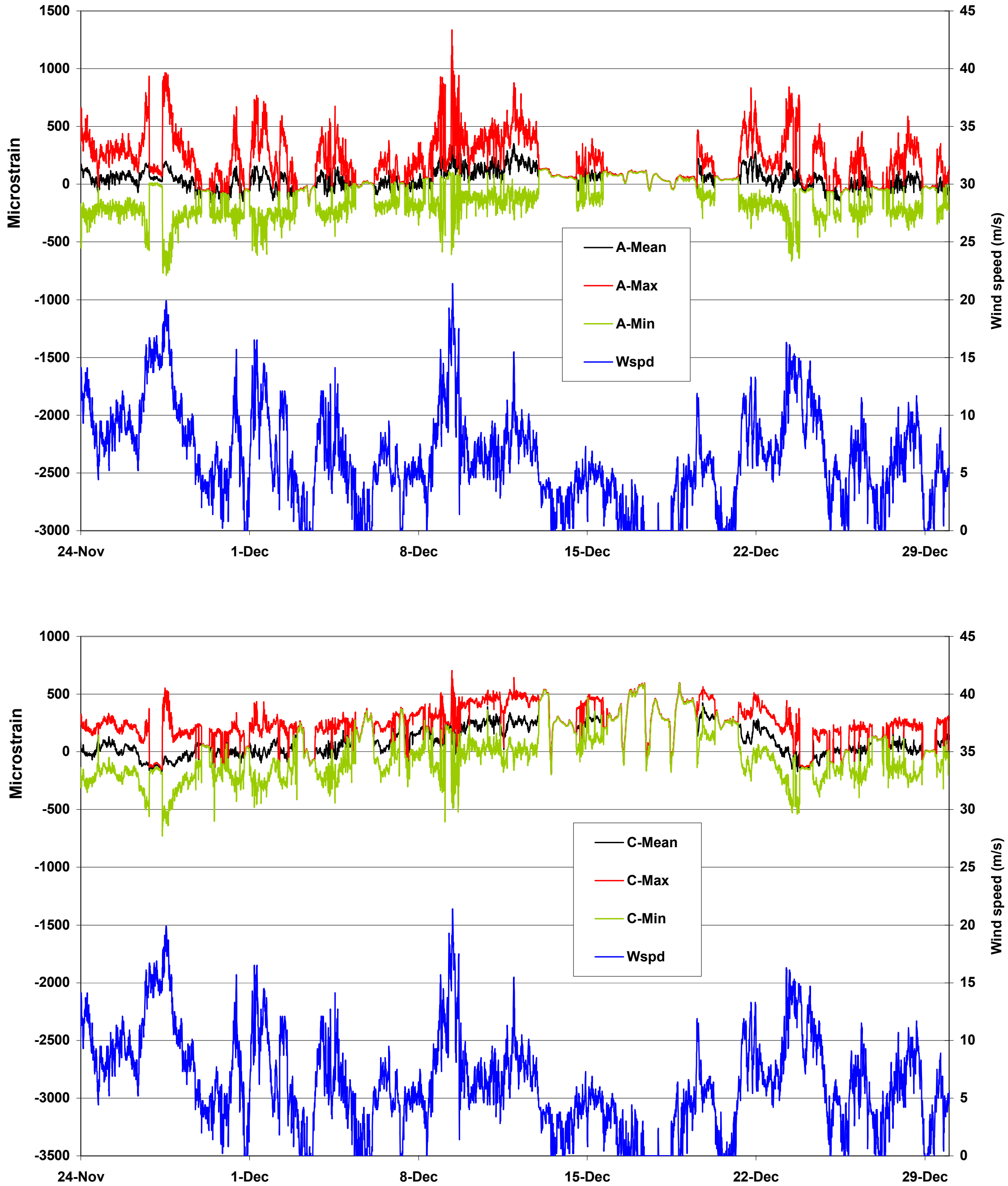
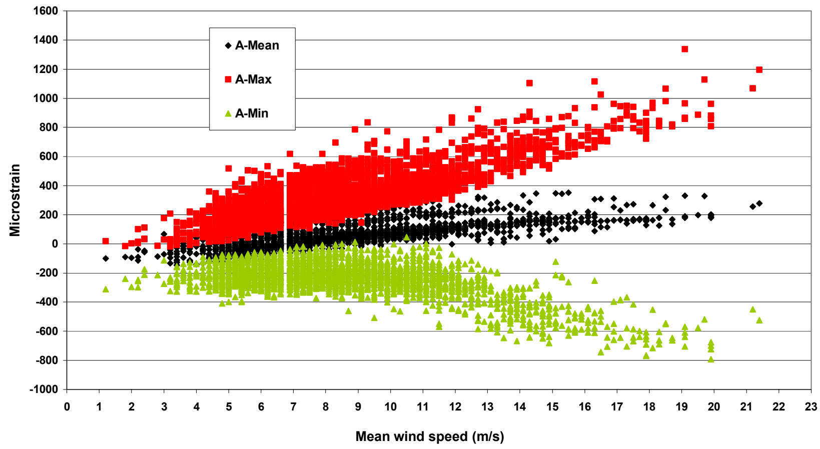


