THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th St., New York, N.Y. 10017

94-GT-436

COMPRESSOR WASHING MAINTAINS PLANT PERFORMANCE AND REDUCES COST OF ENERGY PRODUCTION

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ABSTRACT

This paper reports about the results of a field test conducted over a period of 8000 operating hours on the effect of combined on line and off line compressor washing on a 66 MW gas turbine operating in a combined cycle plant at UNA's Lage Weide 5 power plant in Utrecht. Observations have shown a sustained high output level close to the nominal guaranteed rating, despite difficult atmospheric conditions. Investigations on the correlations between fouling gradients in the compressor and atmospheric conditions are also presented. The evaluation of the results demonstrate the importance of implementing an optimised regime of on line and off line washing in the preventive turbine maintenance program. It will improve the plant profitability by reducing the costs of energy production.

PLANT DESCRIPTION

Unit 5 at UNA's Lage Weide power station is situated beside the Merwedekanaal on the south western outskirts of Utrecht, some 60 km from the sea. A very busy motorway crosses over the canal near the plant and local industries include chemicals and food processing. The UNA power station and district heating complex comprises :

2 combined cycle plants of each 112 MW output including
two 35 MW gas turbines each (PEGUS 10 & 11),
1 combined cycle plant of 225 MW with one 150 MW
gas turbine (PEGUS 12),
1 combined cycle plant of 251 MW on order with one
164 MW gas turbine (Lage Weide 6),
due for commercial service starting in early 1995,

and the Lage Weide 5 combined cycle plant which originally was an Alsthom 270 MW steam turbine with an efficiency of 40.5 %, supplied in 1976. Conversion to a combined cycle was made during an outage at the end of 1986, and the plant returned to service in January 1987, at an output of 271 MW of which 66 MW is contributed by the gas turbine. The gas turbine is an ABB Type GT 11D5 which is designed for use in 60 Hz utility systems. The GT 11D5 was chosen because the exhaust mass flow gave the closest match to the original combustion air requirement. The gas turbine therefore drives a 3000 rev/min generator through a reduction gear box. Together all these various activities give rise to dust, salts and fine aerosols in the air.

WASHING EQUIPMENT AND PROCEDURE

A compressor wet cleaning system was devised by Turbotect which comprises 30 on line injection nozzles, each nozzle having a flow capacity of 0.38 l/min, see figure 1, and 7 off line nozzles which have been linked to the original washing skid which was delivered with the gas turbine in 1986.

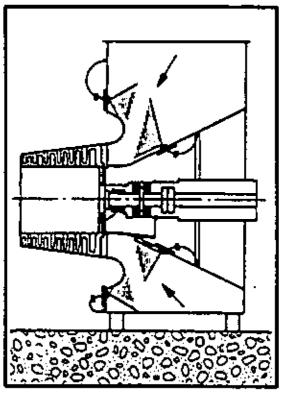

Fig. 1 Arrangement of on line spray nozzles in the intake of the GT 11 D5 gas turbine.

On line washing is performed under normal operating conditions. First demineralized water must be used because otherwise there would be the risk of corrosion in the hot parts due to the dissolved salts. Then the liquid must be applied in a uniform fine spray in order to achieve the maximum possible wetting of the 1st stage stationary compressor blades. The droplets must be small enough that they do not cause blade erosion, and light enough that they do not drop out of the air stream

Presented at the International Gas Turbine and Aeroengine Congress and Exposition
The Hague, Netherlands – June 13–16, 1994

before they reach the compressor blade surface. Also, the injection nozzles, see figure 2, must be designed and positioned so that they do not induce vibration in the inlet air stream. The injection nozzles are integrated in a spherical body which allows adjustement of the atomizing spray and are installed under the surface of the intake structure. The body can be rotated to set the spray angle but penetration of the nozzle into the air stream is minimal. The nozzles are arranged so as to inject a fine atomized spray into the air stream which will mix and be carried uniformly into the compressor bellmouth.

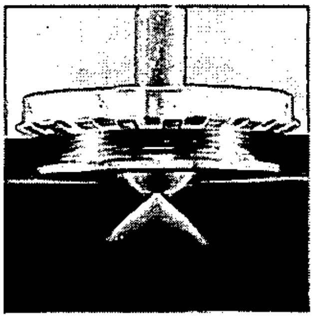

Fig. 2 On line injection nozzle (patented) allowing orientation and fine tuning of the spray in any direction.

The on line washing procedure followed at the plant consists of first injecting a wash solution of 20 % Turbotect T-927, an organic solvent based cleaner, and demineralized water for 10 to 15 minutes, amounting to 23 to 34 liters of chemical cleaner concentrate and 92 to 138 liters of demineralized water, followed by a rinse with demineralized water for a similar time period, requiring a quantity of 115 to 172 liters. The organic solvent based cleaner was selected to dissolve the carbonaceous oily type of deposits found on the compressor blades.

TEST PROGRAM AND PROCEDURE

In the mid 80's UNA started to conduct extensive series of comparative compressor cleaning tests with regimes of crank wash and on line dry cleaning versus on line wet cleaning on their four 35 MW gas turbines of the combined cycle plants PEGUS 10 and 11. In the Spring of 1990 , UNA and Turbotect decided jointly to conduct a long-term series of tests, on the 66 MW gas turbine of the Lage Weide 5 plant to determine the effect of combined on line and off line compressor cleaning on the plant's performance, profitability, and its impact on preventive gas turbine maintenance. A test program and procedure was agreed to, including provision of standardized record sheets and measuring equipment in addition to the plant's existing instrumentation and recording equipment.

Extended time test program

The tests were conducted over 18 months from 18th May 1990 to 18th November 1991. A planned outage for a major overhaul lasted from December 7th 1990 to February 26th 1991. During the entire test period the gas turbine unit operated for a total of 8'089 hours under the combined on line and off line wet cleaning regime.
Before the start of the long term test trial, a hot gas path inspection and an off line wash were performed. Thus the tests aimed to give some comparative indications of the effectiveness of on line washing as applied to a new machine, and to one that operated for several years.

Test conditions

The gas turbine is operated with natural gas from the Groningen field, and fouling of the turbine hot section of the gas turbine can be disregarded. An on line compressor wash was performed, on average every 92 operating hours at full load with the gas turbine on temperature control mode at the same turbine inlet temperature : 1000°C. Gas turbine performance was measured before and after each wash and corrected with the help of a computer program to the original guaranteed value of site ambient conditions for a new and clean unit. Readings were taken approx. $1^1/_2$ hours after completion of an on line wash. Figure 3 summarizes the actual carried out test program.

	Evaluation block I		***Evaluation block II***	
Period	***Start***	***Finish***	***Start***	***Finish***
Date	***5/18/90 -***	***12 /7/90***	***2/26/91 -***	***11/18/91***
Op. hrs. counter	*22'493*	*26'408*	*26'551*	*30'725*
No. on start counter	*359*	*394*	*409*	*483*
No. of starts in period		*35*		*74*
Op. hrs. in period		*3'915*		*4'174*
No. of on line washes		*38*		*45*
Av. hrs. between washes		*95*		*89*
No. of off line washes		*3*		*2*

Fig. 3 Carried out test program, a planned major overhaul lasted from 7 December 1990 to 26 February 1991.

MEASURING EQUIPMENT

In addition to the plant's existing instrumentation and recording equipment, the following instrumentation were added :

2 mercury precision thermometers in the air inlet,
4 pressure taps connected together to a U-tube to measure the compressor air inlet pressure after the silencer and the air inlet elbow,
4 pressure taps connected together to a U-tube to measure the pressure after the gas turbine, in the exhaust.

MEASURED VALUES AT THE PLANT

The following data were measured and recorded :

At the gas turbine control panels :

Number of operating hours
Equivalent operating hours
Number on start counter
GT inlet temperature, instrument and recorder readings
GT exhaust temperature, instrument and recorder readings
CDT compressor discharge temperature
Power factor (cos φ) and power output
Generated power at generator terminals (power meter)
Reactive power meter
Barometer pressure

At the gas turbine unit :

Relative air humidity
Air inlet temperature, before and after filtration system
Pressure loss across the coarse and fine filter as well as across the entire air filtration system
Air pressure after the air inlet silencer and elbow
CDP compressor discharge pressure
Exhaust gas pressure
Gas flow at the gas suppliers metering station
Gas flow at UNA's gas metering station
Gas pressure and gas temperature

On the washing procedure :

Cleaning injection time and cleaning injection flow
Rinsing time and rinsing flow
Quantity, concentration and type of cleaner used .

Natural gas composition, density and heating value :

The PEGUS 12 gas metering station (225 MW combined cycle plant) located in the same complex is equipped with an on line gas chromatograph. Results on gas composition analysis and relative gas density are available, however covering intermittent operating periods only. Monthly analysis results on LHV and HHV from the natural gas supplier are also available.

Other recorded observations :

Weather observations (rain, sun, clouds, fog, snow, etc.)
Wind direction, anti icing system on or off ?.

DATA MEASURED BY THIRD PARTIES

Meteorological measurements

Measurements on the atmospheric conditions made at the local meteorological station located at De-Bilt, some 10 km from the plant, were made available by the Royal National Meteorological Institute. The data covers the entire test period (8'089 operating hours) with hourly readings of :

Air temperature and barometric pressure
Relative air humidity

and daily readings of :

Average daily wind forces and wind directions
Sum of daily precipitation.

Measurements of aerobiological data, atmospheric dust and aerosol concentration in the air

See separate relevant paragraphs.

RESULTS OF THE COMPRESSOR CLEANING REGIME

Figure 4 summarizes the pattern of the corrected power output for the complete test period.

