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THE DEVELOPMENT OF A COST BENEFIT ANALYSIS METHOD FOR MONITORING THE CONDITION OF BATCH PROCESS PLANT MACHINERY

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Abstract: Whereas it is self-evident that large potential cost benefits exist for high capital cost - high consequential loss plant, the scope for achieving realistic cost benefits for lower value, batch process equipment is less obvious and is also difficult to quantify. The results presented in this paper represents an attempt to determine a suitable basis for establishing cost benefits for plant machinery typified by that utilised for the manufacture of pharmaceutical products. In this preliminary investigation, a mathematical model has been devised for pump operation throughout the whole plant. It is based on actual data obtained over a five year period in which a maintenance cost prediction is established and the advisability of utilising condition - based maintenance strategy is decided.

Key Words: Cost Benefit Analysis; Maintenance; Mathematical Model; Pumps;

Introduction: Maintenance of running machinery has been a need as long as machinery has existed. From the onset of the Industrial Revolution until the end of the Second World War machinery was repaired as it broke down. There were no philosophical considerations of any other type of maintenance practice. It was implicit in the running and maintenance of Marine Machinery [1] published in 1965 that this was the philosophy to be followed. However, since then there have been a numerous studies of maintenance practice [2] and a recognition that costs could be as much as 80% of machine capital costs per annum. Hence it is worth analysing whether other philosophies are most cost effective. The current maintenance costs for British industry is estimated to be £20 billion and therefore the scope of prospective saving can be spectacular.

Initially the move away from breakdown maintenance was driven by a recognition that breakdowns had considerable consequential costs if a continuous manufacturing process was interrupted without warning. It was also realised that manning for the peaks in maintenance activity was a very inefficient use of manpower and hence the next philosophy to be advocated was that of preventive maintenance. In this philosophy, machinery was serviced at regular intervals and all worn parts replaced. (This could be considered as one form of condition monitoring where by a full intrusive examination was carried out). The time intervals used for this maintenance activity were decided empirically as detailed records were not available in most areas. In many cases they were done to suit either the resources available or at convenient time intervals (e.g. 26 weeks, 1 year etc.).

In the late 60's and early 70's, in the defence industry, especially in operational units, where machine *availability* was the overriding concern, a philosophy of using the reliability data that was available to establish preventive maintenance intervals was suggested. As the data on machine availability and repair times were available in most combat and continuous running situations for key machinery, MTBF (Mean Time Between Failure) and MTTR (Mean Time To Repair) times were determinable. Thus, statistical analyses could be carried out and confidence limits for machine availability theoretically established. Various elegant mathematical models are available for establishing ideal preventive maintenance intervals [3,4]. However, data to establish this is still not available for most mainstream industry. (The nuclear industry is a particular exception since they have to *prove* the reliability of plant; the National Centre for Systems Reliability was established to collate this data).

As more industries collate real data relating to *their* plant and *their* running conditions, data becomes available which can allow mathematical models to be constructed for general plant. The main problem with this approach is deciding the confidence limit at which normal industry can sustain preventive maintenance costs. Further, when one deals with very general large populations of machines, the levels of maintenance to guarantee machine availability to a high confidence limit becomes very expensive. It is also recognised that if there are components which fail in a truly random manner (e.g. rolling element bearings) the system has only limited usefulness. Nevertheless, Reliability Centred Maintenance (RCM) is now an accepted strategy and there are a number of plants actively employing this approach [5].

From the early 70's, instruments have been used for field testing and measurement of various parameters which give an insight into machinery condition. The first (and still the most widely used) parameter is vibration. This has been used for many years in machinery diagnostics as a trouble shooting method. The technical expertise needed to carry out this function was initially very high and so it was the preserve of a few specialists. However, it was soon realised that overall vibration levels could be easily measured and used as a trending tool to make judgements on machine condition. On a wider front, Michael Neale and Associates were commissioned by the Department of Industry in 1970 to produce a Guide to Condition Monitoring which for the first time also considered the economics of condition monitoring and its place in the maintenance regime [2].

It is quite evident that cost benefits are very high in the case of high capital value plant (see Appendix 1 - A case study). It is not so evident in the case of lower value plant at what level condition monitoring regimes should be pitched. The present study is an attempt to investigate this situation and establish a cost benefit analysis method which could be used in such cases.

