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BEMS AS CONDITION BASED MAINTENANCE TOOLS

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The other publications in the series are:

- TN 1/95 "Condition Based Maintenance for Building Services"
- TN(S) 2/95 "Infrared Condition Based Maintenance"
- TN(S) 3/95 "Vibration Monitoring in Building Services"

TN 1/95 is a general introductory publication and the others consider specific techniques in detail.

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1 INTRODUCTION

This Technical Note is one of a series outlining the results of research into the applicability of condition monitoring techniques to the maintenance of building services. Traditionally maintenance has been performed either on a breakdown basis where plant is run to failure, or on a time basis with overhauls performed at periodic intervals. Due to the high failure rate, **Breakdown Maintenance** is inappropriate for plant which is critical or has high repair costs. **Time Based Maintenance** will prevent a proportion of the failures. However, much of the work may be unnecessary and could even introduce failures.

Condition Based Maintenance (CBM) is performed by selecting and monitoring a parameter which is indicative of plant condition. Any necessary remedial maintenance is then determined from diagnosis of the information collected. CBM has the potential to reduce costs and increase the effectiveness of maintenance in a number of building services applications. This technical appraisal considers the use of Building Energy Management Systems (BEMS) as CBM tools.

BEMS are installed in many buildings to control building services plant. Data on the operation of plant and systems, in particular temperatures and pressures, are collected by a BEMS for this purpose. This data is available for use in a CBM role at no additional cost, ie it is "free". Often supplementary sensors can be added to the system at low cost where they are specifically required for the purposes of CBM. BEMS can store the collected data in logs, perform basic analysis, generate messages/alarms to initiate remedial action and provide the facility for remote off-site monitoring. BEMS therefore have considerable potential as CBM tools.

A summary of the research findings is provided in Section 2. Identification of the CBM applications which offer most potential benefit is considered in BSRIA TN 1/95 [Ref 1]. The two main applications utilising BEMS which have been identified are differential pressure monitoring of filters and temperature monitoring of heat exchange processes. These are analysed in Sections 3 and 4 respectively.

One technique which was established as having considerable potential is vibration monitoring. It can be used to detect failures on rotating plant, eg pumps, fans and motors. The technique is discussed in depth in BSRIA TN 3/95 [Ref 2]. In addition to monitoring conventional parameters, a BEMS has also been employed to automate the monitoring of the overall vibration level of a fan. This is discussed in Section 5.

This document focuses on BEMS applications expected to yield the most widespread benefit. There will be many other applications which will be beneficial for specific installations. An approach similar to those described would be expected to be appropriate in most cases.

2 SUMMARY

The primary areas of application identified by the project are filters and heat exchange processes. Differential pressure monitoring of filters is considered to be beneficial not just in terms of minimising filter replacement and fan energy costs, but also in enhancing filtration performance and reducing the risk of filters "bursting".

BEMS monitoring of heat transfer processes should focus on critical items of plant which are subject to a high rate of degradation. This is both to ensure the benefit is maximised and to avoid overloading the BEMS communication network with condition monitoring data. Monitoring of dynamic processes will require large amounts of data and complex analysis algorithms and so should be simplified where possible, for example by monitoring performance under start-up or steady-state conditions. Two promising applications which have been investigated are calorifiers and air blast coolers.

Monitoring of the overall vibration level by a BEMS has been shown to be feasible using present technology. The cost has been estimated as being in the region of £160/point. Its application will therefore generally be restricted to critical plant items or where the emphasis is on remote monitoring for example via a bureau service. A similar approach should also be possible for high frequency bearing monitoring techniques where the condition is represented by a single parameter.

2.1 DEFINITIONS - BS 3811:1993

Condition Monitoring - The continuous or periodic measurement and interpretation of *data* to indicate the condition of an *item* to determine the need for *maintenance*.

Condition Based Maintenance - The *maintenance* carried out according to the need indicated by *condition monitoring*.

3 AIR FILTERS

Air filtration is typically used in building services to prevent:

- fouling of downstream plant which reduces energy efficiency and performance and/or increases plant cleaning costs
- staining of interior surfaces which reduces redecoration intervals.

In addition, filtration can also improve the air quality within a conditioned space.

At present, replacement or cleaning of filters is widely performed on a time based maintenance schedule. The replacement period selected is normally a conservative estimate of the filter life based on experience, for example 3 months for a panel filter and 12 months for a bag filter. This conservative approach will mean that the filters are often replaced before they have reached the end of their prescribed life, increasing the cost of filtration.

At the other extreme, fan energy wastage and/or loss of system performance can occur if the replacement period is too long. This is due to the overloaded filters restricting air flow. There is also the risk of the filters bursting and spilling their contents into the air distribution system.

In addition to increasing costs, early replacement of filters will also impair filtration performance. The efficiency of most filters in common use improves as they become loaded. Hence, a portion of their life during which the filters are performing at their best will be lost by changing them early, reducing the average filtration efficiency.

An alternative approach commonly employed is to assess the filter condition by means of a visual inspection and change the filter if it "looks" dirty. This is a qualitative rather than quantitative approach and is subject to individual interpretation. As with the time based approach, changing of filters is unlikely to take place at the optimum time.

The resistance of filters to air flow increases as they become loaded with dust. The differential pressure (DP) developed across a filter provides a measurement of its condition. This can be used to determine the optimum change time.

A number of criteria can be applied to determine when a filter should be changed - see Table 1.

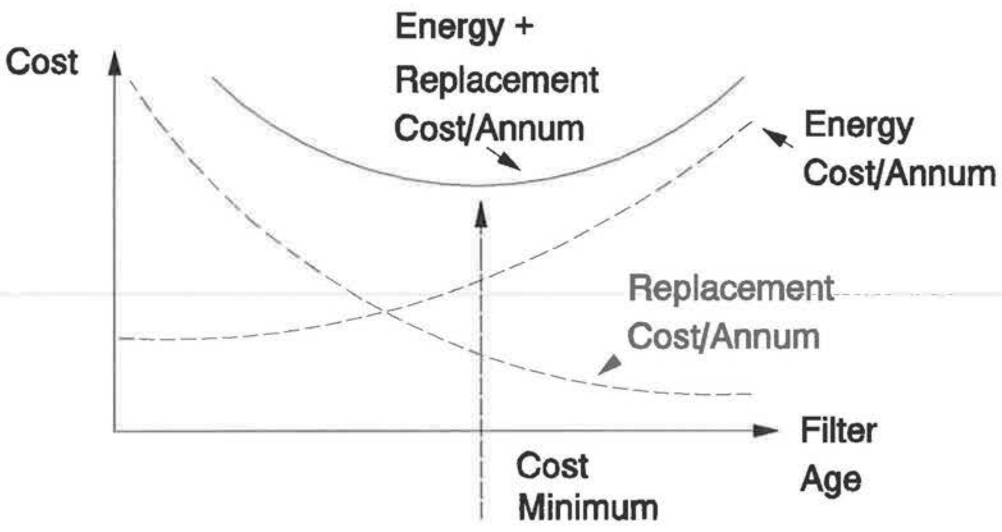
Table 1 Filter Change Criteria

1	Minimising the sum of the fan energy and filter costs
2	Manufacturer's maximum recommended DP
3	Limiting the effect of filter DP on system performance eg what is the maximum drop in volume flow rate which can be tolerated due to the increase in filter DP
4	Microbiological growth
5	Limited availability of plant shutdowns in which to perform the maintenance.

Criteria 1, 2 and 3 will each produce a DP at which a filter should be changed. The change should occur when the lowest of the three is reached. Criteria 4 and 5 may in some cases override these, causing the filters to be changed early.

Criterion 1 (minimising costs) will generally be a valid criterion for variable air volume (VAV) systems but not for constant air volume systems. VAV systems respond to a rise in filter resistance by adjusting fan speed/blade angle/etc to supply the desired air volume but against a higher system pressure drop. Thus fan energy consumption and cost will increase as a filter ages. At the same time, filter costs per annum will fall with the period of time installed. This will create a point where the sum of the costs is at a minimum - (Figure 1).

Figure 1 VAV system filter cost minimum



An increase in filter resistance in constant volume systems reduces the air flow rate. For most common fan types (eg backward curved centrifugal, axial), this will not lead to a significant increase in the fan energy - see ASHRAE [Ref 3]. Indeed, in most cases it will actually fall. Thus the fan energy and filter costs per annum will both tend to fall as a filter ages and no cost minimum will exist for the sum of the two. The filters should therefore be retained until determined otherwise by the other criteria.

Criterion 2 concerns the manufacturer's maximum recommended DP. Filters should be changed when they reach this value. It is based on the results of tests, and performance at higher DPs will be uncertain.

Criterion 3 is relevant primarily to constant volume systems in which increasing the resistance of filters will reduce the volume flow rate supplied. (It will also restrict the maximum flow rate which can be supplied by VAV systems.) This fall in air flow rate will reduce the performance of the system in terms of providing ventilation, heating and cooling. An assessment should be made to determine what level of reduction is acceptable, and hence the corresponding maximum filter DP which can be tolerated. This may vary from season to season as peak performance may only be required at certain times of the year, eg cooling in summer.

As noted above, the filters should normally be changed at the lowest DP determined by these three criteria. Manufacturers' data can then be used to assess the filtration efficiency which would be expected by changing the filters at the selected DP to verify that this meets the required performance. This could be interpreted in terms of the EU Number as defined by the Eurovent rating scheme [Ref 4].

Filter DP monitoring case studies of VAV and constant volume systems are presented in the following Sections. It should be noted that DP monitoring is not a substitute for regular inspection. These will still be required to verify the integrity of the installation and to check for problems such as microbiological growth, for example, although there will normally be scope for reducing their frequency.

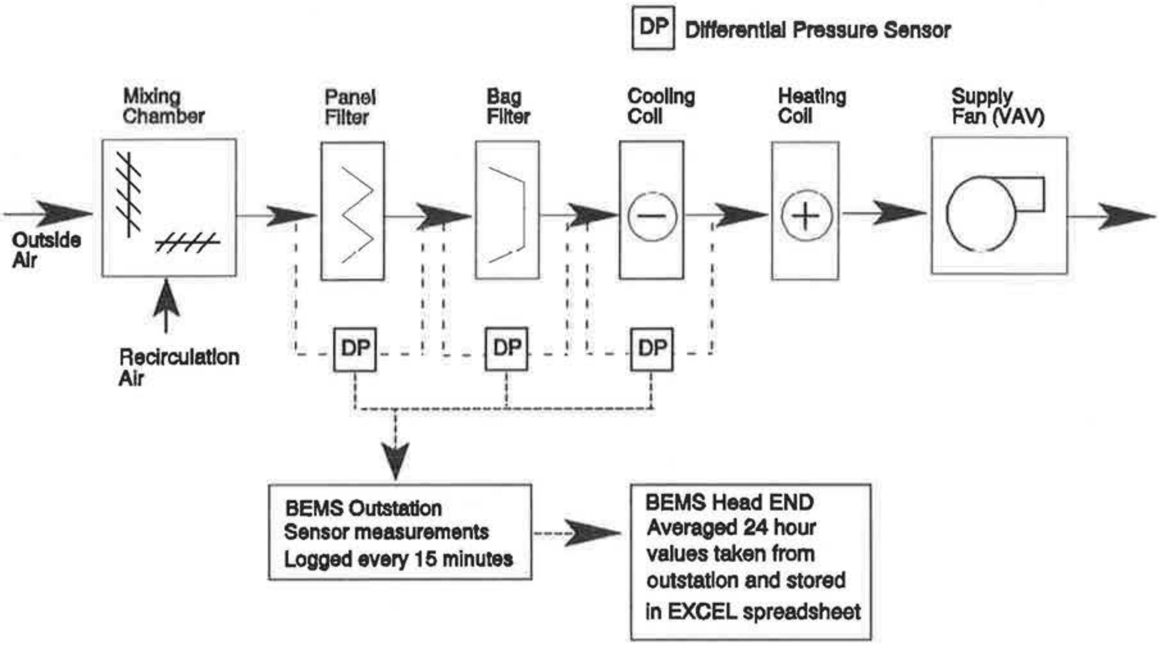
In addition to being able to assess dust loading, DP monitoring can also detect loss of integrity of a filter bank through a drop in the pressure differential developed, caused by leaks etc. A lower than expected initial value would also indicate a problem with the installation.