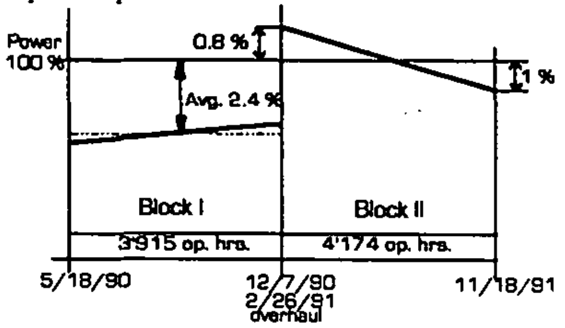

Fig. 4 Summary pattern of the corrected power output

Figure 17 in appendix A shows in more detail this corrected power output pattern as well as the trend analysis against operating hours. Figures 18 to 26 in appendix A show the output variations on an extended time axis of between 900 to 1000 operating hours. For the purpose of evaluation the test period covering in total 8'089 operating hours was divided into two blocks.

Corrected power output in the evaluation block I :

The corrected results of this compressor wet cleaning regime show that the gas turbine plant was operated during the first evaluation block between May 5, 1990 and December 7, 1990 for 3'915 hours at an average power output of 64.56 MW, equivalent to a load factor of 97.6 % or 2.4 % below the original guaranteed site power output at new and clean conditions. The number of operating hours of the gas turbine at start of the test evaluation block I was 22'493 and 26'408 at the end of this period. During this period 38 compressor on line washes were performed, on the average of one every 95 hours or one every 4 days. In addition, three off line washes were performed; the first was performed after 760 operating hours, the second 2'435 hours later and the third 605 hours later. Each off line wash was made with the unit out of service at crank speed and cooled down. Off line washes were performed on a short notice, by taking the opportunity when the gas turbine plant was shut down for a few days during the test period. Due to this, no performance test measurements before crank washing were made in two cases, however the average power output increase after an off line wash in the first evaluation period is estimated to be approximately 1'800 kW. The trend analysis of the performance tests made in this period is nearly horizontal, showing that aging due to mechanical wear and tear of the gas turbine has already stabilized.

Corrected power output in the evaluation block II :

In the second period, February 26, 1991 to November 18, 1991 the gas turbine started in practically new and clean condition as the result of some blade replacement and other work made during the overhaul and unit recommissioning, which took place between December 7, 1990 and February 26, 1991. The corrected results of the compressor wet cleaning regime in the second evaluation block show that the gas turbine plant operated for 4'174 hours at an average power output of 66.23 MW, equivalent to a load factor of 100.16 % or 0.16 % above the original guaranteed site power output at new and clean conditions.

The number of operating hours of the gas turbine at start of the test evaluation block II was 26'551 and 30'725 at the end of this period. During the second period 45 compressor on line washes were performed, on the average of one every 89 hours or one every 4 days. In addition, two off line washes were performed; the first after 1'143 operating hours and the second 1'381 hours later. Two performance test measurements before crank washing are missing, the average power output increase after each off line wash in the second evaluation period is estimated to be approximately 1'000 kW. Three performance test measurements before on line cleaning are missing as well in the second test period.

	Evaluation block I	*Evaluation block II*	*Total*
Operating hours	*3'915*	*4'174*	*8'089*
No. of on line washes	*38*	*45*	*83*
No. of off line washes	*3*	*2*	*5*
Total No. of washes	*41*	*47*	*88*
Total No. of MP's before & after washes	*82*	*94*	*176* *100 %*
Missing MP's before off line washes	*2*	*2*	*4*
Missing MP's by on line washes	*0*	*3*	*3*
Total missing MP's representing ...	*2*	*5*	*7* *4 %*
Available MP's representing ...	*80*	*89*	*169* *96 %*

Fig. 5 Yield of performance test measurements

Corrected efficiency :

One purpose of the extended time test program was to find out the effect of the combined on line and off line washing regime on the corrected gas turbine plant efficiency. The efficiency calculations by heat balance have shown not to be accurate enough for this determination. The calculated turbine inlet temperature, TIT, by heat balance was in many cases slightly higher than the computed TIT, used for turbine temperature control operation, recorded and indicated at the turbine control panel. The computed TIT is calculated by means of the following relation :

$$TIT = k_1 * Te_2 + k_2 * \Pi + k_3$$

with Te_2 the measured gas turbine exhaust temperature , Π the measured compressor pressure ratio and the constants k_1, k_2 and k_3. The cause for the deviation in TIT's between heat balance and computed value is due to the incomplete data over the testing period with regards to results of gas analysis and gas densities required to determine LHV's; the latter are necessary to get accurate corrected efficiencies and turbine inlet temperature by heat balance calculations. The computed value of the gas turbine inlet temperature is more precise, however no secured results on efficiency improvements due to the washing regime can be demonstrated.

MEASURING AND EVALUATION ACCURACY

In order to determine the accuracy of the corrected power output results, calculations of standard errors, mean, maximum and absolute errors due to the instrumentation and its impact on the evaluation have been analysed. The margin of errors and measuring tolerances results in an average measuring tolerance of 0.7 % and a maximum margin of error of +/- 1.5 %. Incorrect readings cannot be excluded, but they are rare and have not impeded the evaluation or the results and the conclusions, which can be drawn.

DISCUSSION OF THE EFFECT OF WASHING

Out of the 83 on line washes made during the total test period covering 8'089 operating hours, 87 % or 72 on line washes have demonstrated a positive power recovery with the unit in operation at full load. No power output recoveries were measured in three cases and power decreases after on line washes were measured in 8 cases (9.6 %) out of all performed on line washes. It is assumed that in one case icing occured during the on line wash which contributed to a loss in power output, whereas four cases showing negative results can be explained with the quality of the recorded instrument readings and three washes have shown power losses for which no explanations can be found at this stage. Figure 6 summarizes the above observations. The average power output recovery measured over the 72 on line washes with positive power improvements was 712 kW. This relative small amount represents 1 % of the unit's power output when new and clean and is dependant on the average power output level at which the gas turbine is operated, in our test program at 97.6 % in the first and 100.16 % in the second test period. The evaluated data demonstrates clearly the advantage of frequent on line compressor wet cleaning, when the unit is being operated at a high power output level. On line and off line cleaning are complementary, however the obtained results show that power recovery, due to off line cleaning, is not as significant, if the unit is operated at high power output, close to full load. This effect can be seen in the power recovery obtained after crank wash in the first test period, on the average 1'800 kW, when operated at a lower power output level (97.6 %) as compared to the second test period when the operated power output level was 100.16 % with 1'000 kW average power recovery after crank wash. The test program confirmed that frequent on line cleaning will extend the time interval between successive off line cleaning operations. Thus it is a real benefit to the operator, because the scheduled down time allowed for maintenance can be reduced, if the frequency of off line cleaning with its associated cooling down time can be reduced. The availability and performance, as well as the overall profitability of the plant will be improved.

Performed on line washes in 8'089 operating hours	*83* *100 %*
Measured power increases after on line washing in :	*72 cases* *86.7 %*
Measured decreases in power output after on line washes : *whereof 1 case probably due to icing* *4 cases due to the quality of the readings* *3 cases with no explanations*	*8 cases* *9.6 %*
No power output modification measured after on line washing	*3 cases* *3.6 %*
Observed power improvements in operating periods between two on line washes in : *due to starts & shut downs in :* *without explanations at this stage in :*	*18 cases* *13 cases* *5 cases*
Antifreeze in cleaning solution was used in :	*5 cases*

Fig. 6 Effect of on line washing on the power output

Influence of unit starts and shut downs on compressor fouling

In total 43 non-continuous operating periods between two on line washes have occurred during the complete test period. It is interesting to observe that out of this number, 13 periods (30 %) show an improvement in power output although the unit operated on the average some 4 days. This phenomenon can be explained by the fact that starts and shut downs can positively affect compressor fouling by spalling off deposits. The deposits may soak humidity during standstill and the weakened and swelled up material will partly spall off as the shaft is accelerated during start up of the gas turbine.

REDUCED COST OF ENERGY PRODUCTION

In the industrial environment at the power station, UNA reports up to a 10 % power loss on the average of over 4000 operating hours when compressor cleaning is not performed. By assuming similar criterias as used in the realistic cost calculation associated with compressor fouling and presented in the ASME Paper 91-GT-228 "Performance Deterioration in Industrial Gas Turbines", this would represent the following for Lage Weide 5 gas turbine plant :

Calculation basis : Engine on base load for 8'000 operating hours

Net power output	66'120 kW
Net heat rate	11'605 BTU / kWh
Cost of electricity is	0.04 US$ / kWh
Cost of natural gas is	2 US$ / MBTU

Taking an average yearly power decrease of 5 %, representing the difference between the actual average power output level at which the plant was operating during the test and an assumed average and realistic power shortfall due to compressor fouling in the assumption that the compressor would not have been maintained clean and an increase in heat rate of 1 %, then the plant production profitability has been improved during the extended time test program with a regime of on line and off line compressor wet cleaning by US$ 1'175'000.- over 8'000 operating hours, representing a very substantial additional profit. An amount of approximately US$ 20'000.- has been spent for the chemical cleaner consumed during the above test program, representing a very marginal cost as compared to the improved profitability.

Further, it has to be noted that without a regime of on line and off line compressor wet cleaning, and in the case of a combined cycle application, there will be an additional loss of profitability due to reduced steam production as a result of compressor fouling, this despite that compressor fouling results in increased exhaust temperature, the reduced exhaust mass flow having a greater negative effect.

CORRELATION BETWEEN POWER LOSSES AND ENVIRONMENTAL FACTORS

An interesting observation of the results are the different gradients of power losses which can occur over the same length of time between measurements. For instance in figures 7 and 8, the power loss gradients between point L-186 and L-187 is only 0.2 % over 71 hours, but 2.7 % over 69 hours between L-188 and L-189. These washes were few days apart; the power output level at which the gas turbine was operated and the time between cleanings are almost the same. Both operating periods were continuous, that is no starts and shut downs could affect the power loss gradients.