It is now accepted that vibration analysis is not the only technique available. For particular classes of machinery (e.g. rail locomotives, earth moving equipment etc.) a more suitable method would be to monitor the oil condition. Oil condition monitoring, and maintenance systems based on it are now common in many industries. Other methods include acoustic emission, stress wave level, temperature measurement; all of which give insight into machinery condition. Thus, the present generation of strategies includes Condition Based Maintenance (CBM). A subset of this philosophy is where CBM is supplemented by low level intrusive inspection (using modern optical equipment or other devices) so that reliability can be **guaranteed** for a particular length of time. This is specially useful in applications such as Aircraft or Nuclear Plant where the consequences of failure are particularly high.

In summary the main approaches to maintenance now available are:

1. Breakdown Maintenance
2. Time-based, planned preventive maintenance
3. Reliability-centred maintenance
4. Condition-based maintenance

Cost Effectiveness of Maintenance Regimes: The comparative life cycle costs of the four maintenance philosophies has not been fully investigated. A start was made by Jardine [3] who looked at different types of machine characteristics in order to arrive at replacement, inspection and overhaul decisions. Implicit in his methodology was an assumption that maintenance was to be part of operating costs but these would vary in a simple manner with time. Hence, as operating costs varied, a replacement decision would become the correct option and this could be mathematically calculated. A number of different possibilities were considered where operating costs decreased with age, increased with age, had to function within a finite (bounded) time horizon, and where the unit was a stand-by machine with all the above possibilities. Using these types of model, he also attempted to develop equations for inspection decisions (intrusive and hence, essentially a "planned maintenance" approach). These models are theoretically defensible but the type of data required to support the equations is generally unavailable. Further, the problem of components with random failure modes is not addressed.

Moubray [5] disputes what a failure is and concludes that this could be perceived very differently by people with differing viewpoints. An example quoted is that of a hydraulic system where a small leak is seen as failure by the Safety Officer, a much larger leak as failure by the engineer and only the complete stoppage of the system as failure by the production staff. Therefore, costs become dependent on the "failure" being investigated.

The authors consider that failure should be judged against performance standards and costs similarly calculated against these standards. However, it is important to take into account consequential costs, which are usually the largest item in a breakdown maintenance regime.

Carter [4] employed a similar approach to calculate whole life cycle costs using a statistical approach in which he defines a failure in terms of a machine failing to perform (the "production" definition).

The current investigation is aimed at establishing a cost benefit analysis method based on evidence obtained from actual maintenance data.

Background to Data Collection: The data used to evaluate the system is acquired from the pharmaceutical industry and is characterised by some unique features:

1. The product is small in volume terms but is of very high value
2. A large number of the production stages are batch process and hence there is machinery which is idle time between batches.
3. As the quality requirements of the product are extremely tight, all machinery used has to work within very stringent operational parameters as this is one way of ensuring consistent quality of the product.

Methodology: The system proposed for the cost benefit analysis is based on a standard spreadsheet package so that it can be easily transferable. It is also based on actual cost data for both direct and consequential costs.

It was recognised at the outset that there would be differences between various classes of machines and hence all machines on-site were divided into groups by machine class. The single group with the largest number of machine trains was "pumps".

Other classifications include fans, compressors, gearboxes, generators and dryers.

Classification: The pump population was divided up according to type and power rating as shown in Table I.

Of the c.6500 machine trains on-site c.3000 are "pumps". Approximately 400 machine trains of all types are subjected to high level vibration monitoring (once a month surveillance with full Fourier analysis of the results and complete diagnostics being generated by an artificial intelligence system) using portable data collection systems. Four hundred pumps are subject to low level vibration monitoring (using only overall vibration levels to establish trends). In addition, forty machines are subjected to monthly oil condition monitoring and analysis, and 40 machines to checks using ultrasonic stethoscope and semi-intrusive examinations (using optical equipment such as introscopes and endoscopes) conducted, as requested, by maintenance engineers.

1. Costs for these services were assessed using three main criteria to ascertain the total costs
2. Capital cost of equipment used using discounted cash flow with a 10 year amortisation period
3. Labour costs. These were assessed at two separate rates. The low level vibration monitoring programme was undertaken by craftsmen who had served a recognised apprenticeship, whilst

all other services were provided by technicians who, additionally, had a three year, in-house, training programme in inspection.

4. Software and equipment maintenance costs. For the low level vibration monitoring carried out there were no maintenance costs since the purchase of the equipment. However, a nominal sum has been taken (equivalent to 5% of purchase price per annum) to allow for any future costs.