Figure 6 - Strain time series: approximately one month's worth of 10-minute strain data showing (*top*) high pressure flapwise and (*bottom*) leading edge edgewise strain; average wind speed is also plotted in both cases.



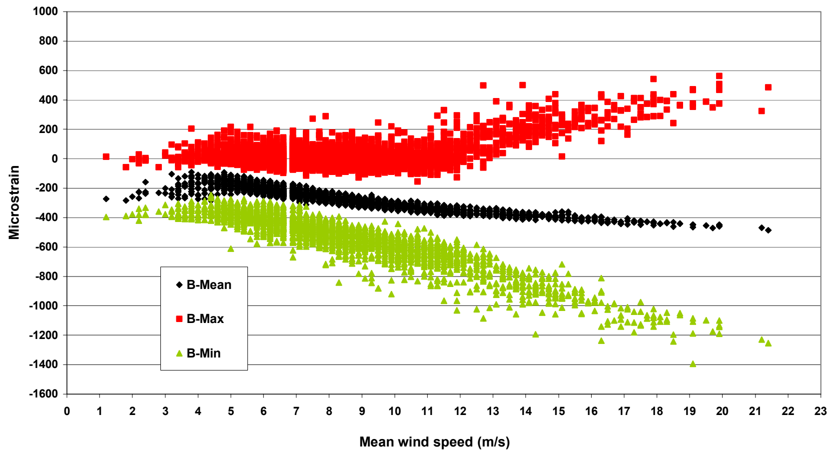
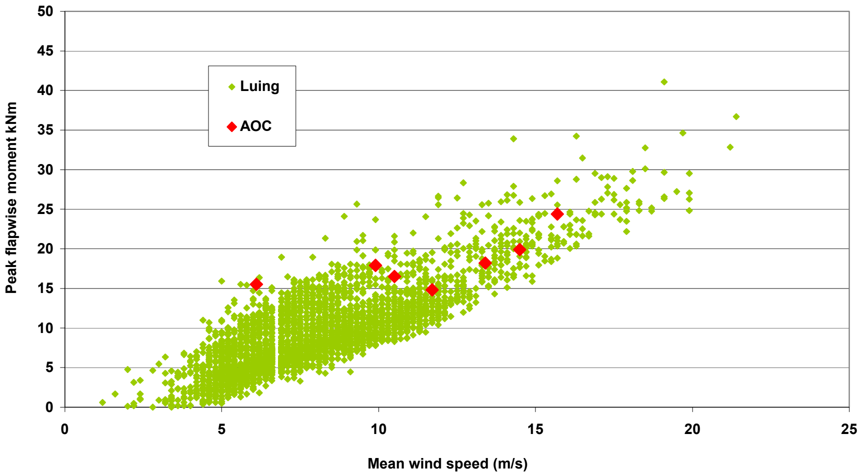


Figure 7 - Mean and extreme strain data as a function of wind speed; (*top*) HP flapwise, (*middle*) LP flapwise, and (*bottom*) LE edgewise strain.