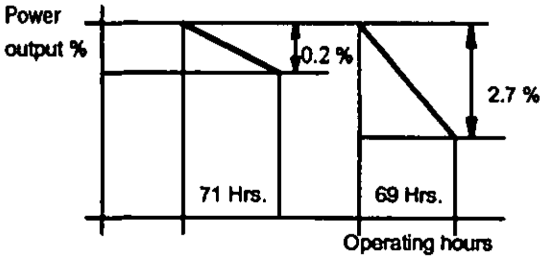

Fig. 7 Power loss gradients

Operating period	*L-186 to L-187*	*L-188 to L-189*
Date	*26th Feb to 1st March 91*	*1st to 4th March 91*
Operating hours	*71*	*69*
Power drop from	*67.66 to 67.56MW*	*67.84 to 65.99 MW*
Power loss	*107 kW / 0.2 %*	*1'851 kW / 2.7%*

Fig. 8 Measured power loss gradients under comparative conditions

It is generally assumed that power losses will increase with the amount of humidity in a specific environment. In an attempt to find a correlation between power loss gradients and environmental factors, the following investigation has been made on the basis of the data collected over the 8'000 operating hours test period.

Selection of comparative continuous operating periods

Out of 40 measured continuous operating periods, a total of 14 (35 %) periods with power output measurements made at the beginning of each period, after on line wash completion of the preceeding period, and at the end of the period, prior on line wash of the next period, can be compared. Each of the selected operating periods have between 70 to 72 hours. Figure 27 in Appendix B show the power output losses over the average 70 operating hours of the selected comparative continuous operating periods; 6 periods of the evaluation block I and 8 periods of block II. Operating period L-230/231 in the second evaluation block, suffered the biggest power loss with 3.1 %, whereas operating period L-198/199 in the same evaluation block gained 0.5 % in power output over 70 continuous hours.

Figure 28 in Appendix B displays the measured power losses versus the average relative humidity for each of the selected comparative continuous operating periods. No correlation could be deduced.

Compressor ingested humidity related water and vapor massflow

The next investigative step was to compare and determine the quantity and pattern of water and vapor massflow the compressor ingested over these comparative operating periods. For this purpose the average between the calculated compressor air massflows at the start and at the end of each operating period was formed. The compressor air massflows have been calculated by means of the heat balance.

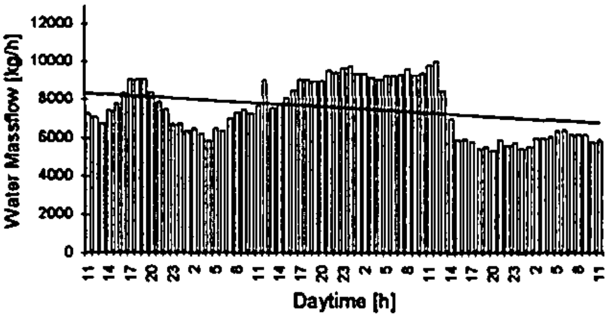

Fig. 9 Humidity related water and vapor ingested by the compressor during the operating period L-142/143

Figure 9 show the pattern, quantity and the trend of the humidity related water and vapor ingested by the compressor during the operating period L-142/143. The average ingested humidity related water amounts to 7718 kg/h, or in total 548 tons of water over the 71 hour operating period. The average compressor air massflow calculated for this period was 287 kg/s. The lowest average quantity of water ingested was in the operating period L-156/157 with 4'160 kg/h. Peaks were recorded with some 13 tons of water per hour.

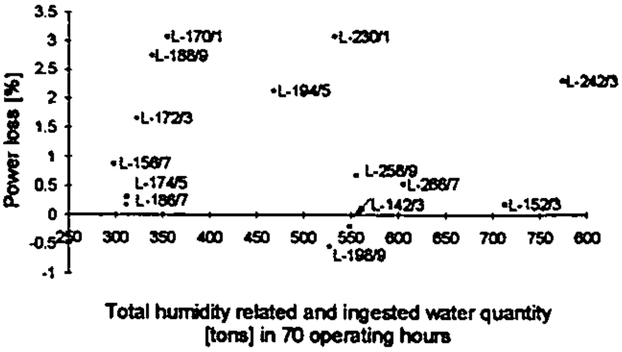

Fig. 10 Power losses vs. total humidity related water quantity ingested by the compressor for 14 comparative operating periods.

The measured power losses versus the total quantity of humidity related water ingested by the compressor for each of the selected comparative operating periods have also been plotted in figure 10 above. No correlation between the quantity of water ingested by the compressor and the power losses could be deduced.

In order to visualize the pattern of the water ingested, a trend analysis by summation of the daily ingested water quantity has been made with the following formula :

$$x_{(n+1)} = x_n + e^{m_{(n+1)}} * y$$

x = quantity of water ingested per hour
y = constant factor 10^{-3}
m = ingested water mass flow
n = hours

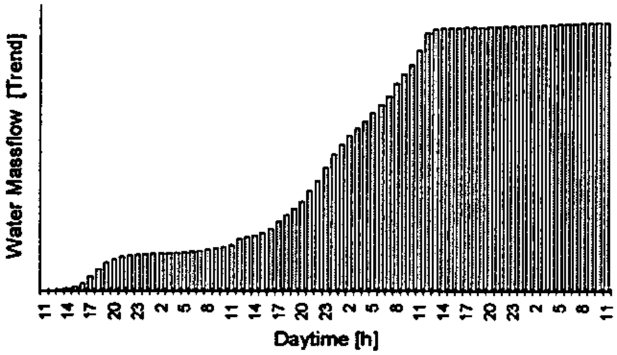

Fig. 11 Trend analysis of the daily ingested humidity related water quantity by the compressor in the operating period L-142/143

The ingested water massflow represented in figure 11 is a trend. It is interesting to note that the ingested water massflow was constant in the first few hours. Thereafter an increase followed by a constant period and again a steep increase between 5pm on September 18 and 2pm on September 19, 1990. The remaining operating hours in this period were characterized by a relative constant ingested massflow. The trend analysis of some of the operating periods are displayed in Appendix C page 16. Some operating periods have already been affected at the beginning of the period with very steep ingested water quantities (See operating period L-108/109), whereas some others have had a constant ingested water quantity, with a steep increase towards the end of the run in the respective operating periods (See operating period L-130/131). These various patterns affect the power loss gradient differently. It is most probable that a high volume of water ingested at the beginning of a period will affect the power loss gradient on a different degree, as if it was ingested towards the end of the operating period. However, no conclusions could be drawn from the analysis of these trends.

Humidity pattern in the compressor

Figure 12 shows the design compressor characteristic CDT vs. CDP for the gas turbine Lage Weide 5 with the ambient conditions measured during the performance tests L-258/9 (average of measuring points L-258 and L-259), that is :

ambient air temperature	12.15 °C
barometric pressure	1.004 mbar

Figure 12 is very significant. By projecting the water boiling curve one can see that the latter is crossing the compressor characteristic CDT vs CDP at approx. 130 °C and 2.8 bar, which conditions are reached at the 6th stage in the compressor.

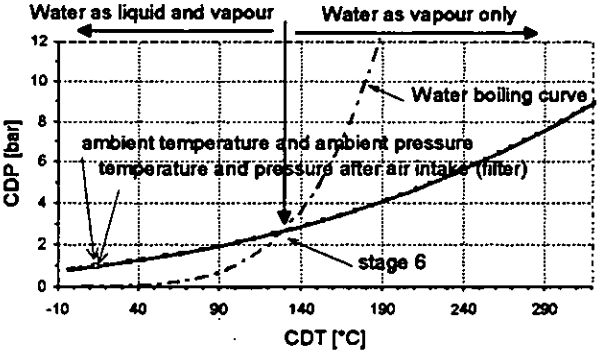

Fig. 12 Compressor characteristic CDT vs. CDP for measuring point L-258/9

This means that the humidity related water will be present in the form of liquid droplets and vapour up to the 6th stage in the compressor, which represents a high sticking probability for deposits and salt particles, thus enhancing the possibility of electrochemical corrosion. After the 6th stage, the humidity related water will be present in the massflow in vapour form only, thus there will be a low sticking probability of deposits and salts and therefore no risk of electrochemical corrosion under normal operating conditions of the gas turbine.

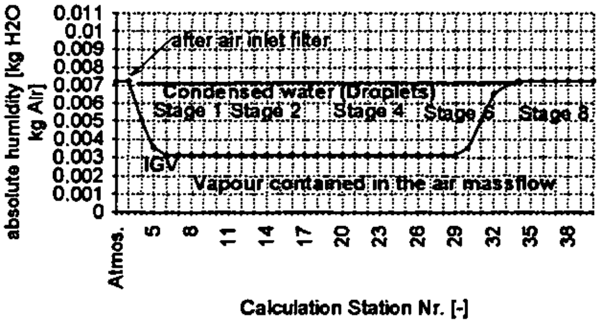

Fig. 13 Absolute humidity pattern over the air inlet filter and the first few stages of the compressor.

Figure 13 above show the pattern of the absolute humidity. The absolute humidity will remain constant through the compressor, however in our case, 4 grams out of 7 grams of water vapour present in the air will start to condense between the air filter and the IGV. These droplets will pass the first 6 stages of the compressor and vaporize again in the downstream stages. It is most probable that the majority of the droplets carried by the air stream will collect on the compressor cylinder wall close to the 4th and 5 th stage and that the collected water will leach along the cylinder wall and vaporize downstream of the compressor 6th stage. To avoid pitting corrosion, gas turbine manufacturers apply protective coatings on the compressor blades.

Other environmental factors influencing the fouling gradient

The daily average wind forces and the hourly measured wind directions have been computed for all 14 comparative operating periods. It was noted that in most periods, the average wind direction was blowing in a 60° sector into the air inlet suction area.

The analysis of the daily precipitation, average precipitation over the individual operating periods in conjunction with the humidity and winds have not helped to find a correlation between the compressor fouling gradient patterns and the environmental factors.