3.1 FILTER MONITORING CASE STUDY OF A VARIABLE AIR VOLUME (VAV) SYSTEM

3.1.1 Monitoring

Monitoring was instigated on a VAV unit which has panel and bag filter banks (Figure 2). Differential pressure (DP) sensors were installed across each of the filter banks and the cooling coil. The purpose of the sensor on the cooling coil is to provide measurements of the volume flow rate for the analysis which is outlined below. Values were logged daily at 15 minute intervals by the BEMS. A summary of the proposed monitoring procedure is given in Figure 3.

Figure 2 VAV filter monitoring



The DPs developed across the filters and cooling coil are assumed to be proportional to the square of the volume flow rate, ie:

$$DP_f = k_f.Q^2 \qquad \ldots(1)$$

and

$$DP_c = k_c.Q^2 \qquad \ldots(2)$$

where DP_f is the DP across a filter bank (Pa)
k_f is the resistance factor of the filter bank
Q is the volume flow rate (m^3/s)
DP_c is the DP across a cooling coil (Pa)
k_c is the resistance factor of the cooling coil

The resistance factor k_f of a filter bank will increase as the filter becomes loaded with dust. Therefore k_f provides a measure of filter condition and has been adopted as the trended parameter to predict the filter life.

Figure 3 VAV filter monitoring procedure

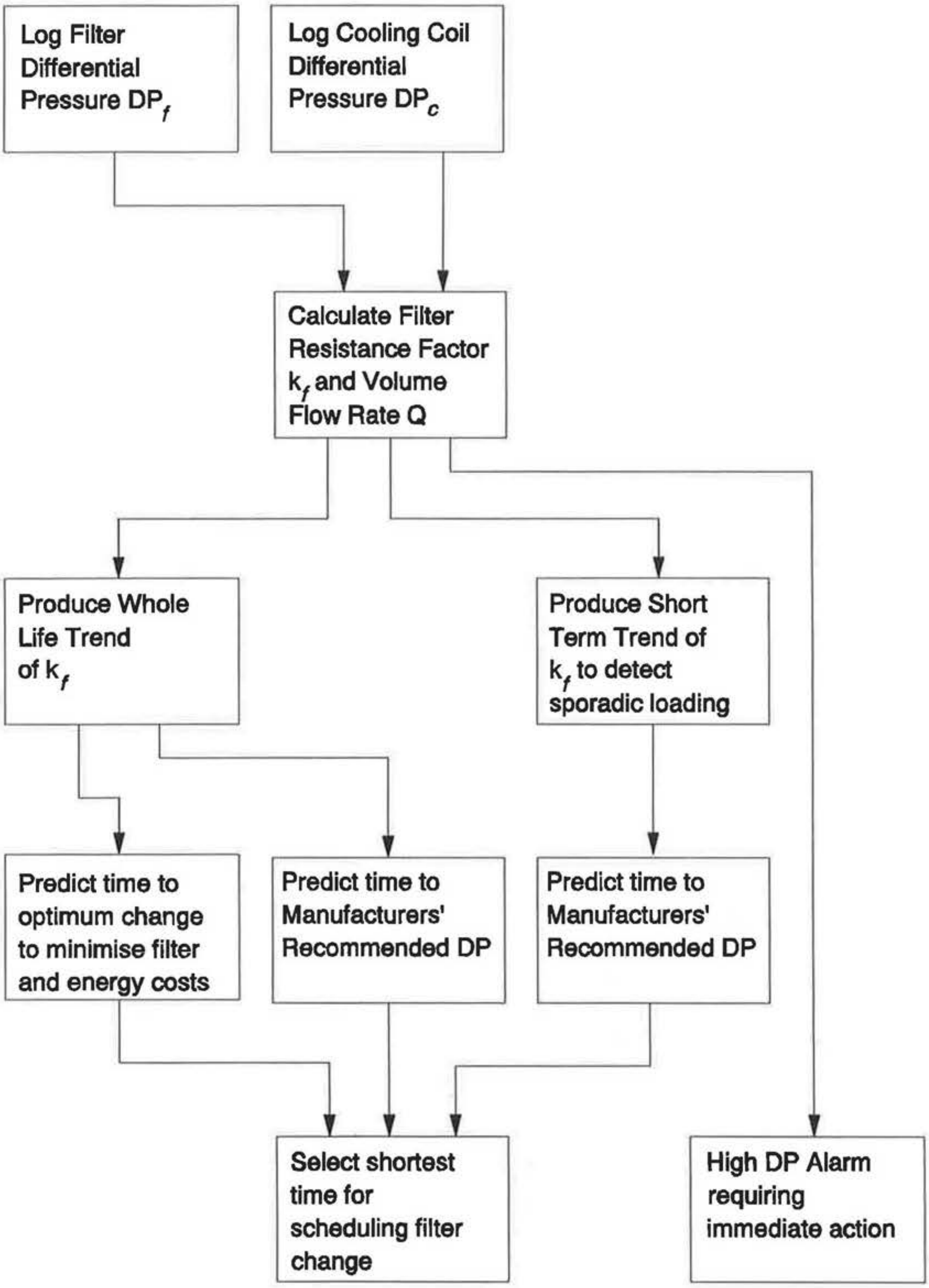
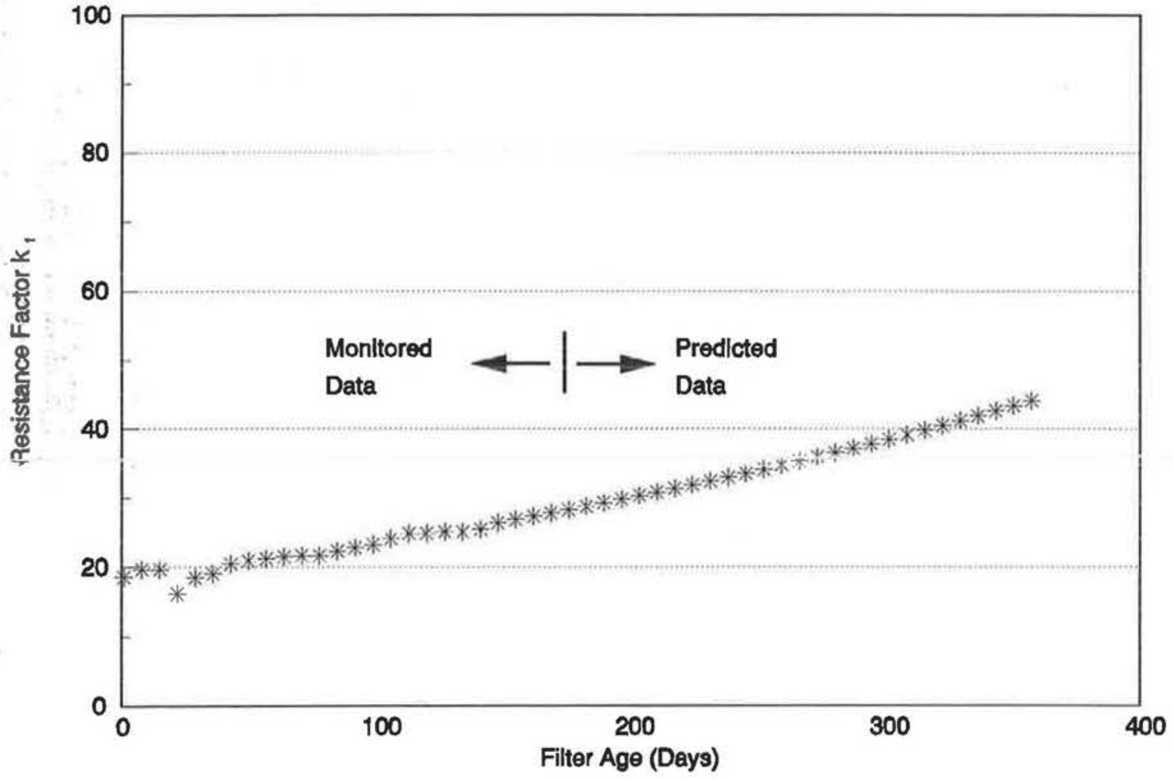


Figure 4 VAV filter monitoring panel filter bank resistance factor k_f



It is assumed that the cooling coil resistance factor k_c does not change significantly during the monitoring period in comparison with the filter resistance factors. *(NB The coils are protected by the filters).* DP_c therefore provides a measure of the volume flow rate Q. Combining Equations (1) and (2) gives:

$$k_f = k_c.(DP_f/DP_c) \qquad ...(3)$$

This expression has been used to calculate the filter resistance factors from the differential pressure measurements and k_c. The value of k_c can be calculated from a measurement of DP_c and Q using equation (2). Q could alternatively be estimated from a measurement of DP_f for a clean filter bank and the manufacturers' test data. Values of k_f for the panel filter bank are plotted in Figure 4. The filter data monitored is for the first five months of its life to mid-January 1994 (150 days). The k_f values show a steady increase over the filter life. The values after mid-January are predicted using trending.

Manufacturers' test data indicates that an exponential function would be suitable for trending purposes to predict future k_f values. The trend shown in Figure 4 is based on the data collected over the whole filter life. This is appropriate in this case as the filter is subject to a low steady rate of loading. Trends based on shorter periods, eg the previous two weeks' data, should also be employed to respond to sporadic high rates of loading. This point is discussed and illustrated by the constant volume case study in Section 3.2.

3.1.2 Change criteria

Criterion 1 noted above for determining when a filter should be changed is to minimise cost. The calculated annual replacement and fan energy costs for the panel filter bank are plotted in Figure 5. The filter replacement cost R_f includes the purchase of the filters (20 @ £7) and the installation cost (0.5 hrs @ £35/hr per filter bank). The equivalent annual value C_f is calculated from:

$$C_f = (365/n).R_f \qquad \ldots(4)$$

where n is the number of days for which the filters have been installed

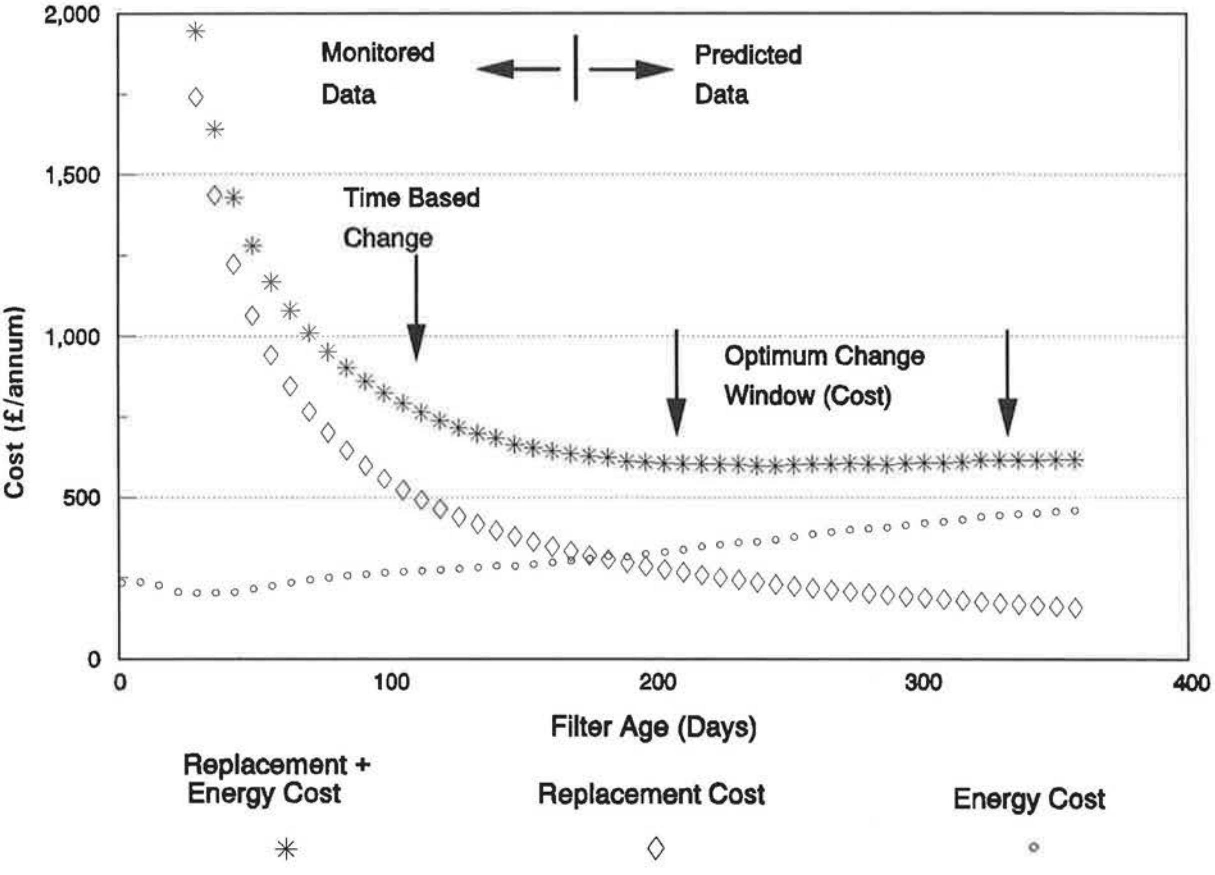
The fan energy cost E_f due to the filters is given by:

$$E_f = (365/n).T.e/1000.\sum_{1}^{n}\{Q.DP_f/(\eta/100)\} \qquad \ldots(5)$$

where T is the operating period (24 hours)
e is the cost of electricity (£.05 p/kWh)
η is the fan efficiency (%)

To simplify the analysis a constant value for the fan efficiency η of 60% has been assumed. This is reasonable as variations in efficiency are generally small compared to variations in volume and differential pressure.

Figure 5 VAV filter monitoring panel filter bank costs

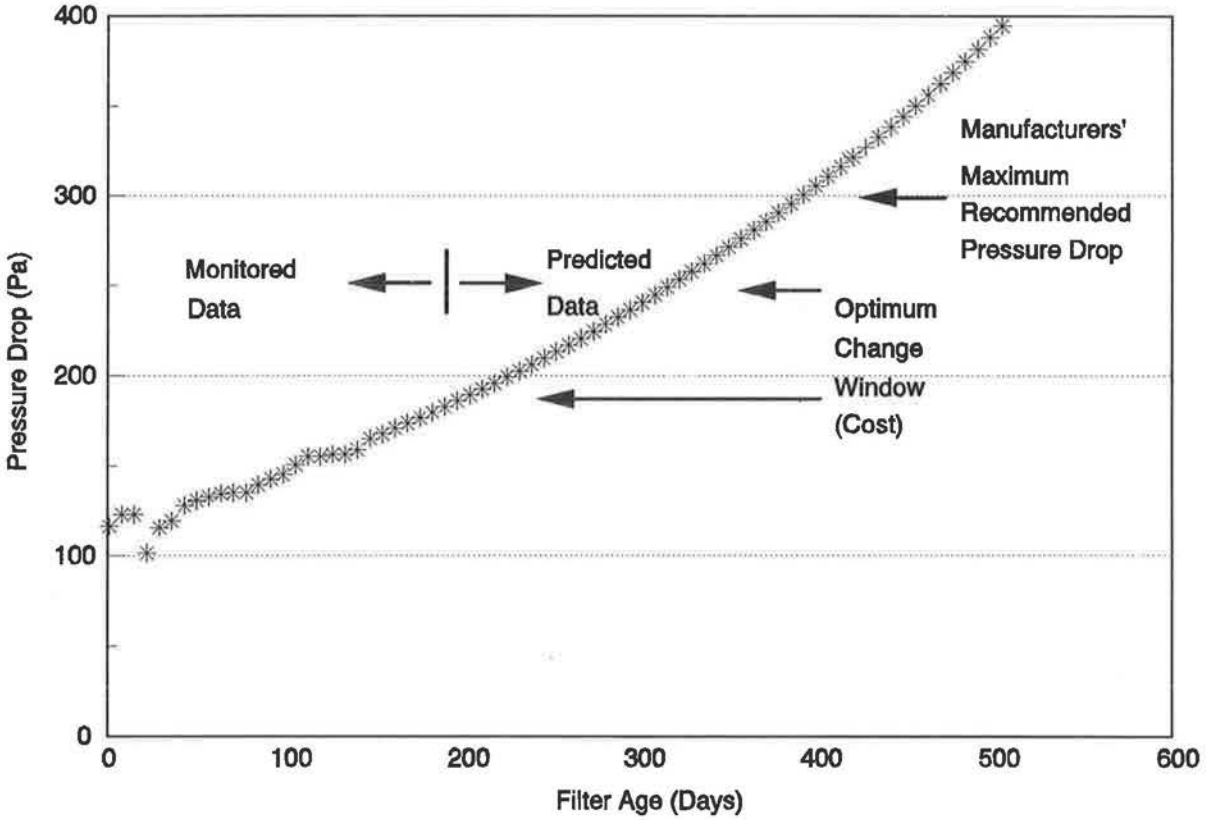


The sum of the filter replacement C_f and fan energy E_f costs is also shown in Figure 5. The predicted values subsequent to mid January are included to show the future expected variation. These are calculated on the basis of k_f values predicted by trending (Figure 4) and historical DP_c values recorded for the equivalent day 12 months previously.

In terms of minimising panel filter costs, replacement of the filters could take place anywhere between 6 and 10 months (180 and 300 days). The overall cost within this period is relatively constant, with the increase in fan energy cost balancing the reduction in filter replacement cost (Figure 5). This is a lengthy period during which filters can be changed with no significant effect on cost. However, as noted above, filters generally become more efficient as they age. Increasing the efficiency of the panel filter bank will reduce the dust passing through, so extending the life of the bag filter bank downstream. Delaying replacement until 10 months (300 days) is therefore favoured. The DPs at a maximum flow velocity of 2.5 m/s are plotted in Figure 6, using the recorded and predicted k_f values. The DP after 10 months is predicted at 250 Pa.

Criterion 2 is to change the filters at the manufacturer's maximum recommended DP, which for these filters is 300 Pa, higher than the change pressure for minimising cost. Figure 6 indicates that 300 Pa will be reached after approximately 13 months (390 days). Delaying the change until this time will incur a cost penalty of £25/annum.

Figure 6 VAV filter monitoring panel filter pressure drop



Criterion 3 is to limit the effect of the filter DPs on system performance. Adequate sizing allowances mean that this will not be a problem in this case as long as DPs do not exceed those recommended by the manufacturer.

The determining criterion for changing the filters in this case is therefore the minimisation of cost. The filters should be changed when the DP (corrected to a flow rate of 2.5 m/s) reaches 250 Pa.

3.1.3 Costs and benefits

The primary expense of instigating CBM for filters is the purchase, installation and connection costs of the DP sensors. These have been estimated at £200 per sensor. Hence the cost of instigating CBM monitoring for the panel and bag filter banks above was in the region of £600. No additional BEMS outstations were required as spare ways were available on existing outstations.

The annual saving will depend on when the filters would otherwise have been replaced. The saving in comparison with a time based regime with panel filter replacement at three monthly intervals is £100/annum. A similar cost saving is predicted for the bag filter bank due to an extension of the replacement interval from 12 to 24 months. *(NB In addition there will also be the attendant benefit from improved filtration performance which will reduce plant fouling and interior staining.)*

The reductions in the replacement costs alone due to the increased filter lives are much larger than the overall savings noted above. However, these are to a large extent offset by increases in the fan energy costs (Figure 5). This installation has 20 filters in each bank. Overall replacement and fan energy costs prior to the instigation of CBM were £30/filter/annum for panel filters and £60/filter/annum for bag filters. The saving due to the introduction of CBM is in the region of £5/filter/annum for both, which corresponds to 17% and 8% respectively of the overall costs.

The frequency of regular inspections can also be reduced by the use of automated filter monitoring, eg from weekly to monthly [Ref 5]. For an inspection time of 15 minutes for both filter banks (@ £35/hour), this represents a saving of £350/annum. Adding this to the reduction in filter replacement and fan energy costs produces a payback of just over one year.

One of the key factors which will determine if CBM of filters can be cost justified is the number of filters monitored by each DP sensor. The higher this number, the greater will be the filter replacement and fan energy cost saving per sensor, favouring CBM. Thus it is particularly applicable to large air handling units, or where one unit can be monitored as being representative of a group of units. One example of this is fan coil units serving a common space.

The variation of inspection time with the number of filters will be limited for a single unit. The majority of the time allowance is for travel to and from the unit and access. This will be largely independent of the number of filters per bank.

Another important benefit of automated filter monitoring using a BEMS is that sudden increases in the rate of filter dust loading can be detected. The rate of dust loading in this case was reasonably constant over the monitoring period. However, sporadic increases in loading can occur for example due to building work in the vicinity. Monitoring via the BEMS enables an alarm to be raised and the risk of the filter bursting to be avoided. The sporadic nature of the dust loading is demonstrated by the case study for the constant volume system presented in the next section.

3.2 FILTER MONITORING CASE STUDY OF A CONSTANT VOLUME SYSTEM

3.2.1 Monitoring

Monitoring was performed on a constant volume system provided with a bag filter bank. Differential pressure (DP) readings across the filter bank were logged by the BEMS two days a week at 15 minute intervals. A summary of the proposed monitoring procedure is given in Figure 7. The data is presented in Figure 8. The filter DP is proportional to the resistance factor k_f as the volume flow rate Q is reasonably constant. *(NB The calculated fall in flow rate as the filter becomes loaded is 10% to 15% - see 3.2.2).*