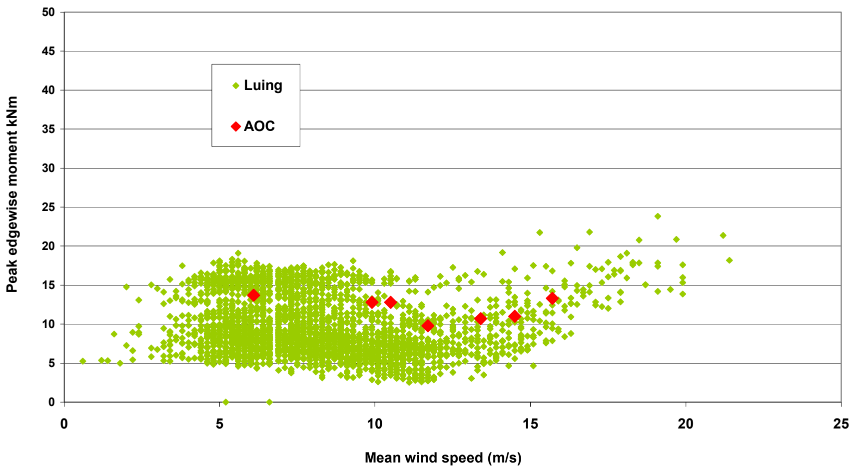


Figure 8 - Peak bending moments (*top*) flapwise and (*bottom*) edgewise, comparing Luing and AOC measured data [5]: Luing data are calibrated using NREL load factors.

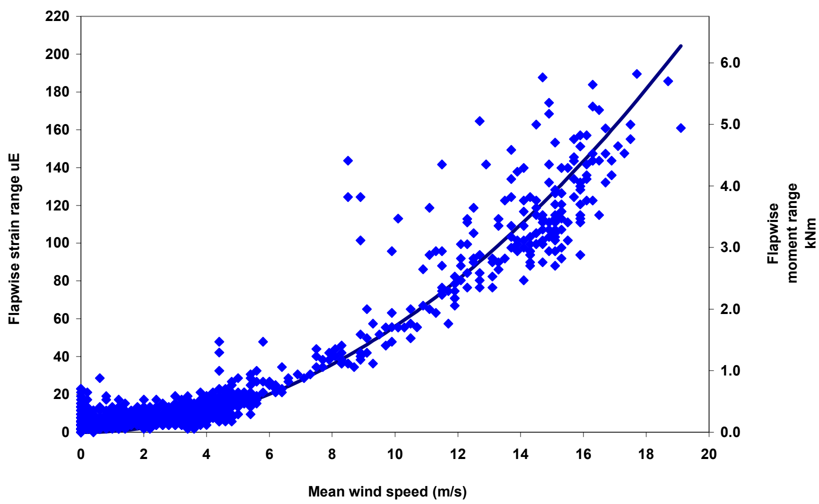


Figure 9 - Flapwise strain range as a function of wind speed, with rotor stationary.