PREDICTING COMPRESSOR FOULING

In an attempt to predict the compressor fouling degree in function of the number of operating hours and the power output level, the corrected power output losses have been plotted and integrated into the assumed Lage Weide compressor fouling curve, see figure 14. As already mentioned, UNA reports an average 10 % power loss over 4'000 operating hours when compressor cleaning is not made. The mathematical function for the Lage Weide plant environment can be closely approximated as follows :

$$P_t = P_0 \cdot (x + (1 - x) \cdot e^{(-p \cdot t)})$$

with :
P_t = Predicted power output at time t
P_0 = Power output, clean unit
x = Degradation factor
p = Curve bending factor
t = Operating hours

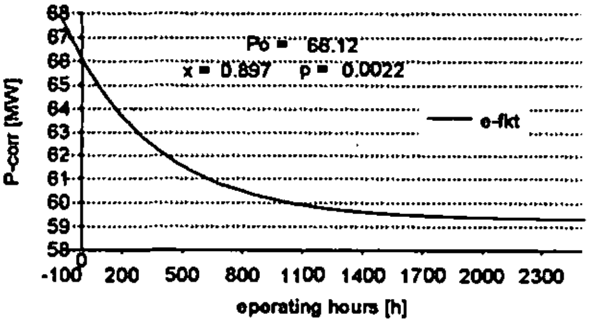

Fig. 14 Estimated Lage Weide gas turbine compressor fouling curve.

The measured power losses of the 14 comparative operating periods have been drawn vs. their power output level after on line washes into the estimated compressor fouling curve. See figure 15 below.

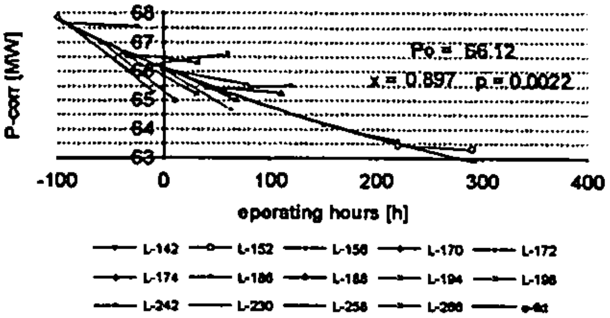

Fig. 15 Estimated compressor fouling curve with actual measured power output losses.

As it can be seen, the obtained results, with the exception of a few positive gradients, match quite well and within a band the power output at which the unit is expected to operate after a certain time period. Thus the above compressor fouling curve will allow us to calculate the output drop for a given point in time.

ATMOSPHERIC DUST CONCENTRATION

RIVM, the National Institute of Public Health and Environmental Protection in the Netherlands started to measure atmospheric dust particle concentrations at various locations in the country in 1992. Measurements of particle size distribution are not available. Hence, no data on atmospheric dust concentrations are available for the Utrecht area for the test period conducted between May 18, 1990 and November 18, 1991.

The 1992 yearly atmospheric dust concentration average of 36 $\mu g/m^3$ measured at the RIVM-station located in Den Hague center are based on monthly averages. The atmospheric dust concentration on a daily average for the month of January 1992 was 57 $\mu g/m^3$. The peak read at 262 $\mu g/m^3$, whereas the lowest concentration was registered at 19 $\mu g/m^3$. The RIVM atmospheric dust concentration measuring program for the Utrecht area only started in October 1992. Figure 16 shows the daily average dust concentration for October 1992 in Utrecht with a monthly average of 29 $\mu g/m^3$. This data on dust concentration does however, require careful screening in order to check if extreme values were not influenced by local factors limited in time, such as road construction site near a measuring station.

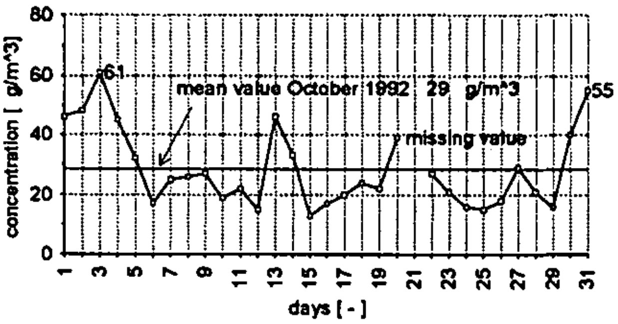

Fig. 16 October 1992 measured atmospheric dust concentration in Utrecht, RIVM measuring station at the Const. Erzeijstr.

Generally higher dust concentration has to be expected in winter. The air density is higher at colder air temperature in winter time as compared to summer periods with lower air density and higher ambient air temperature. The dilution and mix-up air layer can reach an altitude of approx. 1'500 m above ground level in the summer, hence the atmospheric dust concentration will be lower as compared to winter with a dilution and mix-up air layer reaching approx. 500 m above ground level, resulting in higher atmospheric dust concentration. The concentration on suspended dust will be lower during rain precipitation periods, larger dust particles will precipitate to the ground whereas light dust particles will remain suspended in the air. Further, the air masses are mixed-up better during bad weather periods, and hence an improved dilution on suspended dust particles in the atmosphere. Consequently the immission on dust precipitation, measured in $mg/(m^2 \cdot day)$, will be higher during precipitation periods which are influenced by the weather stability differing over the year (winter, summer, dry-, rainy-seasons, etc.). Condensate water resulting from foggy-, misty- atmospheric conditions very often contain from ten to 100 times as much air pollutants as compared with rain water. Dust particles in urban and industrial areas contain heavy metals mainly such as Mercury, Cadmium, Lead and Zinc and air pollutants such as Sulfurdioxide (SO_2), Carbonmonoxide (CO), Nitrogen-monoxide (NO) and -dioxide (NO_2), etc. which are to a large extent caused by traffic, refuse incinerators, heavy industries, refineries, coal and oil fired power stations etc.

AEROSOL CONCENTRATION IN THE AIR

Following aerosol concentration in the air ; sulfates (SO_4), nitrates (NO_3) and chlorides (Cl), have also been obtained from the measuring station at the National Institute of Public Health and Environmental Protection, located at Bilthoven, some 15 km from the plant. Daily measurements for the entire testing period are available. The peak has been recorded March 2nd 1991 with a total of 39 $\mu g/m^3$ of the measured salts and the minimum with 5 $\mu g/m^3$ on October 17th 1991. The average aerosol concentration for the completed test period was 15 $\mu g/m^3$.

AEROBIOLOGICAL MEASUREMENTS, AIRBORNE POLLEN CONCENTRATION

Pollen are fine dust composed of the microspores of seed plants, gathered from the air by means of collecting strips and then counted and measured in pollen grains per m^3 air in 24 hours [P/m^3/day]. Pollen are generated by the vegetation and noticeable in the air already by start of the vegetation period until its end, the development of the airborne pollen period depends on the climatic development. It can already start in February and end in October. No pollen measurements are available for the Utrecht area, howewer measurements made at the University Hospital Leiden, some 50 km North of Utrecht were made accessible. The results show peaks on March 6th and 7th with 1985 respectively 1898 pollen grains, April 13th 1991 with 1262 and on July 5th and 7th with respectively 932 and 1055 P/m^3/day. The size of airborne pollen grains is between 15 to 35 µm. Local differences between Utrecht and Leiden do exist, and strong fluctuations can occur during a 24-hour period. The average airborne pollen concentration during the period 18th May 1990 to 18th November 1991 was 115 P/m^3/day.

AIR FILTRATION SYSTEM

Description of the air filtration system

The Lage Weide Unit 5 air filtration system supplied by Merrem & La Porte consists of 2 filtration stages as follows : A grilled weather louvre air intake in Aluminium, the 1st coarse air filter section with 216 pocket filter elements, the 2nd fine air filter section has also 216 pocket filter elements with the same air flow rate. A security screen with large mesh is located downstream and before the air inlet elbow. The filter also has in front of the weather louvre a pipe grid for distribution and injection of hot air extracted from the gas turbine compressor for anti icing purposes. A number of by-pass doors are located after the security screen, before the air inlet elbow and silencers, for opening at underpressure in case of filter clogging.

Filter media in moist environment

The selection of the appropriate air inlet filtration system for a given plant in its environment is most important. At high humidity, the filter media will become wet, its filtration efficiency will improve because of swelling of the fibre structure, thus a higher collection rate of particles. However, higher pressure losses through the air filter will result in higher power losses.

Further, and from the literature it is known that particles up to 5 µm in size are causing fouling, particles causing erosion are normally 10 µm and greater and the particles between 5 µm and 10 µm are falling in a transition zone between fouling and erosion.

OUTLOOK IN THE FUTURE

The evaluation of the results clearly demonstrates the importance of implementing an optimised regime of on line and off line washing in the preventive turbine maintenance program, this being of more and more importance with the increasing power output sizes of gas turbines and combined cycle plants operating at base load. Hence, it should be acknowledged by the industry and plant operators that a state of the art compressor cleaning system is becoming a necessity. Wash systems should be considered as regular gas turbine auxiliary systems and not options. For example, a state of the art compressor cleaning system for a 520 MW combined cycle plant comprising three gas turbines each of 115 MW and one steam turbine of 175 MW could be equipped as follows :

- One permanent installed off line and on line nozzle system on each gas turbines.
- One mobile off line wash skid comprising only the pumps, connecting hose reels and the necessary armatures.
- One permanently installed water pipe distribution system for the supply of off line water, with one connection hydrant located close to each gas turbine off line nozzle manifold.
- One dedicated on line stationary wash skid at each gas turbine, located close to the on line nozzle manifold. Each wash skid being connected to a common demineralized water pipe system. These dedicated on line cleaning wash skids are designed to allow remote operation from the central control room.
- On line wash software to energize the wash program at each gas turbine. This software could monitor the compressor degradation by measuring the relevant unit- and atmospheric-parameters, calculating the corrected unit power output and energizing on line washing upon a preset percentage fouling. Another possibility would be to energize on line washing by monitoring the compressor operating parameters only and comparing them with the design parameters when new and clean. An easy way is to energize remote on line cleaning on a preset operating time lap, for instance every 70 hours.
- Hourly logging of the calculated corrected power output and resulting compressor degradation together with a graphical display.

With the above equipment, on line compressor cleaning can be considered a part of the plant operation procedure, whereas off line cleaning will remain part of the plant maintenance procedure. This will help to improve the plant profitability by reducing the costs of energy production.