3.2.2 Change criteria

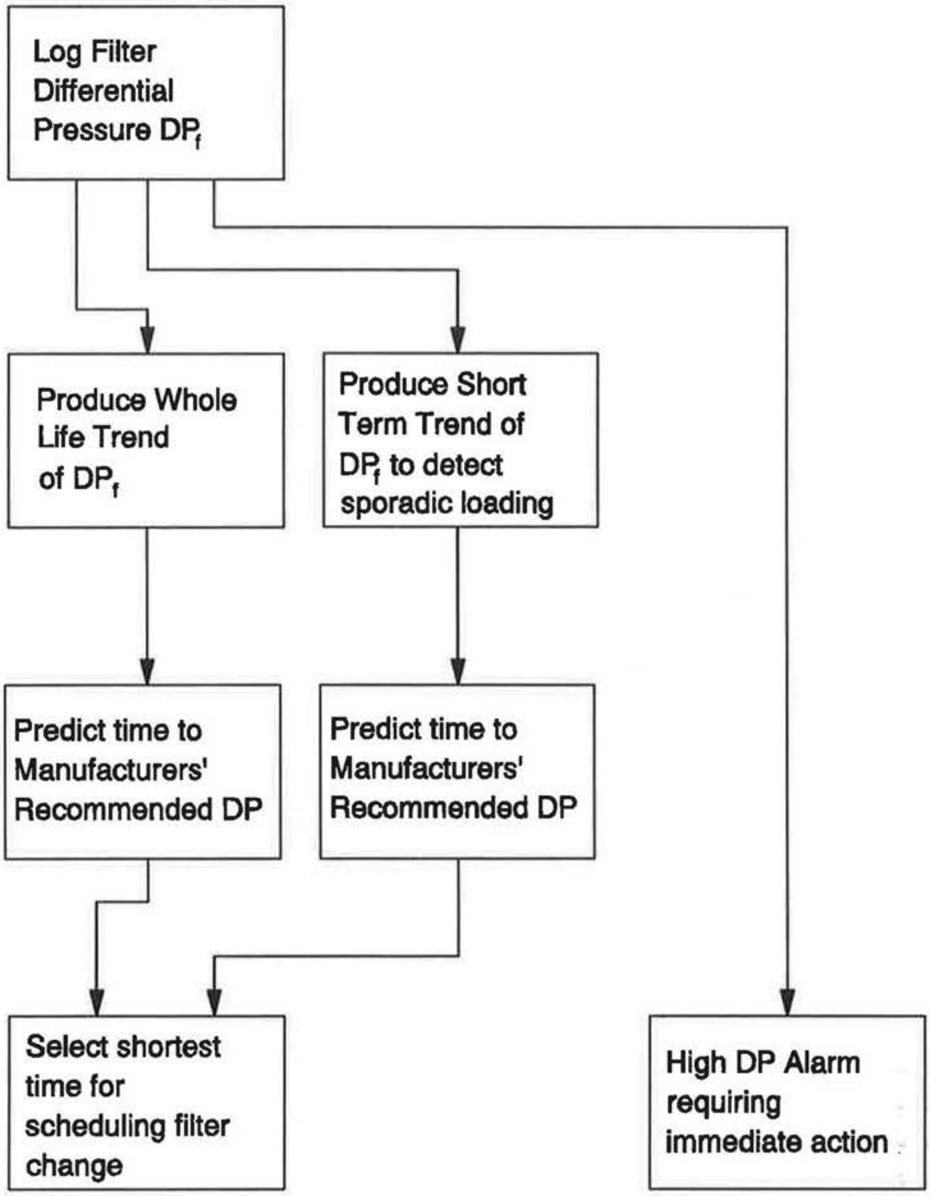
With regard to Criterion 1, minimising the replacement and energy cost, the fan power consumption reduces as the filter becomes loaded. Therefore the cost will fall with age. Hence, the filters should be retained for as long as possible, subject to Criteria 2 and 3.

The filter manufacturer's recommended pressure drop is 250 Pa (Criterion 2). The predicted reduction in system flow rate at this pressure drop is calculated at 10% to 15% by theoretical analysis, which is considered reasonable (Criterion 3). The recommended pressure drop of 250 Pa has therefore been adopted as the change criterion for the filter.

3.2.3 Costs and benefits

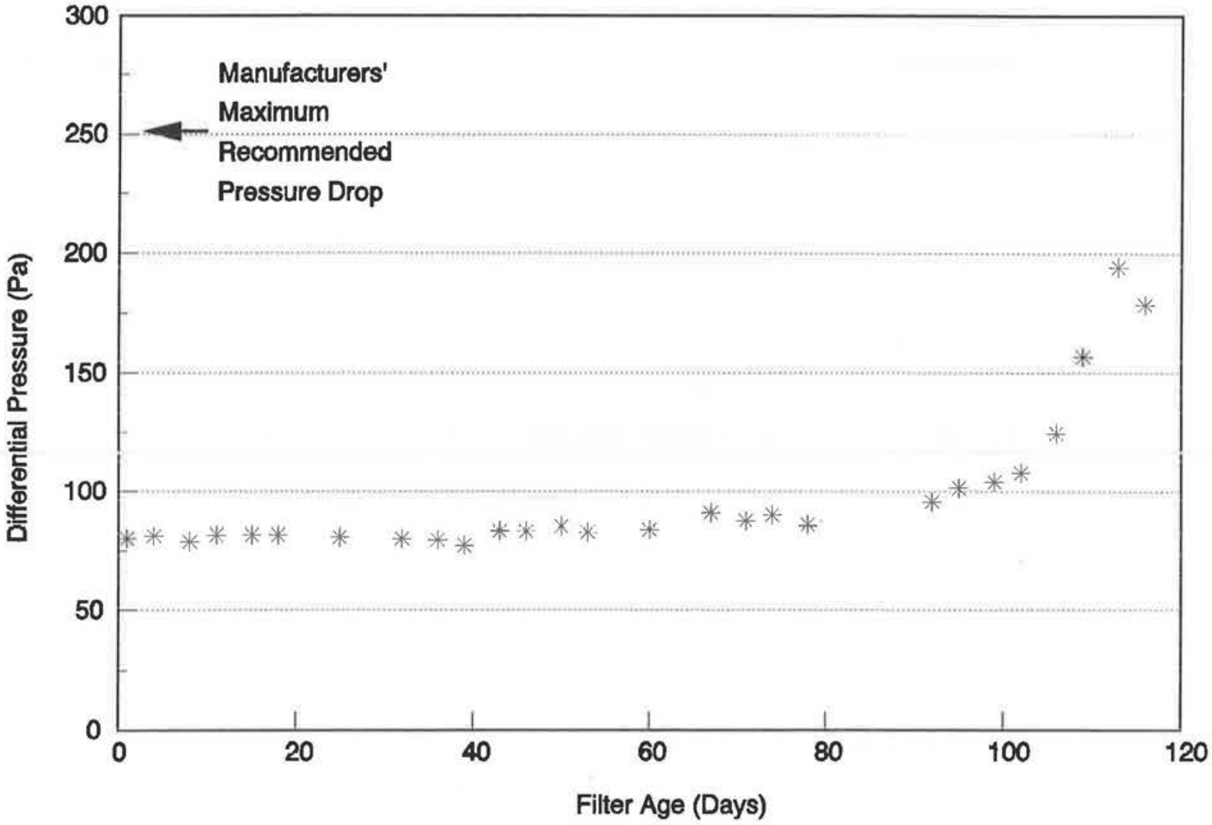
The results in Figure 8 show the increase in differential pressure across the filter over its life. An important point to note is the low rate of increase over the first 90 days, followed by a dramatic rise in the last 30 days. The filter effectively goes from "clean" to "dirty" in one month. This was caused primarily by building work in the vicinity, and illustrates how sporadic filter fouling can be.

Figure 7 Constant volume filter monitoring procedure



The automated monitoring via the BEMS enabled an alarm to be raised and the filter to be replaced at the appropriate time. Without the automated monitoring, there would have been a high risk of the increased rate of filter fouling remaining undetected. The filters could have become overloaded and burst within a few weeks, incurring subsequent clean-up costs.

Figure 8 Constant volume filter monitoring differential pressure data

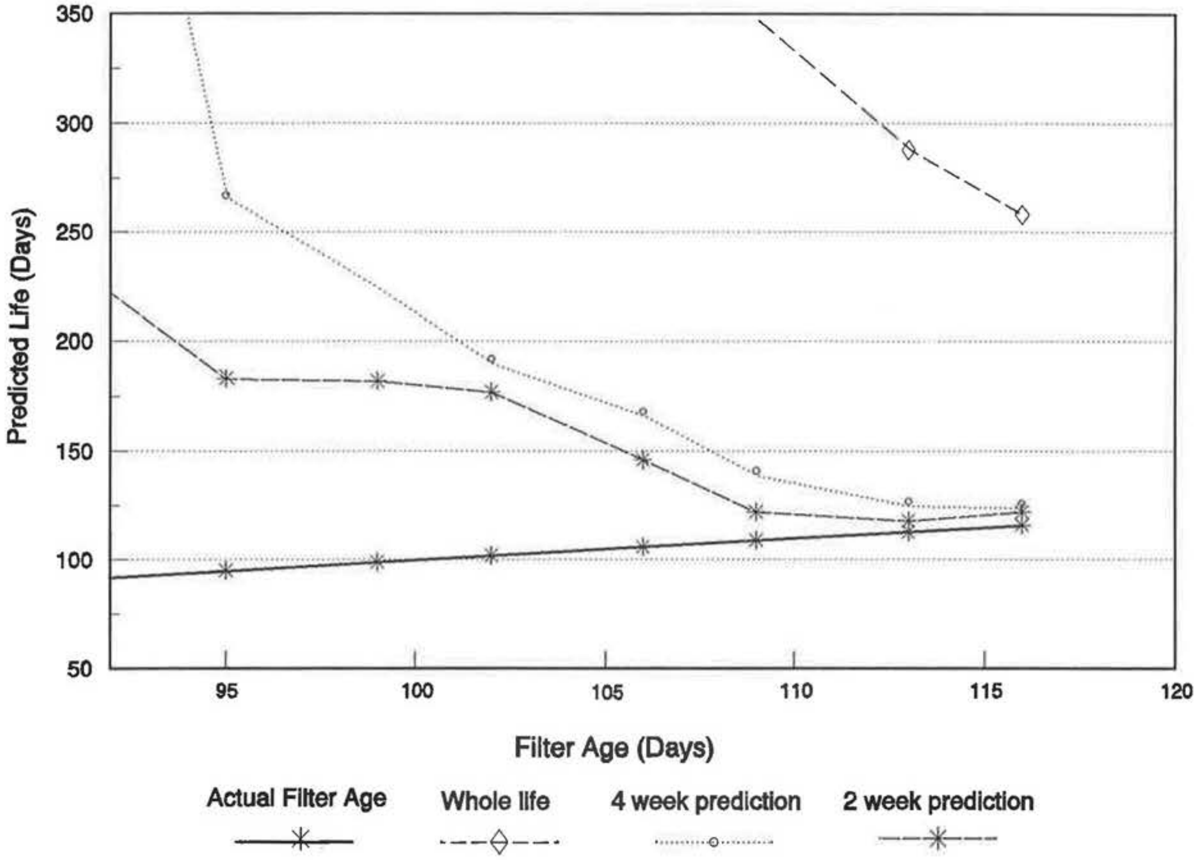


The sporadic nature of filter fouling should be taken into account when trending is adopted to predict filter change dates. The predicted filter life generated from the data collected using three different exponential trends is illustrated in Figure 9. Exponential trends have been selected as these are considered to be appropriate from consultation of the manufacturer's test curves. The three trends are based on the following historical data periods:

1 Whole life
2 Preceding 4 weeks
3 Preceding 2 weeks.

The three predictions are plotted in Figure 9 as the filter ages. The difference between a prediction and the filter age is the estimated filter life remaining. This is the "early warning" which enables the change to be scheduled into the maintenance regime.

Figure 9 Constant volume filter monitoring comparison of trend predictions of filter life



A filter with a constant rate of dust loading would produce a constant prediction throughout the filter life, ie a horizontal line on the Figure. However, for the case considered there is a dramatic increase in the rate of loading after approximately 90 days. In response to this, the filter life predicted by the trends should be revised downwards to a much shorter life. The trend based on the previous two weeks' collected data responds quickly to the change, giving a reasonably accurate prediction (120 days) 2 weeks before a change is required. The 4 week prediction is slower in responding, and the early warning is reduced to one week. The whole life trend for all the data collected over the filter life is particularly unresponsive due to the influence of the early readings. The trend would not have given any warning that a filter change was necessary prior to the high filter loading alarm being activated.

The above illustrates the importance of matching the trending period to the variations which the system is likely to be subjected to. Sporadic variations in the rate of dust loading are likely to be in the region of weeks. The 2 week trend is therefore appropriate in taking these into account. However, under normal loading the 2 week trend will not be appropriate as little variation will occur between the first and last readings. A longer period possibly covering the whole filter life would be suitable to ensure that a trend is detectable. Hence, a combination of two types of trend, short term and long term should be adopted to cater for both possibilities.