Solartron [6], in their model, also consider some cost benefits associated with:
1. Operational safety effects on plant and environment
2. Personnel safety risk
3. Operational issues excluding safety, e.g. severity of machine duty
4. Technical uses

The pharmaceutical industry is highly regulated as there are many fire and bio-hazards associated with it. Hence, on analysis, condition monitoring does not change their safety effect on either the plant or the environment. Therefore, this factor was not considered in the current model. The same situation applies in the case of personnel safety risks.

Operational issues, including severity of duty were found to reveal its effects on the consequential costs of failure and this is included in the analysis of consequential costs. Other technical issues that were considered by Solartron related to selection of in-line monitoring vs. hard wired surveillance methods vs. hand held data collection methods. Since the plant being considered here is primarily a batch production plant with very few machines on continuous duty, only hand-held data collection equipment was considered for this case study.

The need for a mathematical model to assess the cost benefits becomes apparent when the fact that the savings could be small when low capital value equipment is considered. But if sufficiently large numbers of such machines are taken into account, then the situation could alter. To determine the point at which each regime of condition monitoring becomes cost-effective requires a mathematical model so that the situation can be analysed.

Mathematical Model: To be able to *predict* costs, the model proposed is in two parts:

1. Costs of damage to the machine itself
2. Consequent costs to the process (or product)

All costs have been converted into current costs by compounding their book costs on the date of acquisition, or of repair, by using the published RPI figures within the spreadsheet.

Costs of damage to the machine: A number of models have been proposed [4] but in every case the cost of repair has been treated as one of the "knowns". To be able to take the condition monitoring "decision" it was felt that an ability to *predict* this cost was essential and hence the proposed model uses the capital cost (which is known in every case) and a factor K_d which is derived from analysis of the model. A similar index K_q will be used to predict consequential costs where appropriate.

A simple model is proposed:

Cd = Ci*Ip*lc*lpr*Kd
where, Cd = Direct costs of machine breakdown
Ci = Initial cost of machine corrected to present day value
lp = Power Index
lc = Criticality Index
lpr = Process Index
and Kd = Direct costs factor

The Power Index is a method by which the relationship of power to costs was brought into the analysis in a non-dimensional form. A number of alternatives were tried but offered no significant advantages over a simple relationship on a scale of 1 to 10. As the powers of the pumps in the study varied from fractional kilowattage to c.250 kW the relationship shown below was used.

Power (kW)	3	8	15	30	50	80	110	150	200
Ip	2	3	4	5	6	7	8	9	10

The Criticality Index is a measure of how critical the machine is to the process of which it is a part. This index is again a number on a scale of 1 to 10 which was determined by studying the process and evaluating the criticality of the machine. If, for instance, a machine was one of a series in which a stand-by machine could be put directly into service without interrupting the process, the criticality index was automatically set at 1. On the other hand, if machine failure had the result of immediately stopping the entire process, then it had a criticality rating of 10 (e.g., the failure of a motor or gearbox on the stirrer drive of a reactor vessel would immediately halt the reaction and would have a criticality index of 10). If the machine failure was such that the process could be maintained but only at reduced throughput then I_c = (Through put available/throughput possible) x 10.

The Process Index was evaluated on the basis of how much of value had been added to the product at that point in the overall process. This index is again a number on a scale of 1 to 10. Hence, all machines at the stage where the raw material is fermented would have a process index of 1, while all machines in the finishing suites would have a process index of 10. Figure 1 shows the general process flow through the plant.

Using these factors and costs, the direct costs factor was evaluated and plotted against power. This could then be used to *predict* direct costs of breakdown of any machine in that particular class.

The frequency of breakdown was evaluated from pump field data collected since September 1989. A total of 329 pumps in the solvent recovery area (see Appendix 3) were studied and 711 failures took place over a 5 year period giving a machine reliability of 0.57 per machine per year (using the definition as proposed by Carter (6) after Carhart:

R(t) = Cumulative probability function of occurrence of survival

Planned maintenance costs and inspection costs were calculated using the company standard hourly rates and published prices for spares. Capital costs were taken from the company records and adjusted for inflation using the published RPI figures. These figures were then compared with new quotations for the same machines from the manufacturers so that confidence could be gained in this method. The comparison showed that if prices were extrapolated from pre. 1990 data the deviations became very large for smaller pumps, though (taking a 10% deviation as the maximum acceptable) larger pumps could be regressed over a longer period.