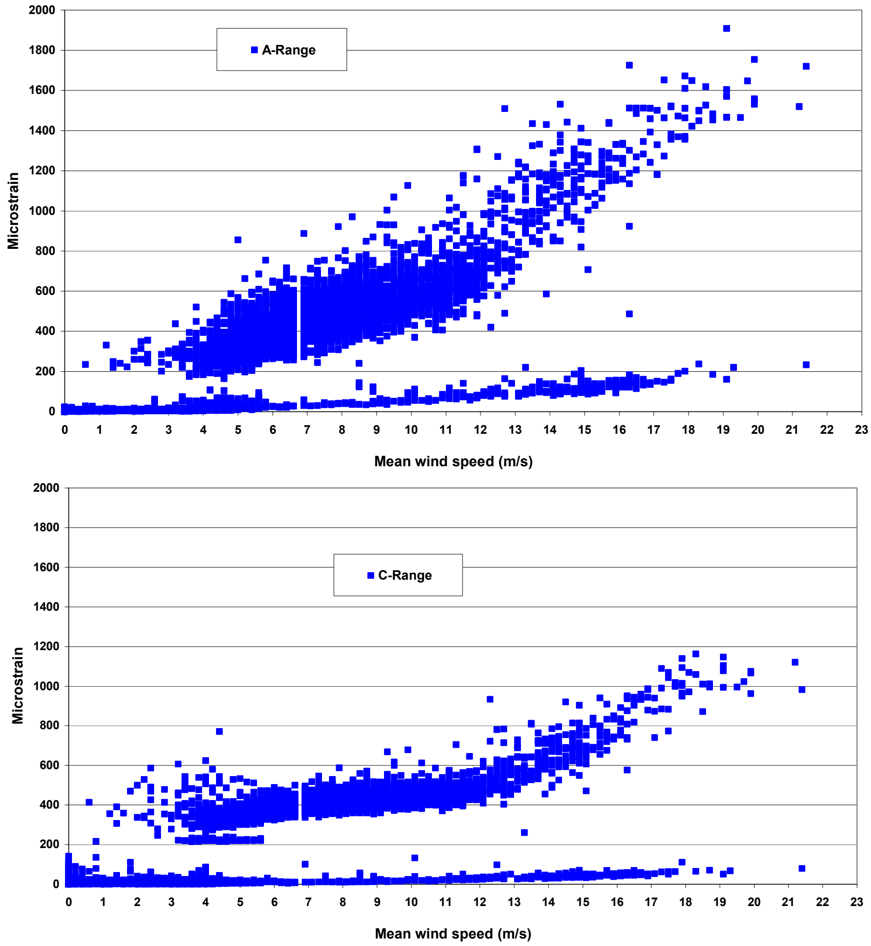


Figure 10 - Extreme strain ranges: (top) HP flapwise, (bottom) LE edgewise, as a function of 10-minute mean wind speed.

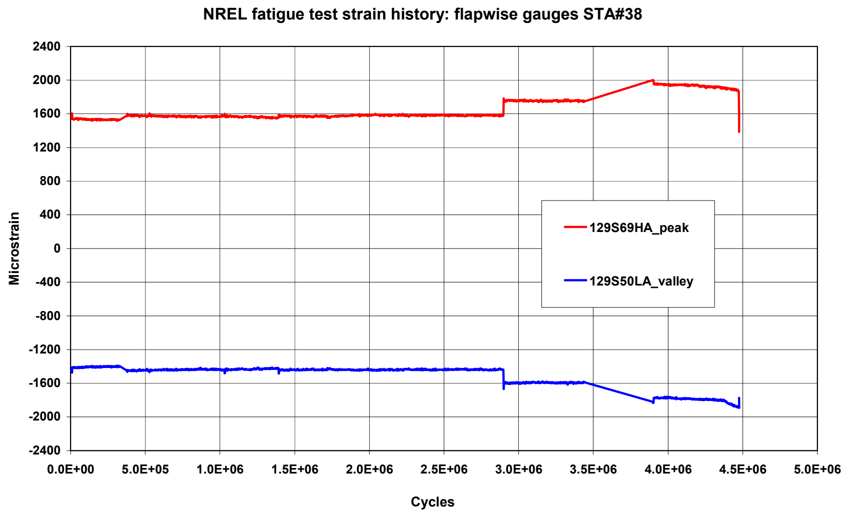


Figure 11 - Time series from NREL flapwise fatigue test [3], showing peak cyclic strain for (red) high-pressure and (blue) low-pressure gauges. Note the increases in applied load at 2.9×10^6 and 3.9×10^6 cycles, and eventual failure at 4.4×10^6 cycles.