The primary benefit of CBM in the case study presented above is the avoidance of a potential failure due to the filter bursting, rather than a reduction in the filter replacement costs. Detailed analysis of another constant volume system with a panel and bag filter combination has been performed. This indicates that a saving of £250/annum of the total panel and bag filters replacement cost could be achieved by adopting a CBM instead of a time-based approach. This equates to 35% saving for the 12 sets of filters. *(NB In contrast to the VAV system, there is no increase in fan energy cost to offset this saving.)*

The cost of DP sensors would be similar to those for the VAV installation, ie £200/sensor. One sensor would be required for each of the filter banks, giving a total cost of £400 for the unit. Thus, the payback on the basis of filter replacement costs is 1 to 2 years. A reduction in the inspection frequency would also be expected in line with those for the VAV plant (£350/annum), reducing the payback period to less than one year.

4 HEAT EXCHANGE PROCESSES

Generic types of heat exchangers which are common in building services include the following:

- Calorifiers
- Air blast coolers
- Air heating and cooling coils
- Cooling towers
- Evaporative coolers
- Water and air cooled condensers
- Water and air evaporators
- Boilers.

Degradation of heat exchange processes can be caused by fouling, scaling or corrosion of the heat transfer surfaces, or by blockage of tubes/passages reducing flow. This degradation can result in a drop in energy efficiency and prevent the system from achieving the desired level of performance. In some cases there may also be an increased risk of microbiological growth, such as legionella in cooling towers and evaporative coolers.

The conventional approach to maintenance is to inspect and clean heat exchangers at regular intervals. This can lead to unnecessary work being performed if the intervals are too short. Conversely, if the intervals are too long, excessive degradation between inspections may lead to energy wastage and poor performance. Monitoring the condition of heat exchangers would enable cleaning to be performed at the optimum time.

One factor favouring the monitoring of heat exchange processes by BEMS is the number of parameters which are already likely to be measured for control purposes. These represent "free" data for CBM. However against this must be balanced the complexity of many of the processes and any deleterious effect which the monitoring may have on the normal operation of the BEMS.

The complexity of many of the processes is due to their dynamic nature. One key parameter which often varies is flow rate, either as a result of valve/damper modulation or pump/fan speed changes. If large rapid variations occur during normal operation, frequent logging of parameters (eg minute-by-minute) may be required to determine the performance and complex analysis algorithms will be needed to process the data. A simpler approach is, where possible, to monitor the plant under steady flow conditions. These will often occur under start up conditions. A less favoured approach would be to impose steady flow conditions for a period specifically for the purposes of condition monitoring.

Using the BEMS communication network to transport large amounts of condition monitoring data could impair the performance of the BEMS in its primary function of controlling plant. Frequent logging of dynamic processes as noted above should therefore be avoided. Monitoring should also be restricted to key items of plant or, where similarity exists, rationalised to focus on one plant item which is typical of the group. Examples of this are air handling units installed on a floor-by-floor basis and fan coil units serving a common space.

The benefits which will accrue from the instigation of CBM will depend on the criticality of the process and the likely rate of degradation. Critical heat transfer processes in building services include heat rejection from computer installations. The highest rates of degradation and therefore maintenance cost would be expected for processes exposed to a replenishable source of contamination. Examples of this are air blast coolers exposed to the atmosphere and calorifiers supplied by mains water. The rate of degradation in closed systems with a finite source of contamination would be expected to be less.

Against these benefits must be set the cost of additional sensors and software modifications. Case studies of two of the most promising areas of application, calorifiers and air blast coolers, are presented in Sections 4.1 and 4.2 respectively. In addition to being exposed to a replenishable source of contamination, the processes monitored required no additional sensors to those previously installed and so set-up costs were minimal. CBM of the other types of heat exchange processes noted is discussed in the ensuing Sections.

4.1 CALORIFIERS

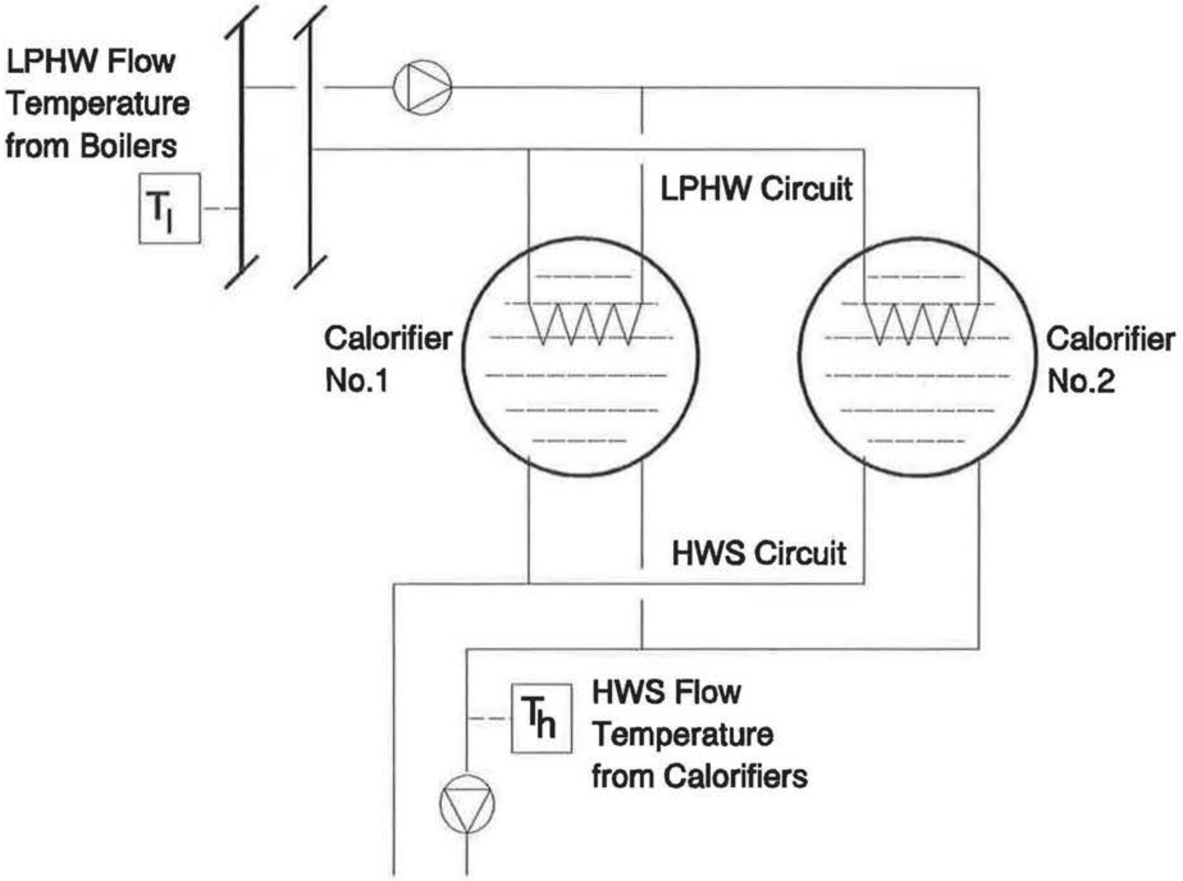
The installation monitored consists of two calorifiers connected in parallel (Figure 10). Primary heat is supplied by a Low Pressure Hot Water (LPHW) system which also provides space heating. The temperature of the LPHW system is compensated against outside air temperature and so varies throughout the year. Dedicated LPHW constant volume pumps are controlled on an on/off basis to maintain a secondary Hot Water Service (HWS) supply temperature of 65°C. The HWS system has constant volume pumps circulating water around a loop from which water can be drawn off. Temperature sensors are installed to monitor both the LPHW and HWS flow temperatures for control purposes.

Heating and hot water are required during normal working hours only, and so both the LPHW and HWS systems operate on an intermittent basis. The HWS system operates in conjunction with the LPHW system to achieve the required HWS temperature prior to the LPHW being used for space heating. The start-up period prior to occupancy is therefore the heat-up time for the HWS system plus that for the building in general.

The current maintenance approach is to annually open up and chemically clean the calorifiers to remove scale etc which may be impeding heat transfer. Degradation of the heat transfer efficiency would increase the heat up time and hence energy consumption via boiler casing, flue and pipework heat losses, and pump energy consumption. HWS temperatures may also drop below the required levels during periods of high draw-off.

When performed on a time basis cleaning may be too frequent so wasting effort, or not often enough, leading to excessive degradation. Condition monitoring of the heat transfer performance will enable the optimum time for cleaning to be determined. Logging of HWS system temperatures also has the benefit of providing records as part of a procedure to minimise the risk of legionella. Poor performance of the system should be alarmed by a minimum set point for the HWS supply temperature during the occupied period.

Figure 10 Calorifier monitoring



The monitoring is aimed at measuring the heat transfer effectiveness of the calorifiers. LPHW and HWS flow temperatures were logged at 1 minute intervals during the Monday morning start-up period. During the start-up period the dedicated LPHW pump set will run continuously until the required HWS temperature is achieved. Draw-off from the HWS system should be negligible. Hence steady flow conditions should exist in both systems during this period. Monday was selected as temperatures will drop further over a weekend than over a single night. The temperature differentials and rises will therefore be greater on a Monday, assisting monitoring accuracy.

The heat transfer effectiveness (ϵ) is calculated from:

$$\epsilon = \{(T_{hf}-T_{hi})/N\}/\{\Sigma T_l/N-\Sigma T_h/N\} \quad \ldots(6)$$

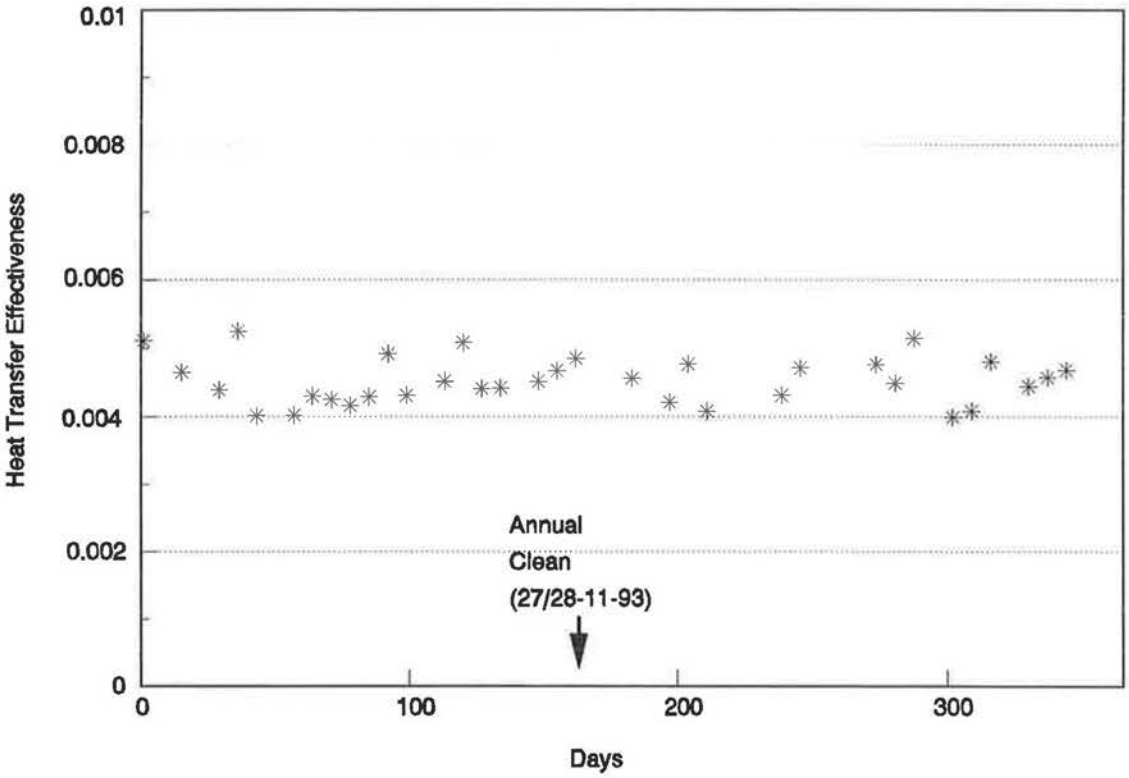
where T_{hf} is the HWS temperature at the end of the measurement period (°C)
T_{hi} is the HWS temperature at the start of the measurement period (°C)
ΣT_l is the sum of the LPHW temperatures over the measurement period (°C)
ΣT_h is the sum of the HWS temperatures over the measurement period (°C)
N is the number of readings included in the measurement period

A 20 minute period during heat up was selected for measurement, ie N = 20. The numerator is the temperature increase of the HWS system during this period which is proportional to the heat transferred (assuming negligible draw-off). The denominator is a measure of the average temperature differential driving the heat transfer. The resulting value of ε will therefore be proportional to the U-value.