COMPRESSOR DEGRADATION VS. PLANT LAYOUTS

An optimum plant layout is one of the most important considerations prior to construction of a new power station, this with respect to the life expectancy of the plant. However, very often compromises are the basis for a plant layout, for instance in a power plant extension. Nevertheless orientation of air/water cooling towers versus air inlet suction in a combined cycle plant and the predominant wind direction can dramatically affect the power degradation pattern of the gas turbine compressor, respectively the cost for generating power. The same can apply to exhaust gas recirculation into the air inlet, or orientation of air inlet suctions with other local conditions such as location of highways, industries etc. versus the predominant wind directions.

CONCLUSIONS

The objectives of the extended time test program over 8'000 operating hours on the benefits of an optimized regime of on line and off line compressor wet cleaning on a larger gas turbine have demonstrated its value. The plant was operated at a sustained high output close to nominal guaranteed rating despite difficult atmospheric conditions. The plant production profitability has been substantially improved during the extended time test program with the performed regime of on line and off line compressor wet cleaning by some US$ 1'175'000.- over 8'000 operating hours. No direct correlation between fouling gradient and humidity due to atmospheric conditions could be demonstrated at this stage, despite the impressive amounts of data collected. Closer monitoring of the unit's performance together with the air inlet filtration system's performance and conditions in conjunction with its maintenance as well as atmospheric dust size distributions could have enhanced the finding of such a relation. However it is expected that such a correlation exists. A further result of the extended test program is the determination of the specific compressor fouling curve allowing the user to calculate the power output drop for a given point in time. Compressor fouling is a specific problem to each site, related to its environment and the type of equipment installed. Its remedies are particularly rewarding and depend on the degree of involvement and quality of the performed preventive maintenance.

ACKNOWLEDGEMENTS

The authors wish to thank Mannhart, B., student at the Swiss Federal Polytechnique School in Zürich, Gaal, T. and Schaffner, L., students at the Engineering School of Brugg-Windisch, Switzerland, for their co-operation and support in the evaluation of the impressive amounts of data collected, as well as Asea Brown Boveri for providing the necessary information and data on the compressor design and gas turbine performance.

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APPENDICES

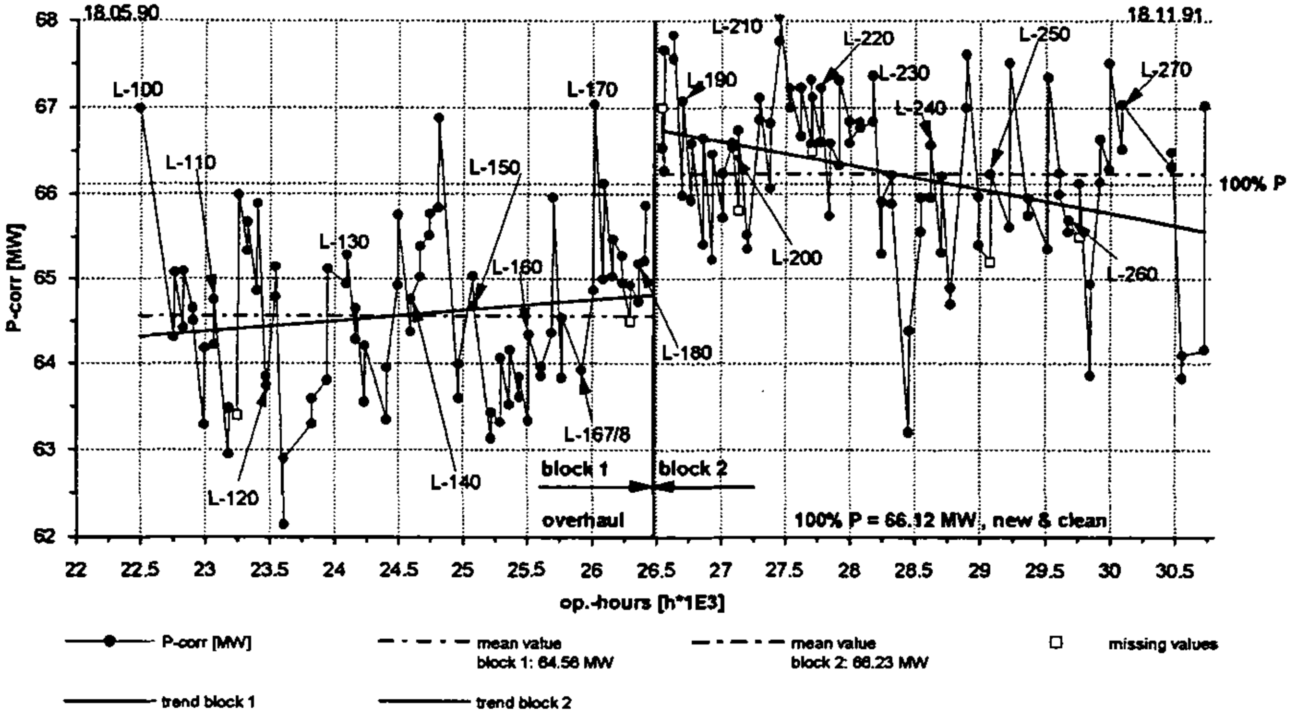
Appendix A, Corrected power output to site condition, new and clean for the complete test period. Figures 17 to 26, pages 10 to 14.

Appendix B, Power losses over 70 operating hours for 14 comparative operating periods. Figures 27 and 28, page 15.

Appendix C, Trend analysis of humidity related and ingested water by the compressor for 10 operating periods in the first evaluation block I, page 16.

Appendix A Corrected power output to site condition, new and clean for the complete test program

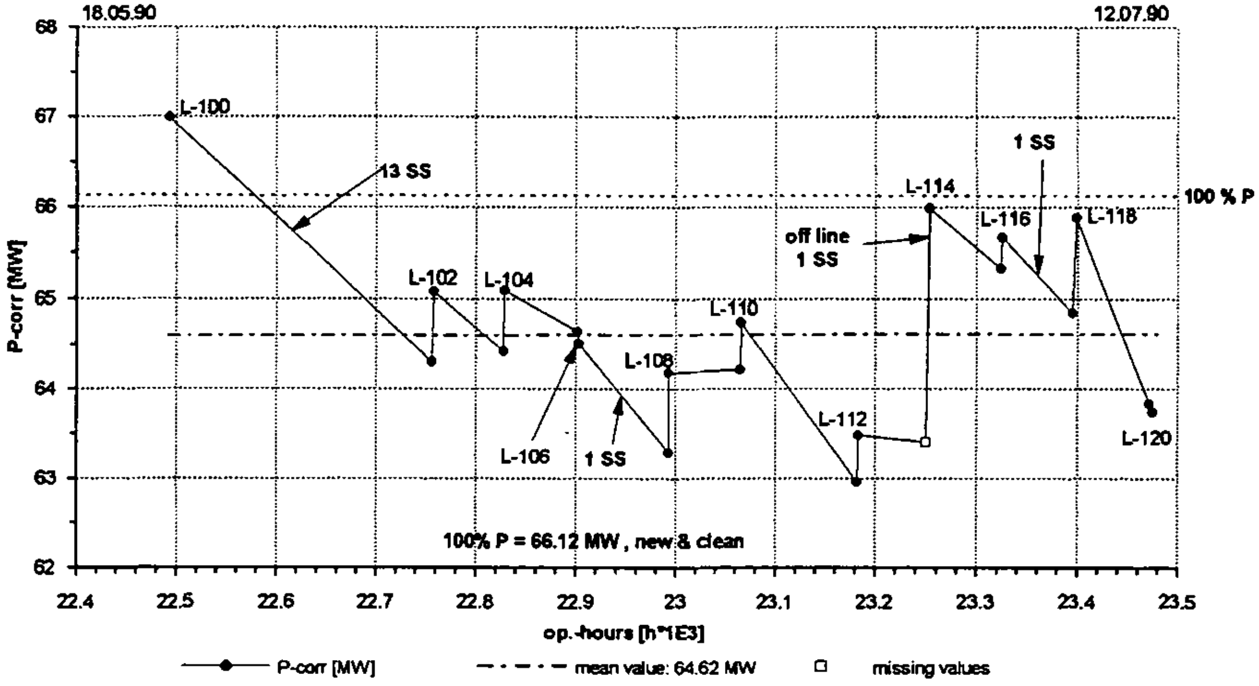
Corrected power output to site condition, new & clean



L = measuring point measured before and after washes; L-100 to L-276, period block 1: 18.05.90 to 07.12.90
block 2: 26.02.91 to 18.11.91

Fig. 17 above

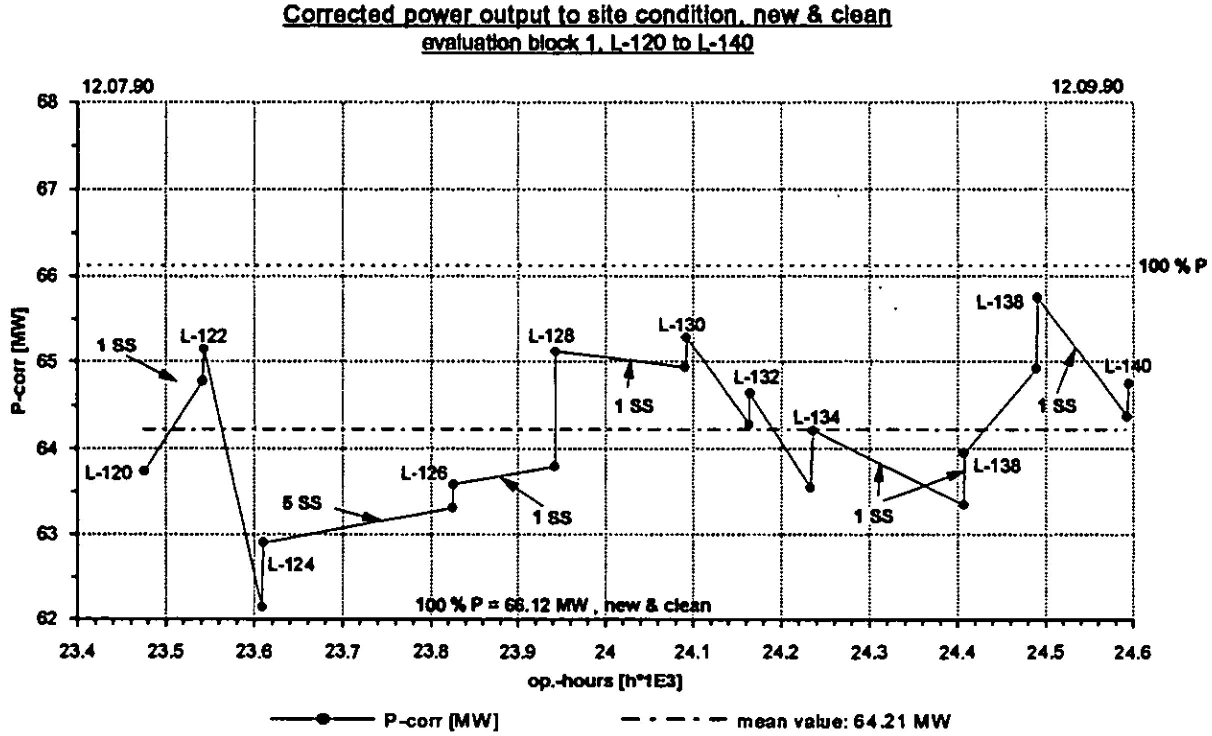
Corrected power output to site condition, new & clean
evaluation block 1, L-100 to L-120



