condition monitoring of machinery and plant

MEP

Papers presented at a Seminar organized by the Fluid Machinery Committee of the Power Industries Division of the Institution of Mechanical Engineers and co-sponsored by the Power Division of the Institution of Electrical Engineers

I Mech E PROGRESS

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Papers presented at a seminar organized by the Fluid Machinery Committee of the Power Industries Division of the Institution of Mechanical Engineers, co-sponsored by the Power Industries Division of the Institution of Electrical Engineers, and held at the Institution of Mechanical Engineers on 6 June 1985.

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CONDITION MONITORING OF MACHINERY AND PLANT

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CONTENTS

Wear debris evaluation

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SYNOPSIS The evaluation of debris liberated from lubricated components is a powerful method of condition monitoring of machinery. This paper reviews the methods available, including simple on-line devices and laboratory based techniques. An attempt is made to indicate the particle size range over which each techique is valid.

1 INTRODUCTION

The examination of used lubricating oils and allied techniques involving wear debris represents just one class of condition monitoring for machinery. Undoubtly the selection of a particular class of techniques is not solely dependent on the possible failure modes but is also a function of the skills available or accessible to the organisation, coupled with the maintaince philosophy of the organisation and the personnel problems involved in the implementation of these techniques.

Whilst wear is inherent in the operation of machinery, destructive modes of wear (rapid surface removal) exist e.g. scuffing, fretting, surface fatigue, etc., which can result ultimately in component destruction and hence machine breakdown.

This paper describes the available methods of wear debris estimation.

2 WEAR DEBRIS GENERATION

Within engines and gearboxes there are many sliding/rolling contacts that carry load or transmit power, these surfaces are generally oil washed. At these contact surfaces wear occurs, this wear may be as a polishing of the surface, it may be more aggressive involving significant surface removal e.g. by the action of a physical milling away of a surface by a hard edge or particle, it may involve the disintegration of the surface layer by the application of a cyclic load e.g. fatigue spalling of a bearing surface thus a variety of particles of a wide range of size and shape can be removed from surfaces and be swept from the original location by the oil flow. The wear particle content of the lubrication system is therefore able to yield useful information about the wear processes predominant in the machine.

Monitoring techniques such as SOAP, magnetic plug debris evaluation and Ferrography exploit the presence of wear particles carried by oil, they do so by assessing different particle ranges, see Fig. 1. From this representation the complementary and inter relative nature and use of the techniques can be seen.

3 SPECTROMETRIC OIL ANALYSIS PROGRAMME

At present, effective laboratory based techniques exist - the most widely used analyses the wear particles (less than ten micron) held in suspension in oil and assesses the concentrations By doing this on a regular programme basis, Spectrometric Oil Analysis Programme, a wear rate can be established for each element deemed necessary by a study of likely failures, any changes readily appreciated. From a multi-element wear trend pattern, and with experience, a diagnostic indication of the failure may be given. Supplementary tests can also show whether the oil meets its specification or has contaminants such as fuel, water or carbon etc.

4 MAGNETIC DEBRIS COLLECTORS (MAGNETIC PLUGS) AND FILTERS

The orginal idea in capturing wear particles released from the load bearing, oil lubricated component surfaces of a system was to limit any secondary damage they may cause. The realisation that the amount, size and shape of these captured particles could give an indication of both the parent component and the progression of the failure when viewed by an experienced monitor led to the start of this form of early failure detection. The advent of self closing housing permitted removal of the magnetic debris collectors without any appreciable loss of oil and hence a simple and quick inspection was then possible. This inspection and viewing of the particles lends itself admirably to the health monitoring of aircraft components within an oil system and since a substantial portion of the mechanisms involved in engine or power transmission is manufactured from a ferrous material, it is logical that many of the wear particles will be ferrous. Much emphasis is now placed upon the siting of magnetic plugs such as to be able to pinpoint the module or sub-assembly in which the component is failing.

However, the number and siting of personnel for this task of monitoring raises problems particularly in some military applications, e.g. the single helicopter of a frigate, for the throughput of debris samples has to be maintained above a certain level for the monitor to retain his expertise. Unfortunately the majority of naval aircraft are not stationed such as to enable the above system to be brought into being. Hence the need for an instrument that will, in some simple way, give a measure of the wear debris such as to be found on magnetic plugs and so provide a substitute in certain applications.