The calculated values for the monitoring period are plotted in Figure 11. These remain within 10% of the average value. This consistency demonstrates the validity of the approach as a condition monitoring technique. The fluctuations around the average value are due to variations in:

- the difference between ambient building and HWS temperatures which will affect heat loss from the system
- the LPHW and HWS temperature differential which will influence convective heat transfer within the calorifier.

Figure 11 Calorifier monitoring heat transfer effectiveness data



There is no discernible trend in the results, indicating that deterioration in the heat transfer effectiveness over the period monitored is insignificant. The calorifiers were opened for inspection and chemically cleaned on the 27/28 November 1993. This is performed annually as part of the time based approach to maintenance. The results of the monitoring are supported by the fact that negligible scaling was observed.

The data shows that no detectable improvement in the heat transfer efficiency was achieved by the cleaning. Adopting condition monitoring to determine when cleaning is required would avoid unnecessary maintenance work such as this being performed. The cost of the work is estimated at £1000. Benefits from minimising the heat-up period are less readily quantifiable.

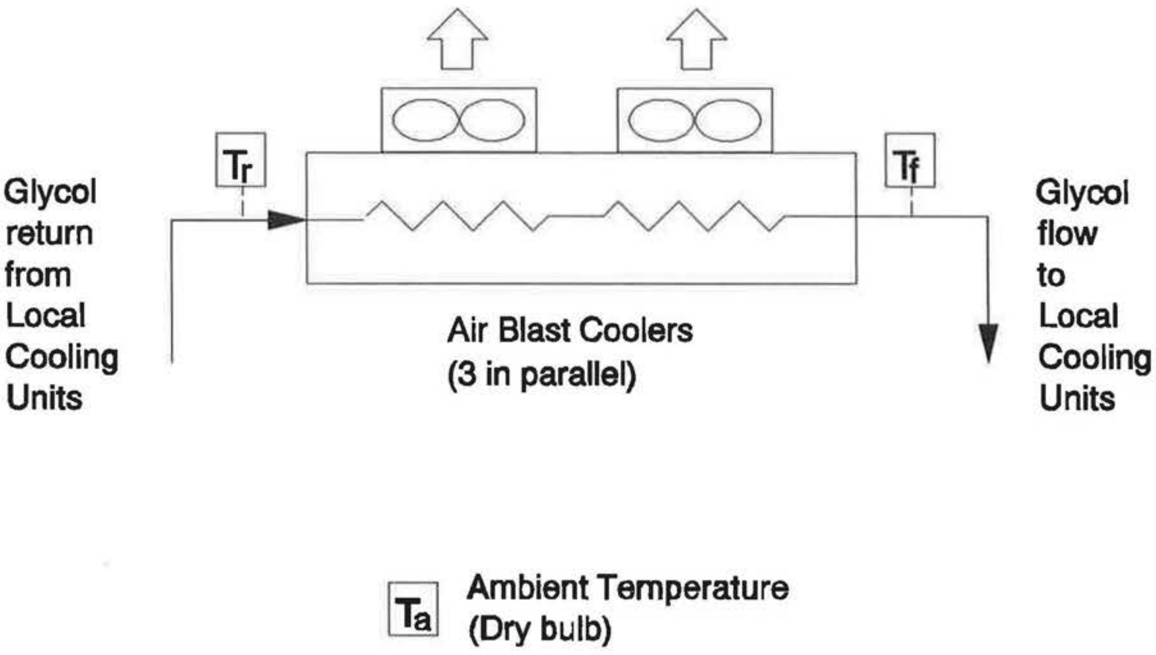
It should be noted that opening and inspection of the calorifiers may also be required for other purposes, eg compliance with the Pressure Systems and Transportable Gas Regulations 1989 and to minimise the risk of legionella. These requirements may dictate that the minimum frequency of inspection is less than that determined by CBM for cleaning. In these cases the saving due to CBM will be restricted to avoidance of unnecessary chemical cleaning.

(NB The heat-up period did not occur at the same time each week. The start-up strategy adopted meant that it could vary considerably depending on whether or not the space heating was operational. Account needed to be taken of these variations for data logging/analysis).

4.2 AIR BLAST COOLERS

The system monitored consisted of three air blast coolers connected in parallel (Figure 12). The air blast coolers reject heat from glycol circuits to atmosphere. The glycol is used to cool refrigerant condensers contained in air conditioning units which serve computer rooms.

Figure 12 Air blast cooler monitoring



The current maintenance approach is to clean the air blast coolers annually to remove dirt build-up and fouling on the air-side surfaces. Degradation of the heat transfer performance increases temperatures in the glycol circuits. This increases compressor energy consumption in the air conditioning units as these have to operate against a greater condenser/evaporator temperature differential. System capacity will also be impaired, possibly preventing the cooling load being met during periods of high ambient temperature.

The systems operate 24 hours a day. The fans on the air blast coolers are controlled to minimise the glycol temperature, and so run continuously producing steady flow conditions on the air side of the coolers. (The effect of minimising the glycol temperature is to reduce the condenser/evaporator temperature differential experienced by the air conditioning unit compressors, which in turn reduces their energy consumption.) The glycol flow is also constant volume. Therefore the only variables will be the air and glycol temperatures.

The temperatures which were monitored are illustrated in Figure 12. The required temperature sensors (glycol flow and return plus ambient dry bulb temperature) were already installed for control purposes and so no additional sensors were needed. A value for the heat transfer effectiveness was then calculated using the following equation:

$$\epsilon = (T_r - T_f)/(T_r - T_a) \quad \ldots(7)$$

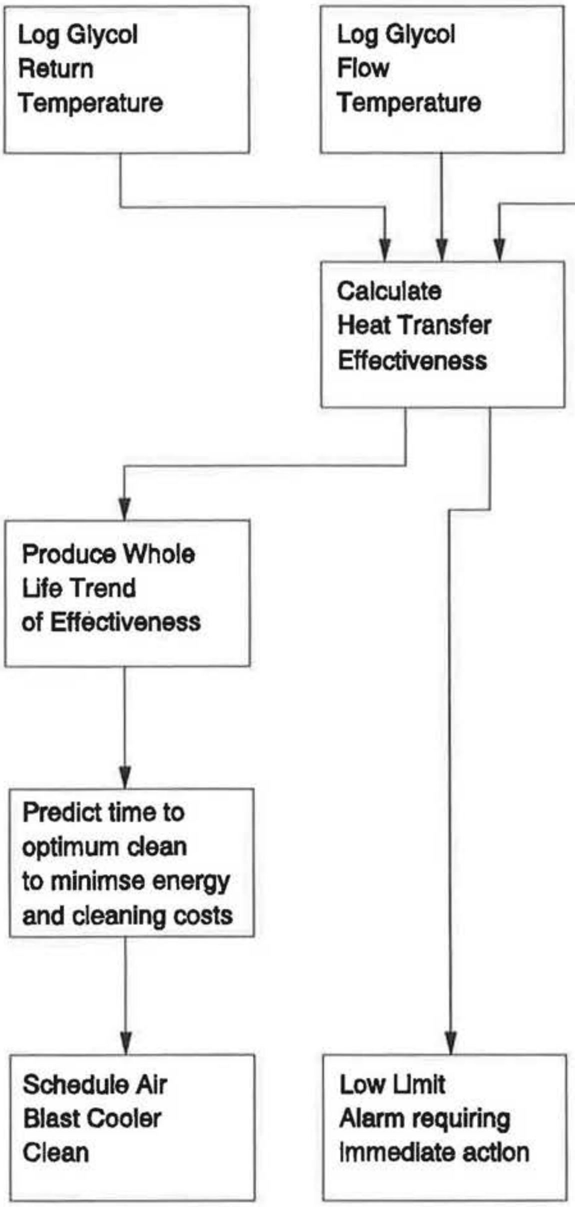
where T_r is the glycol return temperature to the air blast coolers (°C)
T_f is the glycol flow temperature from the air blast coolers (°C)
T_a is the ambient dry bulb air temperature (°C)

This expression represents the cooling actually achieved by the air blast coolers as a fraction of that which could be achieved if they were 100% effective and cooled the glycol down to the ambient dry bulb air temperature.

Eight sets of temperature readings were logged by the BEMS at 15 minute intervals over a 2 hour period 1 day a week. The average effectiveness was calculated for each period from the readings. Where there was a significant solar radiation effect on the ambient temperature readings the values obtained have been discarded. The results are subject to a large degree of scatter. This is caused by variations in the weather conditions. Wind and rain both act to increase effectiveness, whereas any sun impinging on the heat transfer surfaces reduces it. A summary of the proposed monitoring procedure is given in Figure 13.

As can be seen from the results presented in Figure 14, there is a significant increase in the effectiveness due to cleaning. Both the glycol system and the air side of the coolers were cleaned. A rate of decrease in the heat transfer effectiveness of 0.18/annum has been calculated from regression of the post-clean data. The following analysis is based on the assumption that this decrease is primarily caused by fouling of the air side of the exchanger.

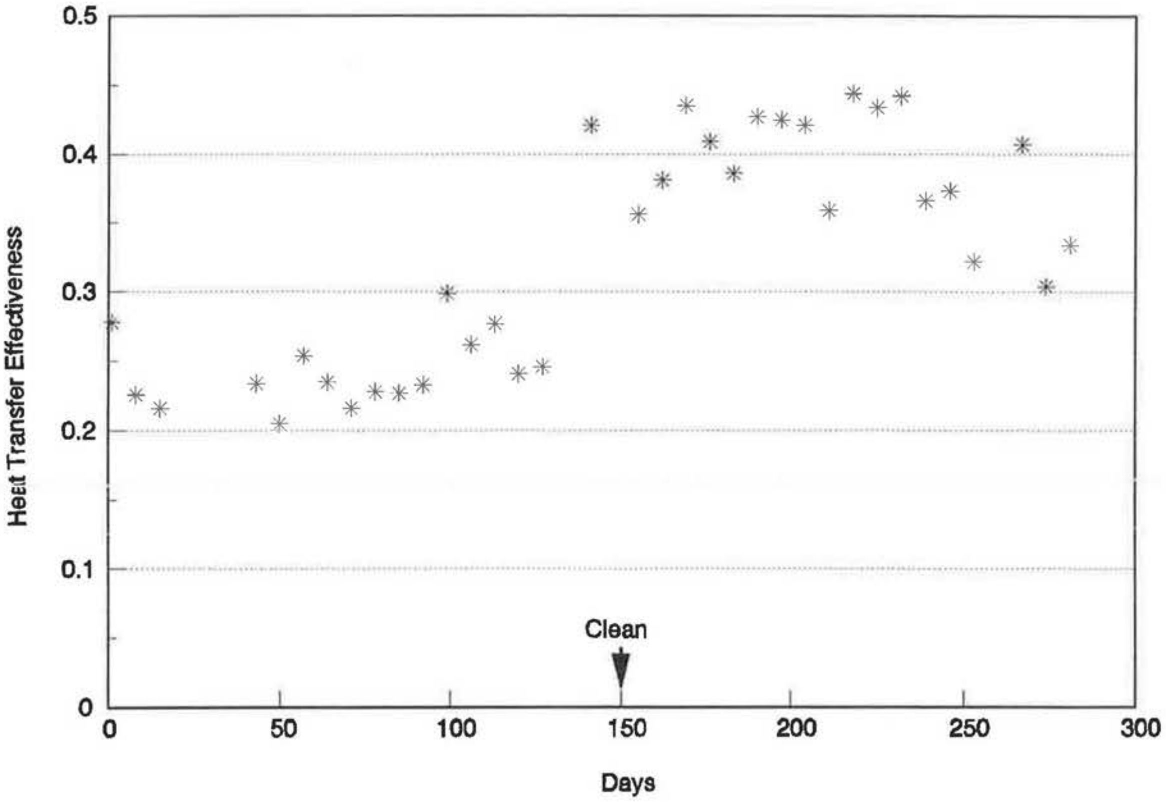
Figure 13 Air blast cooler monitoring procedure



The cooling rejected by the system is 800 kW. The estimated energy cost of the air handling unit compressors with an annual air side clean is £53k. This is based on a constant rate of decrease in the effectiveness of 0.18/annum, ie an average annual effectiveness of 0.31.