To determine k_d values, the raw data acquired from the 329 pumps was analysed using curve fit routines using several methods. It was evident from this that the best fit was obtained from using the expression $y = m^\wedge x+b$ (Figure 2) and hence this is used in the subsequent predictive work.

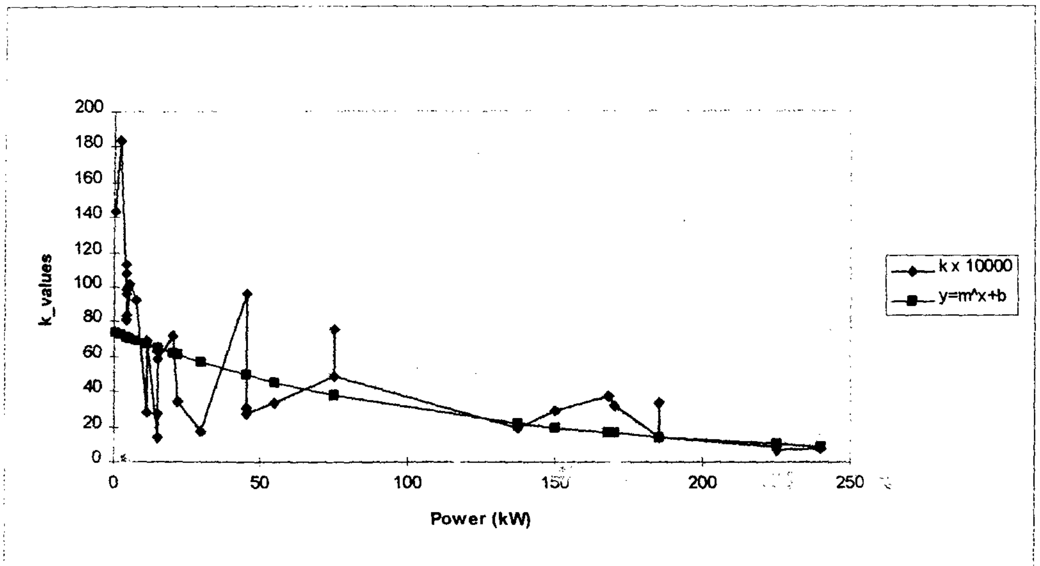

Figure 2 Curve Fit for K_d Values

Analysing the data for the period from 1990 (when low level vibration monitoring was commenced for pumps with less than 15 kW motors) to the present, the average saving by using vibration measurements to trigger maintenance against a time-based system, was £1124 over the five year period, i.e., £224.80 per annum per pump. The monitoring costs were a one off purchase of a vibration meter in 1990 at £1750 (which has now been completely written off) and labour costs at 1.5 hrs per pump per annum, which, at the company's present rates, equates to £21 and hence, there is a saving of £203.8 per pump per annum.

From the above figures, it is evident that if payback of two years is used as the criterion, and the current cost of a vibration monitor is £4500, then a minimum of 11 pumps must be within the group for the system to be more cost effective than a time-based planned maintenance system.

Breakdown maintenance costs were difficult to acquire but using a small sample of pumps that had broken down it was estimated that breakdown costs were 1.8 times of planned maintenance costs per pump because of greater damage sustained within the pump. Using the data to estimate pump reliability gave a figure of 0.57 per pump per year. The planned maintenance system generated 0.86 pump overhauls per pump per year. With properly targeted planned maintenance, there were almost zero breakdowns and hence, with the population of 329 pumps studied, breakdown maintenance costs were only £7.7 per pump per year greater than if planned maintenance was used.

If a high level condition monitoring system was to be used, the capital cost of the instrumentation and software would be £26000. The cost of data acquisition and analysis is £81.9 per machine train per annum. If the capital costs are amortised over 5 years, the saving would be £127.1 per pump per annum. Hence, for this system to be cost effective with a payback period of two years, a minimum of 205 pumps need to be monitored.

These calculations are now coded into a spreadsheet which makes an assessment of whether condition monitoring will be cost effective over whatever payback period is selected. The "Frontsheet" of this MS Excel spreadsheet is shown in Appendix 2. Two separate examples are shown, one of a 22 kW pump and another of a 240 kW pump. The decision arrived at in each case was based on the predicted costs of repair which were as shown. The actual costs of repair of these pumps were £510 and £1050, respectively which gives errors of 20.9% and 9.5% respectively.