L = measuring point measured before and after washes; L-100 to L-120, period: 18.05.90 to 12.07.90
SS = shut down & starts between 2 washes total number off SS: 16

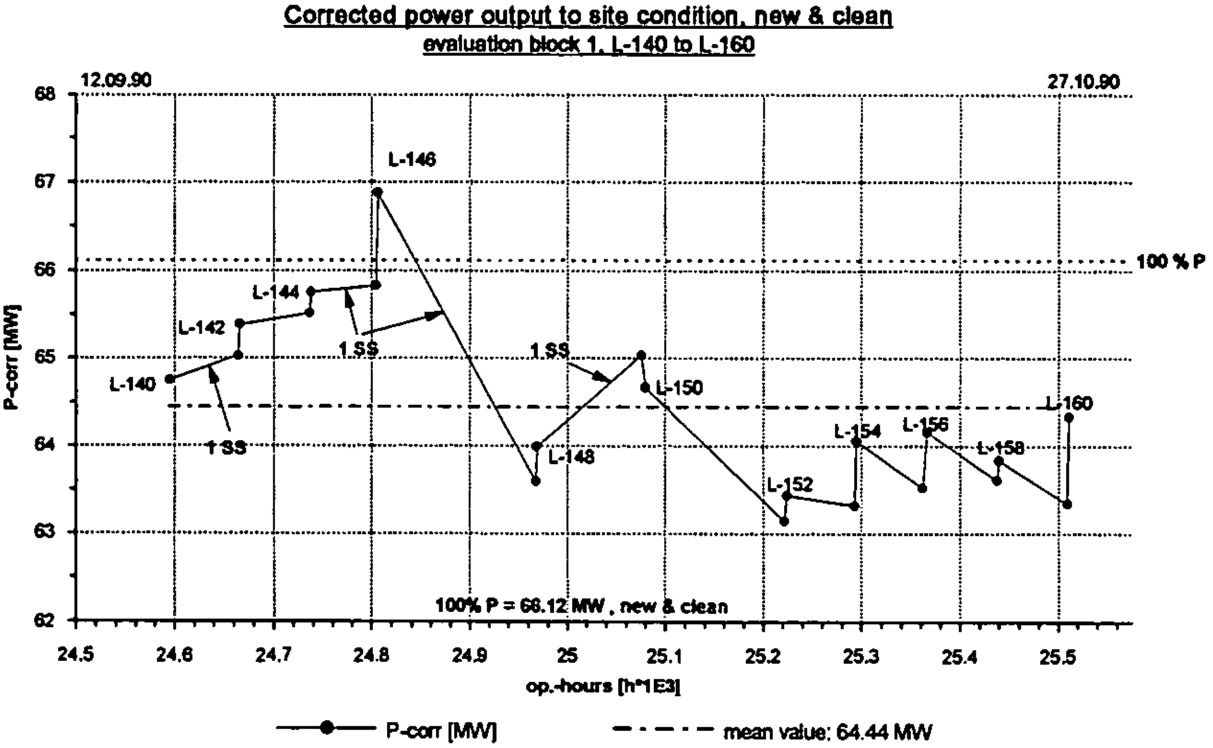
Fig. 18

Appendix A, cntd.



L = measuring point measured before and after washes; L-120 to L-140, period: 12.07.90 to 12.09.90
SS = shut down & starts between 2 washes total number off SS: 11

Fig. 19 above

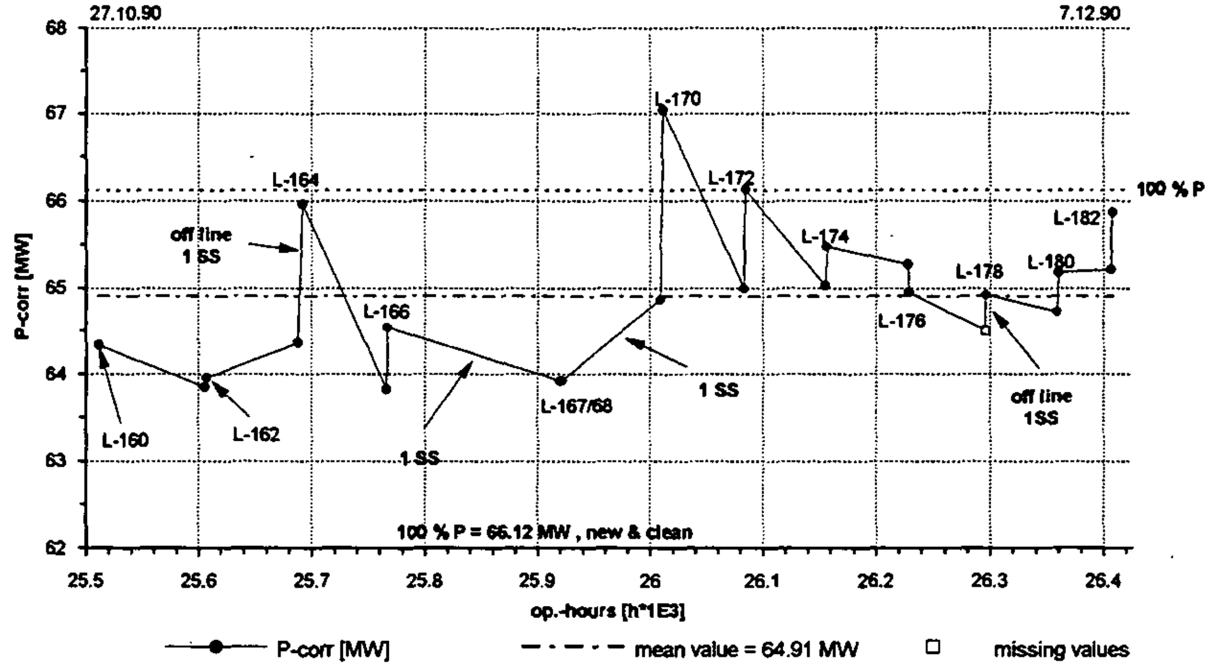


L = measuring point measured before and after washes; L-140 to L-160, period: 12.09.90 to 27.10.90
SS = shut down & starts between 2 washes total number off SS: 4

Fig. 20

Appendix A, cntd.

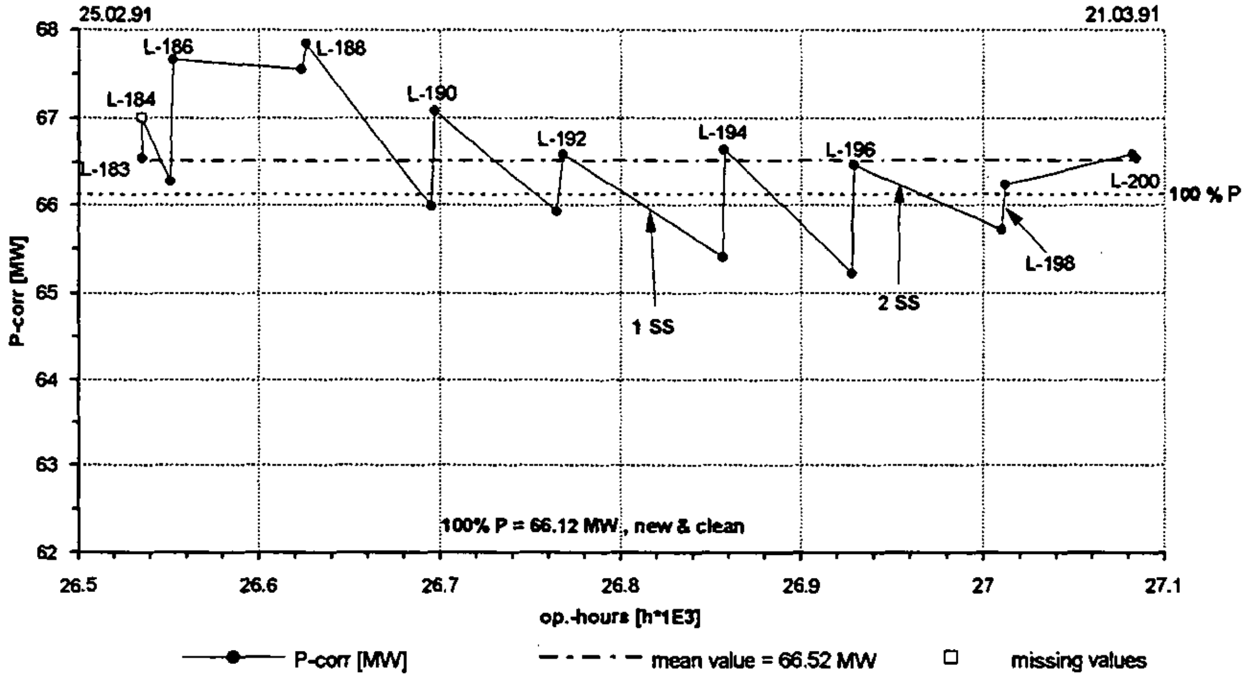
Corrected power output to site condition, new & clean
evaluation block 1, L-160 to L-182