Improvements in this value can be achieved by increasing the cleaning frequency. Cleaning bi-annually will give an annual average effectiveness of 0.36 and an estimated compressor energy cost saving of £6k. *(NB This will depend to a large extent on the refrigeration controls)*. The cost of cleaning the air side of three units is in the region of £1k. Hence there should be a significant net cost saving (£5k/annum) from adopting bi-annual cleaning.

Figure 14 Air blast cooler monitoring heat transfer effectiveness data



Further increasing the cleaning frequency to quarterly will reduce the estimated energy cost by a further £2k. However, this will be offset by the increase in cleaning costs and so will not yield any financial benefit. *(NB It may be considered beneficial in terms of maintaining the effectiveness at a high level with regard to minimising the risk of "high head pressure" tripping and system failure - see comments below).*

It is evident from the above that the adoption of CBM can result in significant cost benefits by optimising the cleaning frequency. However due to the high criticality of this particular installation, a more important benefit is likely to be the capability to trigger remedial maintenance if the effectiveness falls below a prescribed minimum level. A poor heat transfer effectiveness will increase the glycol temperatures and hence the condenser temperatures in the air conditioning units. Eventually the units will trip out on "high head pressure", and the cooling to the computer rooms will be lost with potentially disastrous consequences. The calculated increase in condenser temperature due to a drop in heat transfer effectiveness from 0.40 to 0.22 is 9 K.

A minimum acceptable level of effectiveness could be determined and used as an alarm level. This would be used as a trigger to initiate remedial maintenance. The alarm level may vary from season to season. Better performance would be required in the summer to accommodate warmer ambient temperatures. *(NB This is taken into account in the current strategy of cleaning the units in March so that the best performance will occur during the ensuing summer months).*

As highlighted in Section 3 for filters, sporadic increases in the rate of atmospheric fouling can occur. This will accelerate the rate of degradation. Adoption of a CBM approach using BEMS monitoring increases the probability of detection, so reducing the risk of system failure.

4.3 AIR HEATING AND COOLING COILS

Air heating and cooling coils tend to be both limited in size and protected by filters. The benefits available will therefore be small. In addition, water flow rates will vary with valve movement and air flow may also be variable, complicating monitoring and analysis. CBM will therefore not generally be beneficial except for large coils, or where one coil can be monitored as being representative of a group.

4.4 COOLING TOWERS AND EVAPORATIVE COOLERS

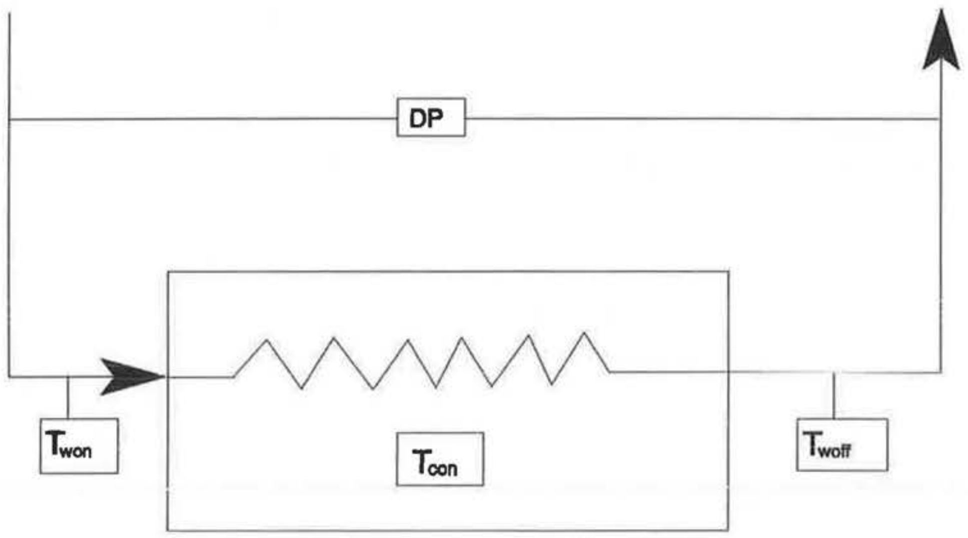
Cooling towers and evaporative coolers are particularly susceptible to fouling and degradation. Maintenance expenditure to minimise the risk from legionella is also high, and potentially large benefits would be available from effective CBM. However, in practice, replacement of current established manual maintenance tasks with automated monitoring by a BEMS is unlikely to be acceptable because of the sensitivity to legionella. An additional problem is that the sensors used for monitoring will be subject to the same fouling and degradation as the plant. This will inevitably affect the reliability and accuracy of the monitoring. A possible approach would be to use the BEMS as an additional automatic check on performance between manual inspections and to verify the effectiveness of the maintenance performed.

4.5 WATER AND AIR COOLED CONDENSERS

A strategy for monitoring the heat transfer effectiveness of water cooled condensers is illustrated in Figure 15. The condenser refrigerant temperature is not normally monitored by a BEMS, and an additional sensor or communication with the refrigerant unit will be necessary. An alternative approach commonly adopted for water cooled condensers is to install a differential pressure sensor across the condenser to detect blockage of the tubes.

CBM of air cooled condensers where air is drawn through the coils into an enclosure before being discharged could be achieved by the addition of condenser refrigerant and air off temperature sensors (Figure 16). The air on temperature will normally be measured by the BEMS as the ambient temperature. Measurement of the air off temperature where it is drawn straight through the coils and discharged to atmosphere by fans will be more difficult in practice. In theory, measurement of the DP developed across the coils would provide an indication of fouling and blockage. However, wind effects will dramatically affect readings making this approach impractical.

Figure 15 Condition monitoring of water cooled condensers



$$\text{Effectiveness} = \frac{T_{woff} - T_{won}}{T_{con} - T_{won}}$$

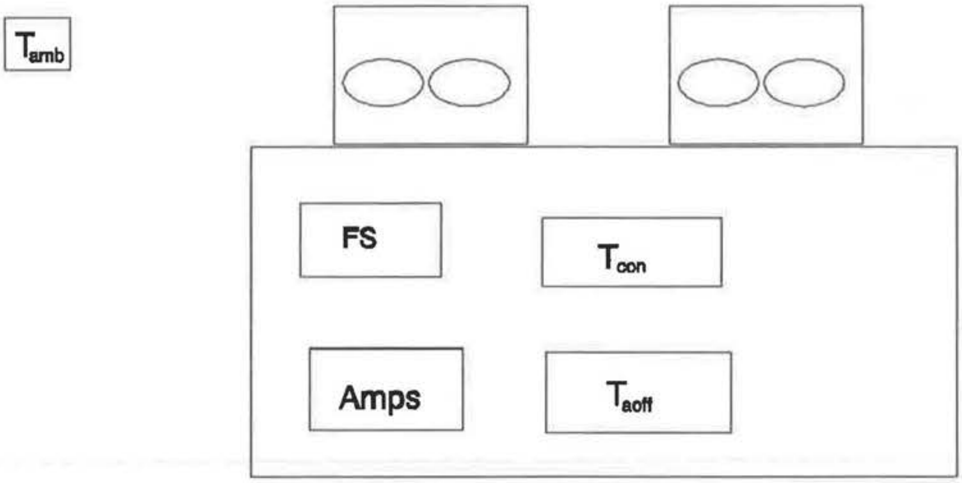
Parameters to be monitored:

T_{won} - Water on temperature
T_{woff} - Water off temperature
T_{con} - Refrigerant condensing temperature (or pressure)
DP - Differential pressure.

Notes:

1. *Water flow rate is assumed to be constant.*

Figure 16 Condition monitoring of air cooled condensers



$$\text{Effectiveness} = \frac{T_{aoff} - T_{amb}}{T_{con} - T_{amb}}$$

Parameters to be monitored:

T_{amb} - Ambient air temperature
T_{con} - Refrigerant condensing temperature (or pressure)
FS - Fan Status (eg high/low/off)
Amps - Current drawn by unit
T_{aoff} - Coil air off temperature

Notes:

1. *Monitoring of T_{aoff} is necessary to define the thermal performance.*
2. *Blockage fouling may be indicated by an increase in the current drawn for certain types of fan (eg propeller).*

Another alternative would be to monitor the current drawn by the fan motors. Fouling and blockage of the coils will change the load on the fan, which may alter the current drawn by the motor. ASHRAE [Ref 6] indicates that current will generally vary in proportion to power for most fan types. The magnitude of the change in power and current will depend on the fan type and its operating characteristic. ASHRAE [Ref 3] and laboratory tests indicate that current will be relatively insensitive to changes in system load due to fouling/blockage for backward curved and axial fans in general as these have reasonably flat power characteristics in the operating region.

In practice, the feasibility of this approach can be tested by artificially blocking a portion of the coil free area and observing if a significant change in motor current occurs.

4.6 WATER AND AIR COOLED EVAPORATORS

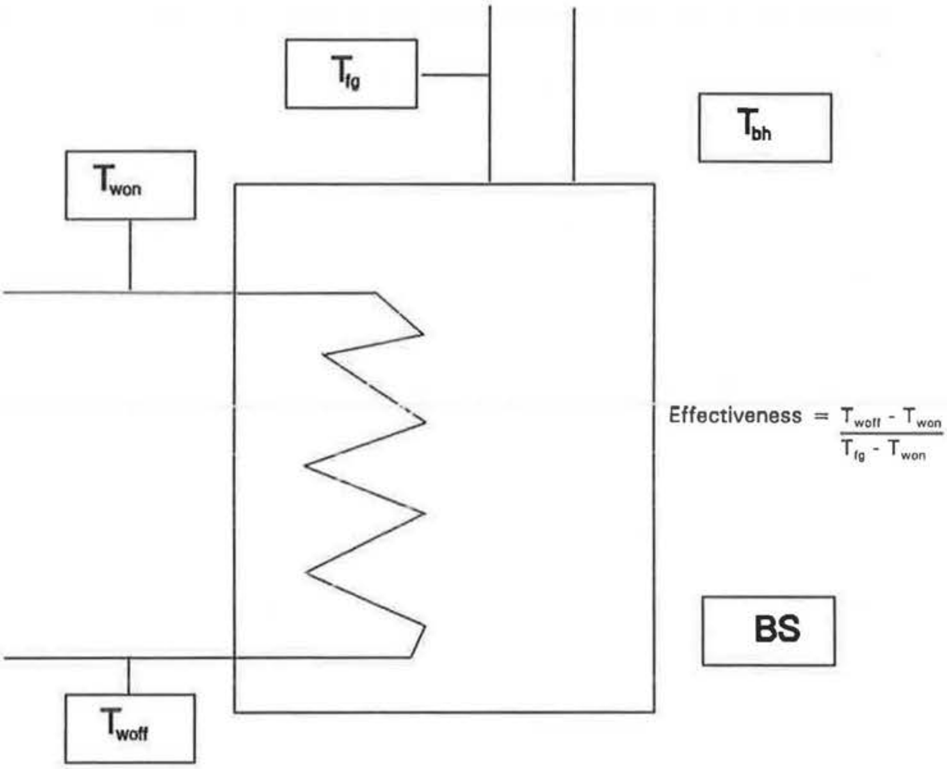
Water cooled evaporators are generally part of a closed system eg chilled water. Air cooled evaporators tend to be exposed to conditioned air and/or protected by filters. Both are therefore only likely to suffer a low rate of degradation, restricting the potential benefits of adopting CBM.