The cost saving per pump per year by using condition monitoring is given by:

C_p = 0.8 *Predicted repair costs - (Capital cost of condition monitoring equipment/ No. of machines in the group) - (Running costs of condition monitoring)

Conclusions: The conclusions of the study show that:

1) A simple model can be used to predict maintenance costs for the population of pumps. These costs are related to the capital cost of the pump. The agreement between predicted costs and actual costs become increasingly better as pump powers increase.

2) Capital costs of purchase can only be meaningfully extrapolated using the original costs and the RPI figures for a comparatively short time span (< five years).

3) The costs of maintenance using the different regimes in decreasing order of costs are:

a) Breakdown maintenance
b) Planned (time based) maintenance
c) High level vibration monitoring based maintenance
d) Low level vibration monitoring based maintenance

4) The above conclusions should be read with the following caveats:

a) Breakdown mainte. ance is only marginally more expensive than planned maintenance. A slight increase in pump reliability will bring down breakdown maintenance costs below that of planned maintenance.

b) The extra information acquired as part of a high level vibration monitoring based maintenance system does not lead to any greater reliability of the pumps than if a low level vibration monitoring based system were used.

c) The break even point rises dramatically between using the low level system and the high level system and hence, in the introductory stages, a low level system will deliver benefits much more positively than a high level system.

d) The above study was composed of pumps, all of which are fitted with stand-by machines and hence failure has no consequential costs. When the study is extended into Fans, Compressors, Generators, Dryers, etc. many of which have no stand-by machines, the consequential costs will play a dominant role.

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Pump Type	**Power Rating - kW**				
	0-3	3-8	8-15	15-30	30-50
Centrifugal	√	√	√	√	√
Positive Pressure	√	√	√	√	√
Single Stage	√	√	√	√	√
Centrigugal	√	√	√	√	√
Positive Pressure	√	√	√	√	√
Multi-Stage	√	√	√	√	√
Centrifugal	√	√	√	√	√
Vacuum	√	√	√	√	√
Single Stage	√	√	√	√	√
Centrifugal	√	√	√	√	√
Vacuum	√	√	√	√	√
Multi-Stage	√	√	√	√	√
Positive Displacement	√	√	√	√	√
Positive Pressure	√	√	√	√	√
Single Stage	√	√	√	√	√
	50-80	80-110	110-150	150-200	>200
Centrifugal	√	√	√	√	√
Positive Pressure	√	√	√	√	√
Single Stage	√	√	√	√	√
Centrigugal	√	√	√	√	√
Positive Pressure	√	√	√	√	√
Multi-Stage	√	√	√	√	√