L = measuring point measured before and after washes; L-160 to L-182, period: 27.10.90 to 7.12.90
SS = shut down & starts between 2 washes total number off SS: 4

Fig. 21 above

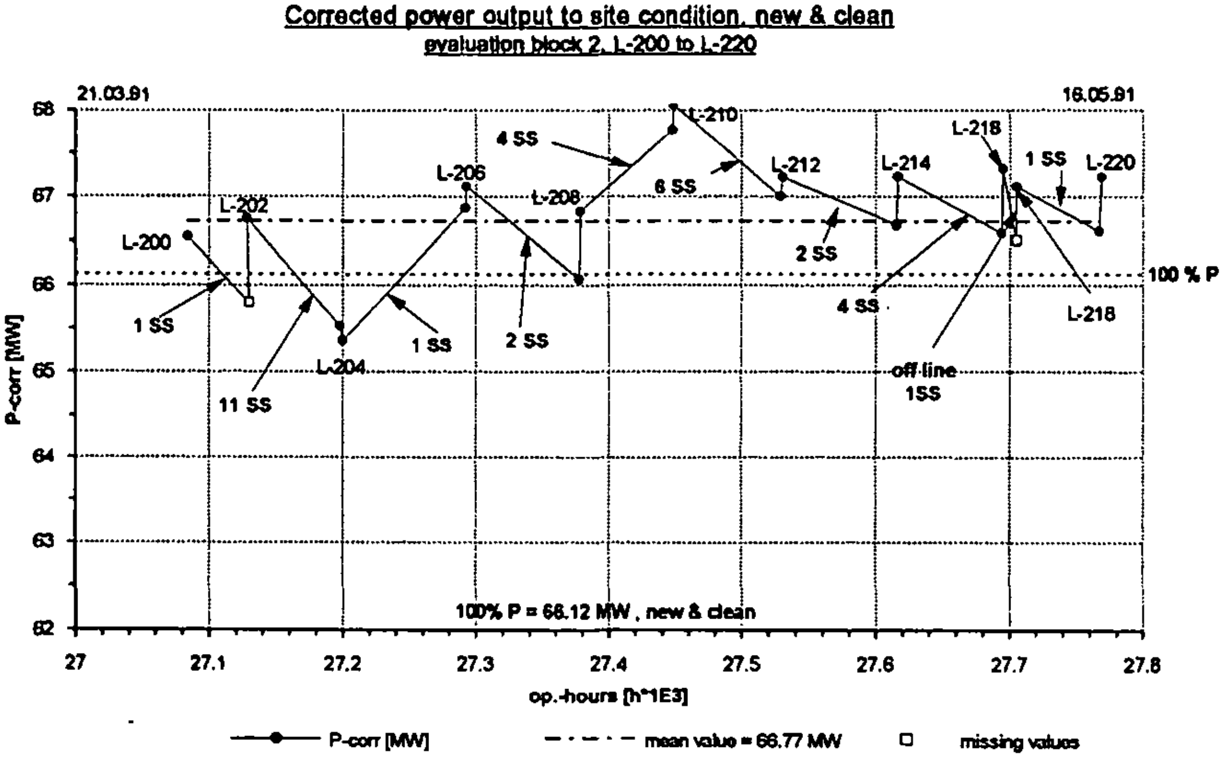
Corrected power output to site condition, new & clean
evaluation block 2, L-183 to L-200



L = measuring point measured before and after washes; L-183 to L-200, period: 25.02.91 to 21.03.91
SS = shut down & starts between 2 washes total number off SS: 3

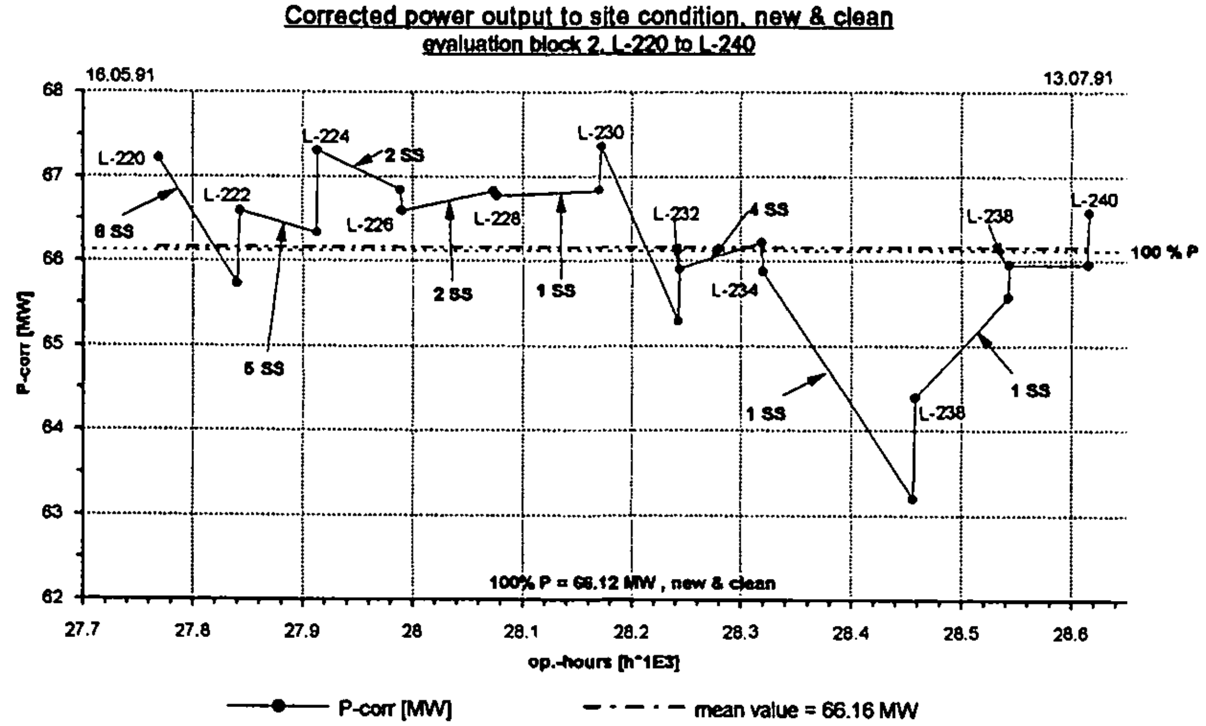
Fig. 22

Appendix A, cntd.



L = measuring point measured before and after washes; L-200 to L-220, period: 21.03.91 to 16.05.91
SS = shut down & starts between 2 washes total number off SS: 33

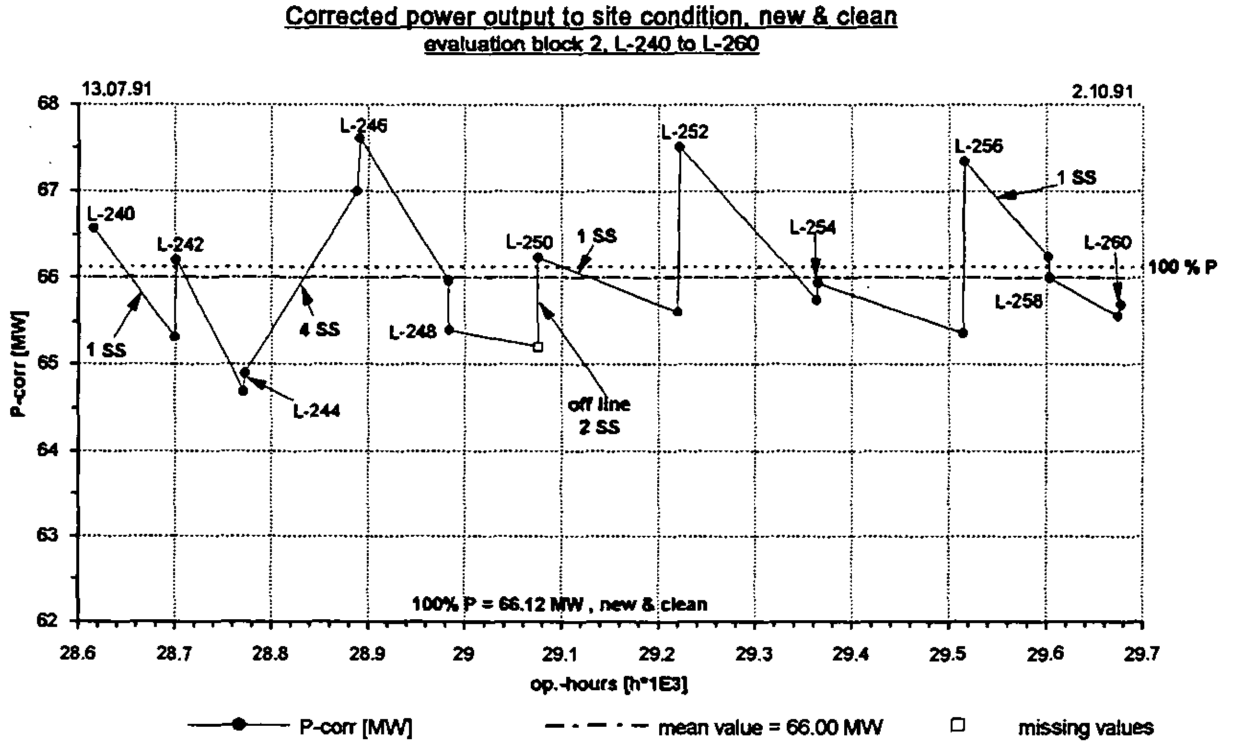
Fig. 23 above



L = measuring point measured before and after washes; L-220 to L-240, period: 16.05.91 to 13.07.91
SS = shut down & starts between 2 washes total number off SS: 24