4.7 BOILERS

CBM could be performed on oil fired boilers, in particular shell and tube types, by the addition of a sensor to measure flue gas temperature (Figure 17). For modulating boilers, monitoring should be performed at a prescribed output, normally 100%. An increase in the flue gas temperature would indicate a decrease in the heat transfer efficiency due to scaling for example. Gas fired boilers are less susceptible to degradation of the heat exchange process and so this form of CBM is unlikely to be beneficial.

A drop in the flue gas temperature would be associated with a fall in the combustion efficiency of the boiler. Changes in combustion efficiency can also be detected using solid state oxygen sensors.

Figure 17 Condition monitoring of boilers



$$\text{Effectiveness} = \frac{T_{woff} - T_{won}}{T_{fg} - T_{won}}$$

Parameters to be monitored:

T_{won} - Water on temperature
T_{woff} - Water off temperature
F_{fg} - Flue gas temperature
T_{bh} - Boilerhouse temperature
BS - Boiler Status (eg high/low/off)

Notes:

1. *Water flow rate is assumed to be constant.*
2. *Monitoring measurements at a preset boiler status are preferred, eg at 100% output during building warm-up.*
3. *Monitoring of both the heat supplied to the water and the flue gas temperature are required to discriminate between reductions in heat transfer and combustion efficiencies. The heat supplied to the water will drop in both cases. However, the flue gas temperature will rise as heat transfer efficiency falls, and fall with combustion efficiency.*

5 AUTOMATED VIBRATION MONITORING

Vibration monitoring has been identified as a CBM technique of considerable potential benefit - refer to BSRIA TN 1/95 [Ref 1]. It can be used to monitor rotating plant such as pumps, fans and motors which are common in building services. Failures which are detectable by vibration monitoring include bearings, imbalance and misalignment.

There are three generic types of vibration monitoring:

- Overall level
- Frequency analysis
- High frequency techniques.

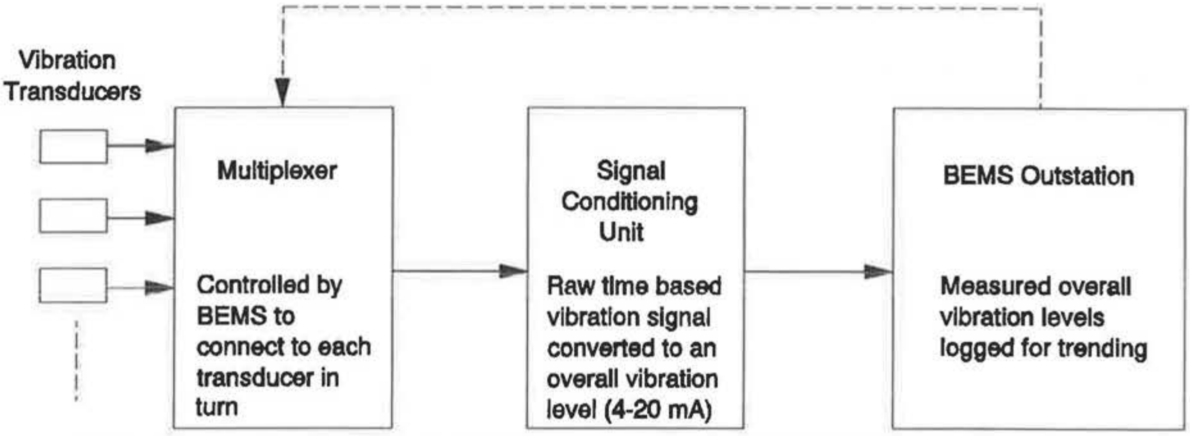
The simplest measure of vibration is the overall level, which will detect that a fault is developing. Better sensitivity and diagnosis are provided by frequency analysis. High frequency techniques are specifically aimed at detecting bearing failures. These are often used in conjunction with overall vibration monitoring which is relatively insensitive to bearing failures. The technique in general and the different approaches available are considered in depth in BSRIA TN(S) 3/95 [Ref 2].

Normally vibration monitoring is based on manual collection of data using hand held equipment. BEMS provide a means of automating the collection and analysis of simple vibration measurements. These include overall vibration levels and single values indicative of bearing condition. Collection of vibration spectra is not possible using existing technology. Utilising the BEMS to automate the monitoring will save labour time and increase the monitoring frequency. Remote condition monitoring via BEMS based bureau services is also possible.

The equipment configuration adopted for the project is illustrated in Figure 18. The raw signal produced by a vibration transducer is converted into an overall vibration level by the signal conditioning unit. The overall vibration level output from the signal conditioning unit is in the form of a 4-20 mA signal which can be read by the BEMS. Weekly measurements are logged and trended by the BEMS. Alarm limits are provided on the trend to flag up a rise in the overall vibration level which is indicative of a developing fault. This will trigger a detailed investigation of the nature of the fault, most probably incorporating vibration spectral analysis to determine the nature of the fault so that appropriate remedial maintenance action can be taken. The vibration spectrum measurement can be performed using hand held equipment connected to the installed transducers.

The set-up costs include purchase and installation of transducers, signal conditioning units and cabling, plus software modifications. Additional BEMS outstations or expansion boards may also be required where spare capacity is insufficient. Transducer costs will generally be of the order of £100 each. It should be noted that fixed transducers will in some applications be required for manual data collection in any case, such as fans in air handling units. Hence, transducers will not always represent an additional cost when comparing BEMS to manual data collection.

Figure 18 Overall vibration level monitoring



Signal conditioning units typically cost approximately £400 each. However, as monitoring is not continuous, one signal conditioning unit can be used to serve a number of transducers, scaling down the cost per point. A multiplexing unit can be installed between the signal conditioning unit and the transducers (Figure 18). The BEMS would control the multiplexing unit, connecting to and taking a reading from each transducer in turn. The cost effectiveness of this approach will depend on the distance between monitoring points with regard to the magnitude of the cabling costs.

The cost of the BEMS monitoring of overall vibration instigated as part of the project is estimated at £160/point. The installation consists of 14 points. No additional outstations were required as there was sufficient existing spare capacity. This level of expenditure will not be justifiable for the monitoring of building services plant in general, but may be appropriate for critical plant.

The effectiveness of overall vibration monitoring is demonstrated by the data plotted in Figure 19 which shows a trend taken from a fan. The development of a fault is indicated by the upward direction of the trend. The equivalent frequency spectra recorded at the same time are included in Figure 20 for comparison. The increase in vibration is at running speed. The fault was diagnosed as a coupling problem.

Although effective in identifying this failure, the overall vibration level is not particularly sensitive to bearing failures. For this reason, it is often used in conjunction with a bearing monitoring technique. A similar automated approach should be possible for bearing monitoring techniques which produce a single value which is indicative of condition.

Figure 19 Overall vibration level trend

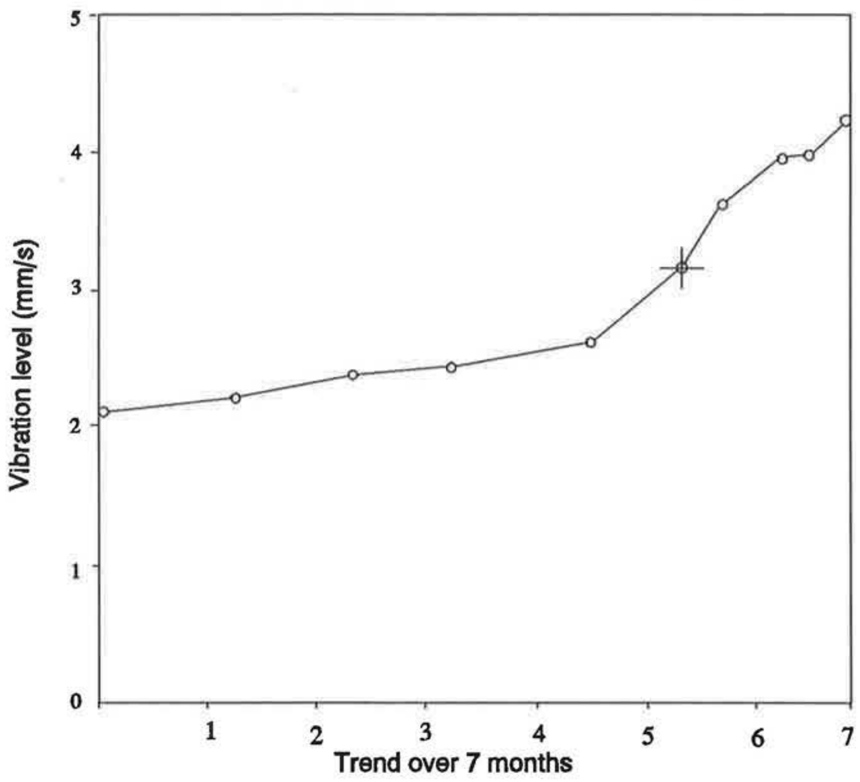
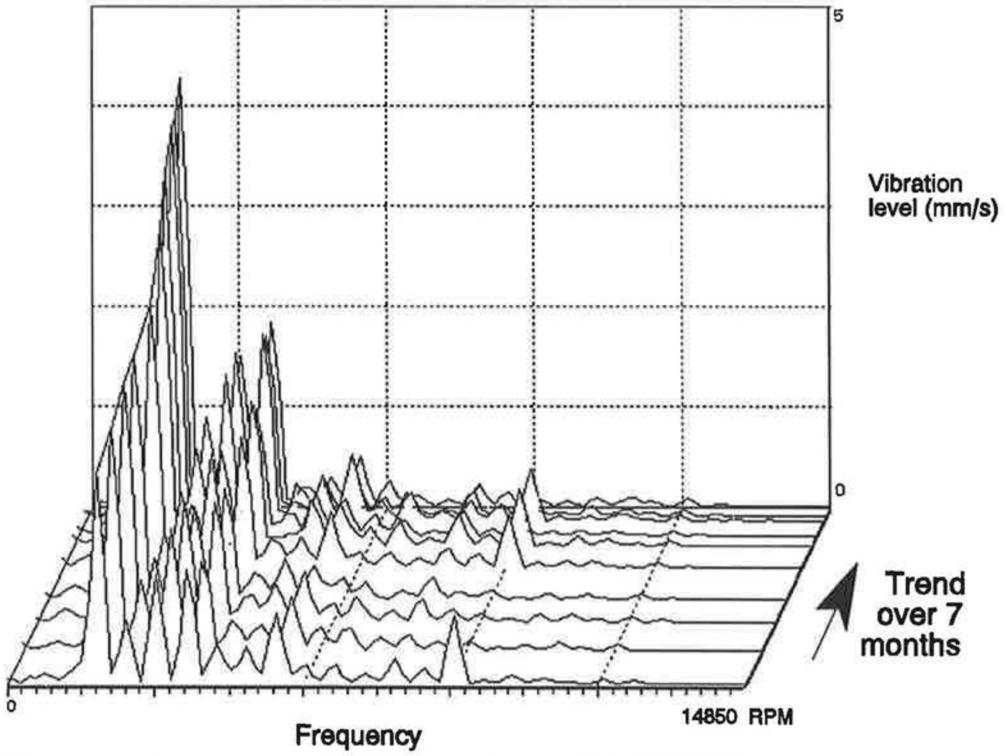


Figure 20 Waterfall plot of vibration frequency spectra



Data shows an increase in vibration at the running speed of 1800 RPM

6 REFERENCES

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