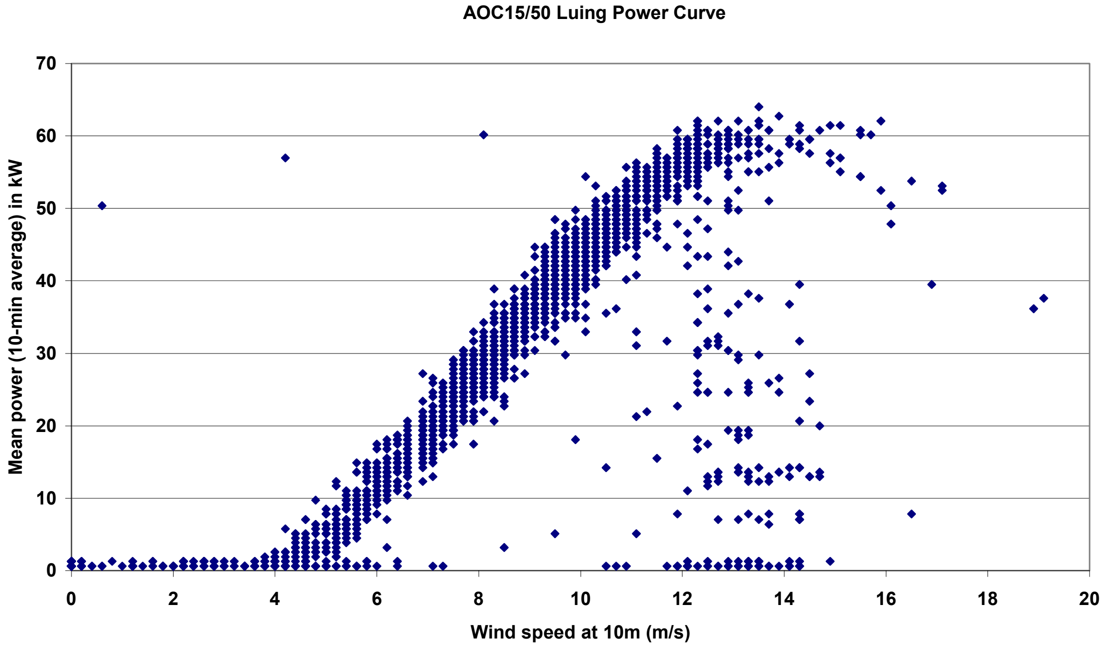


Figure 12 - Measured electrical power curve.

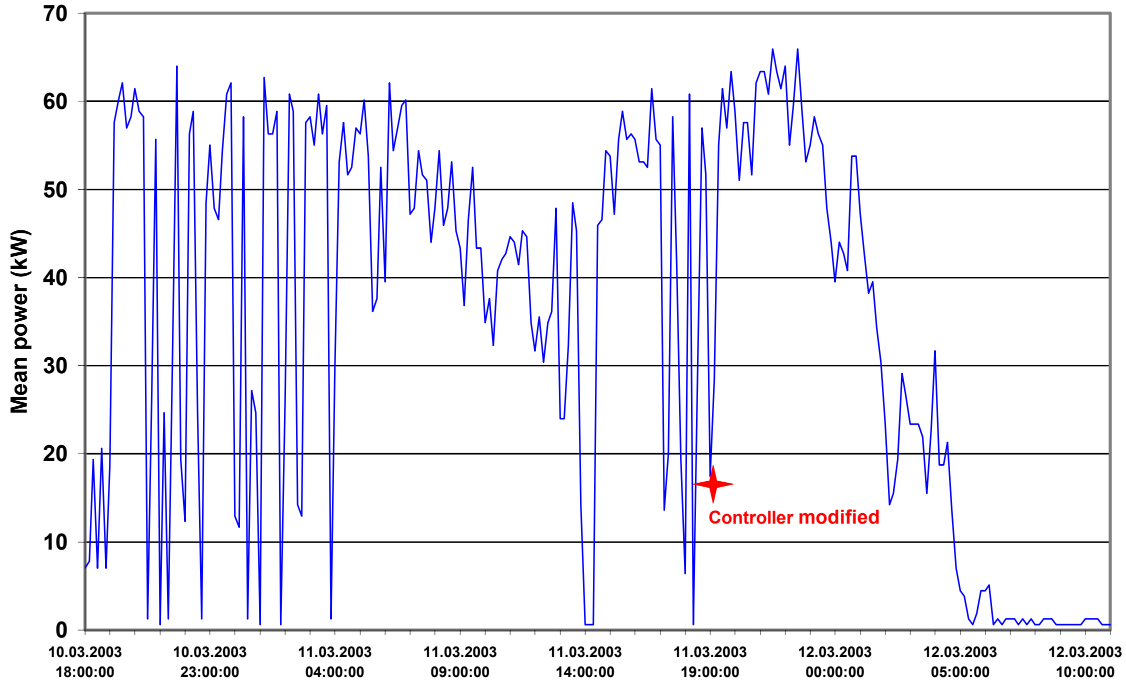


Figure 13 - Mean (10-min) power before, and after controller modification; note the uninterrupted period of high power operation subsequent to the change.