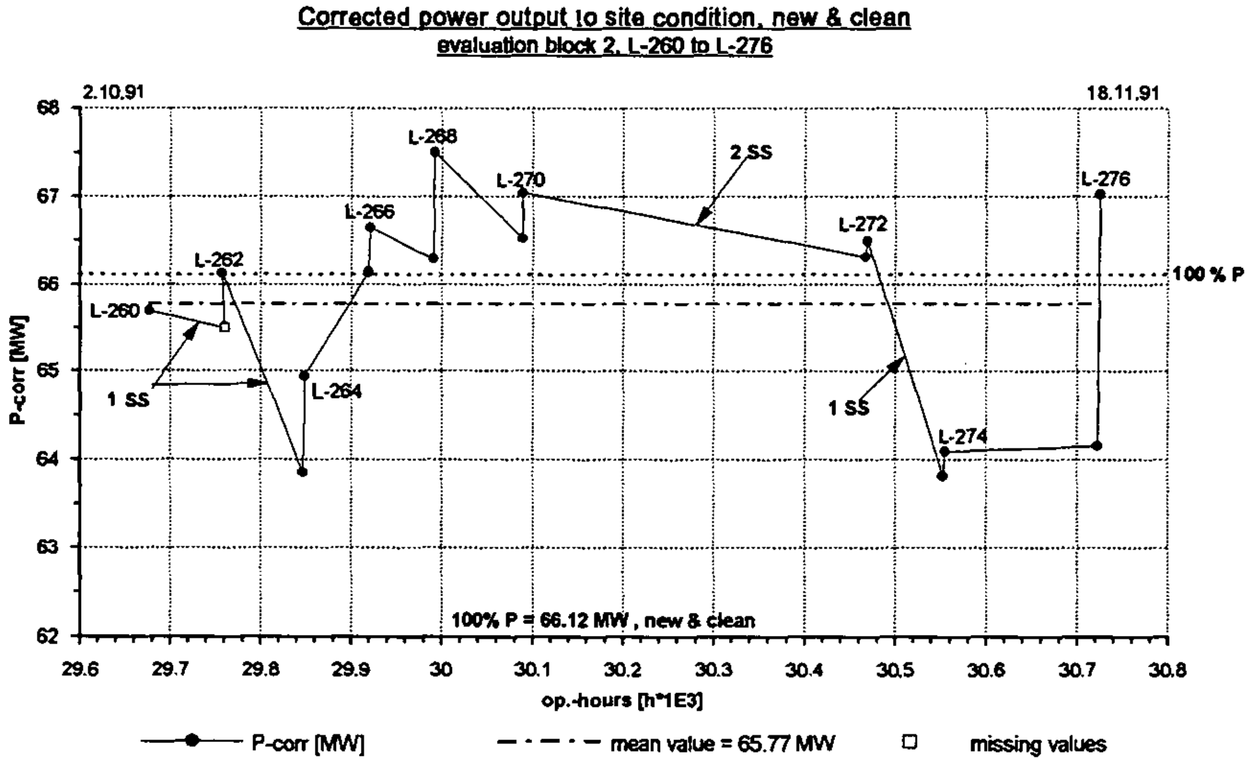
Fig. 24

Appendix A, cntd.



L = measuring point measured before and after washes; L-240 to L-260, period: 13.07.91 to 2.10.91
SS = shut down & starts between 2 washes total number off SS: 9

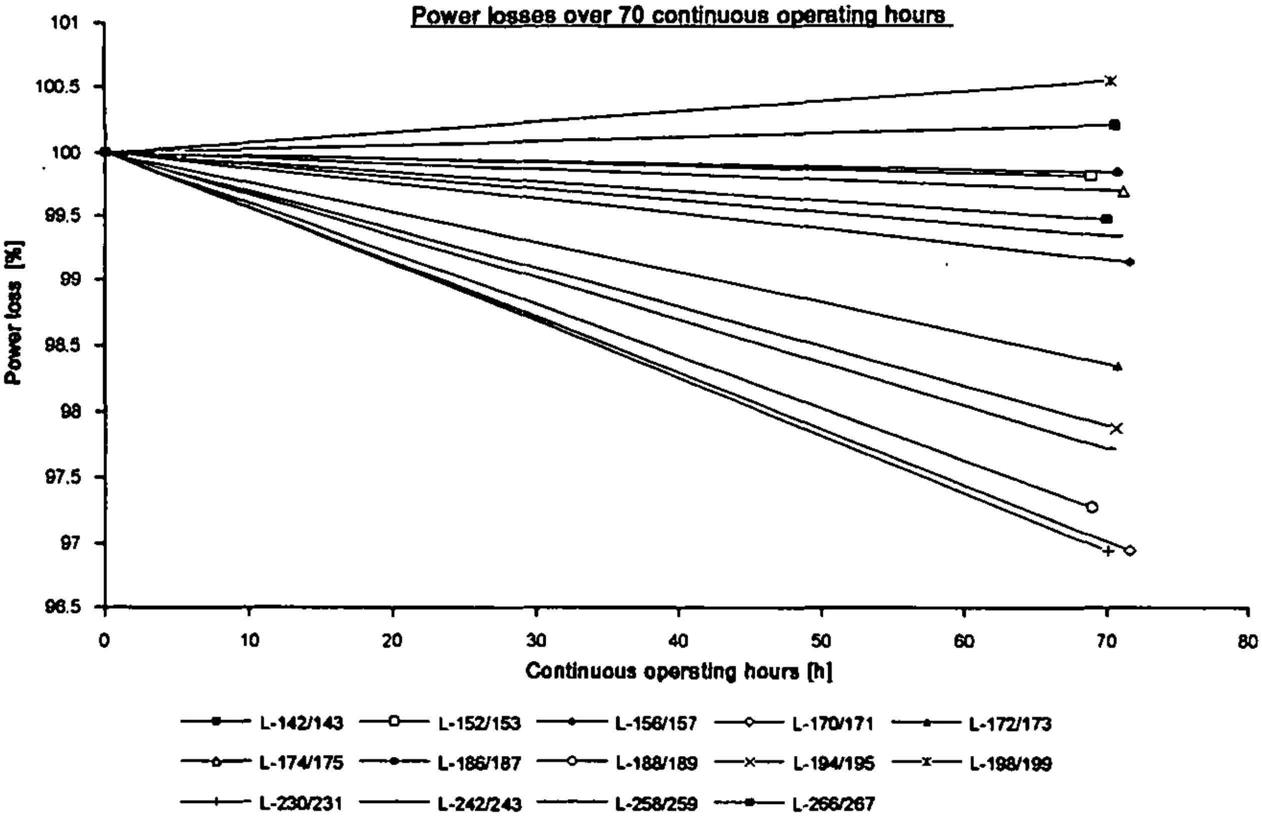
Fig. 25 above



L = measuring point measured before and after washes; L-260 to L-276, period: 2.10.91 to 18.11.91
SS = shut down & starts between 2 washes total number off SS: 5

Fig. 26

Appendix B



Operating periods between two measuring points.

Fig. 27 above

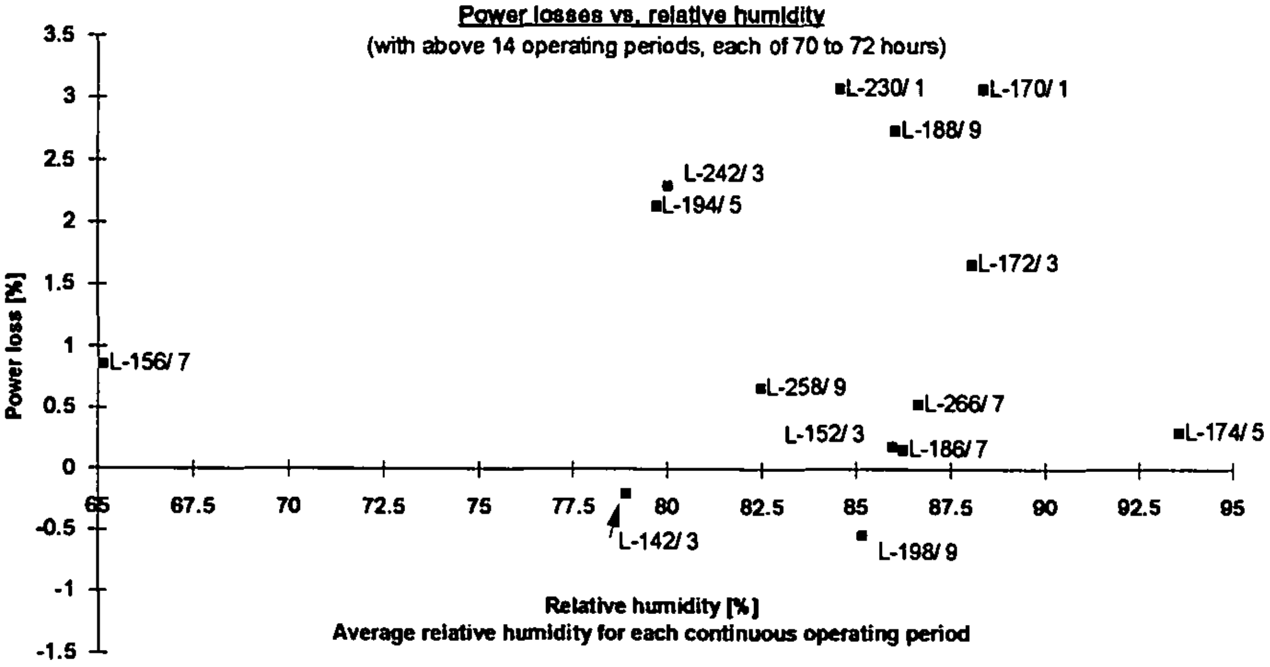


Fig. 28

Appendix C Trend analysis of humidity related and ingested H2O (water and vapor) by the compressor during continuous periods of 70 to 72 operating hours

An exp. function has been used for visualisation purpose