Table 1 - Classification of Pump Type and Power Rating

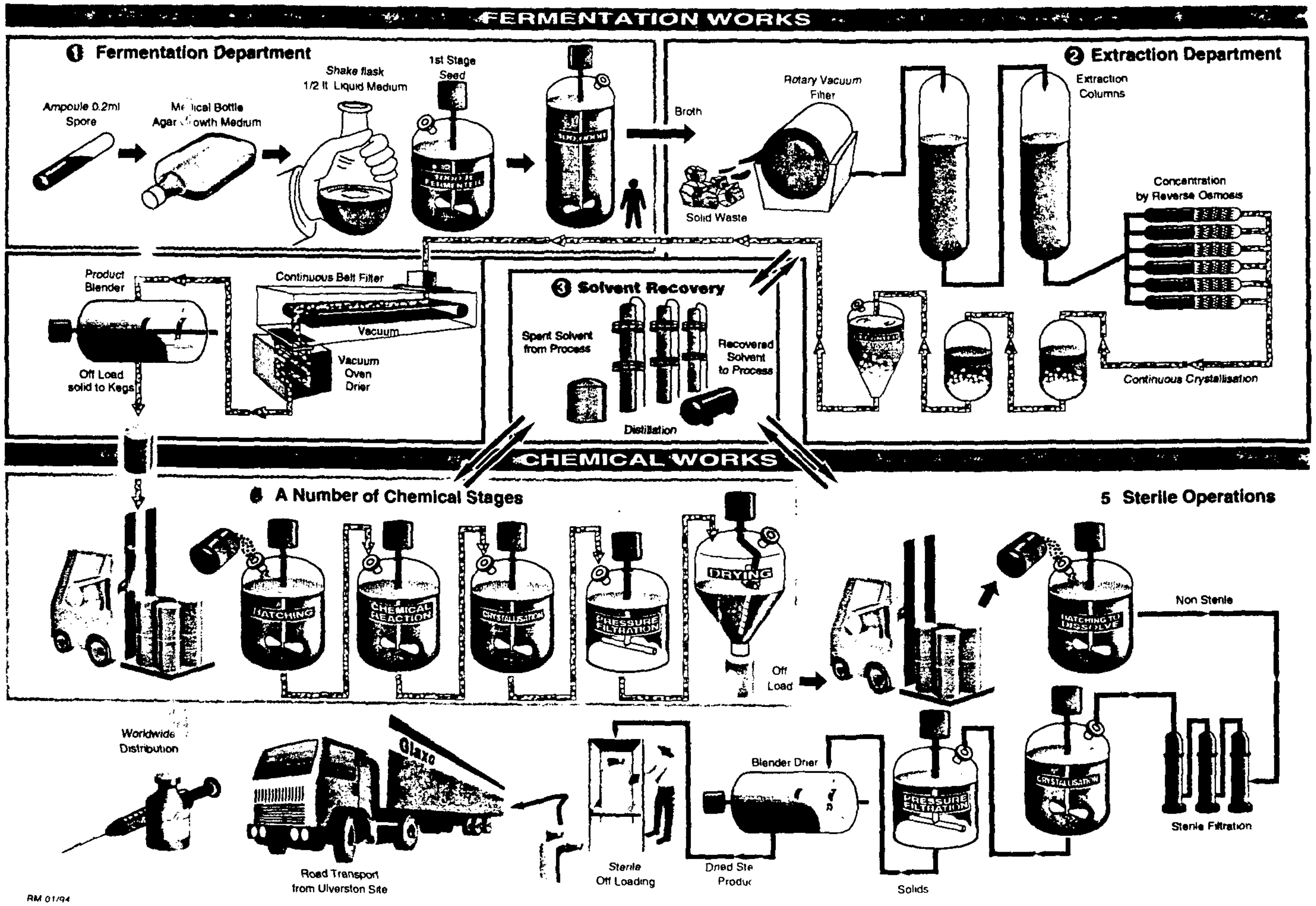

Figure 1 Schematic Representation of Pharmaceutical Products Process

Appendix 1

A two stage centrifugal fan was supplied as part of a new installation. This fan has two bearings, both Cooper Split type, with the first stage overhung beyond the second bearing. The fan is powered by a 110 kW motor. The capital cost of the fan (normalised to 1995 prices) was £96,890.

Post installation vibration checks carried out on the fan gave cause for concern. Alignment was considered partially responsible and the drive motor was realigned. Subsequent vibration readings showed a steady deterioration and analysis of the spectra showed presence of bearing outer race problems at *both* fan bearings. The main installation contractor and the fan manufacturer were invited to comment as the process on which it was being used was now in full production.

The comments received were that the vibration levels were quite acceptable for normal operation and that the machine was covered by a maker's guarantee.

After nearly 8 months operation the fan completely self-destructed. During the 8 months of operation the vibration levels had shown steady deterioration. It cost the manufacturer £47,130 to repair the fan (normalised to 1995 costs). It was estimated that modifications costing less than £5,000 could have avoided the incident.

Appendix 2 - Examples of Master Sheets Used for Assessment of Cost Effectiveness of Pumps

Give power of pump in kW	22	240
How many pumps are there in the group	10	10
What was the capital cost of the pump at time of purchase	£4,644	£17,084
What year was it purchased	1991	1991
Predicted capital cost of purchase on current date	£5,270	£19,388
Is there a stand-by pump in the circuit (Y or N)	y	y
If no stand-by pump enter criticality index	2	2
Pump process index	5	7
Enter hourly rate for labour	£14.00	£14.00
Predicted pump repair cost	£645	£1,168
Predicted pump condition monitoring cost (p.a.) - (l.l)	£63.50	£63.50
Predicted pump condition monitoring cost (p.a.) - (h.l)	£249.98	£249.98
Payback period for assessment	2	2
Is use of low level condition monitoring justified	Yes	Yes
Is use of high level condition monitoring justified	No	No
Capital cost of low level Condition Monitoring Equipment	£4,250	£4,250
Capital cost of high level Condition Monitoring Equipment	£20,000	£20,000
Year of Purchase	1995	1995
Corrected cost of low level equipment	£4,250	£4,250
Corrected cost of high level equipment	£20,000	£20,000
Cost saving with use of l.l. equipment	£452	£871
Cost saving with use of h.l. equipment	£266	£685
Years for payback on low level equipment	9.4	4.0
Years for payback on high level equipment	75.2	29.2