Such an instrument, an 'Inspection Instruments' Debris Tester, a purpose built instrument, provides a quantitive assessment of the ferrous debris, this assessment is made periodically and the cumulative total plotted versus operating hours has provided a useful system health monitoring technique.

5. PRINCIPLES OF FERROGRAPHY

The Analytical Ferrograph is a means of desposit-ing chiefly the magnetic wear particles from an oil sample on to a glass substrate. In the instrument a 3 cc oil sample is diluted with a fixed volume of solvent to encourage the required particle "precipitation", passed down a central path of the glass slide and thence draining to waste. The rate at which the liquid is pumped down the slide is very slow to allow the wear particles to be pulled down through the liquid and deposited on to the glass slide by the action of an applied magnetic force. The field strength is varied along the slide by having the slide set at an incline to the magnetic pole pieces. A relatively low field strength pulls the large magnetic particles down from the oil as it contacts the slide, thereafter the increasing field strength deposits progressively smaller particles along the slide. A solvent wash across the deposited particles removes the oil film. The prepared glass slide plus deposited magnetic particles has been titled a Ferrogram.

The quality, size distribution and the morphology of the particles of the Ferrogram are all of importance. An optical microscope is used to view the glass slide with the adhering particles which are sufficiently dispersed to allow the study of the shape and features of individual particles. The usual form of particle deposition is 'strings' across the width of the slide i.e. lying along the lines of magnetic flux. With experience the particles can be recognised and then related to the obvious wear mechanisms that are predominant in the assembly being monitored.

The percentage area of the slide covered by the wear particles at two fixed positions on the Ferrogram is estimated by measuring the amount of light obscured from a light source beneath the Ferrogram. These readings give an indication of the quantity and size distribution of particles on the slide.

Ferrography itself spans the range of particle sizes 0.1 micron to 50 micron (10^4 micron = 1 centimetre).

6 HYDRAULIC FLUID CONTAMINATION DETERMINATION

Modern developments and increased sophistication in aircraft hydraulic systems, reduction in size of components and the associated high pressures frequently involved have resulted in very stringent requirements for standards of cleanliness in the hydraulic fluid used. Because of the very small amounts of particulate contamination involved and the specific relationship between system malfunction and particle size, the measurement of the contamination levels has been quantified as the number of particles present in specific size ranges (largest particle dimension)/100ml. Earlier methods of determining contamination levels relied upon filtration of the fluid through membrane filters and the subsequent examination of the membrane surface by reflected or transmitted light microscopy for the number or particles removed. This method (IP275/71T), besides being a time-consuming process, has been evaluated by the Institute of Petroleum as having only a ± 100% reproductibility.

On the introduction of the HiAc instrumentation speed and repeatability was introduced into the NAML monitoring, although much discussion took place as to the relationship between the automatic particle count and the 'true' microscopic count. Nevertheless the measurement of contamination in hydraulic systems became a realisable technique with excellant standards of reproducibility. By limiting contamination, greater pump life, reduction in the silting of servo mechanisms, reduction in servicing costs are achieved.

7. ON-LINE DEVICES

The magnetic plug inserted into the oil flow has been the basis for a number of developments that have led to on-line sensors. Those listed are capable of giving a reading or indication of the presence of debris.

Chip detectors (TEDECO) have a magnet to attract the ferrous particles, these particles when attracted in sufficient quantity bridge two contacts thereby closing a circuit and switching on a remotely located warning light. This device has been further developed by the addition of a pulsed charge which is activated when the debris bridges the gap. The electrical energy is sufficient to distrub any minor debris but large particles or large quantities of small particles will pass the current. If the gap is still bridged after the discharge occurs, the remote warning light is illuminated.

A Continuous Debris Monitor (Gabriel Microwave)is a sensor which utilises the Hall effect to register as a voltage the change in magnetic field above pole pieces as the ferrous debris is caught. This voltage output can be manipulated to trigger outputs or alarms. These devices have found favour in mining industry machinery.

TEDECO have produced a Quantitative Debris Monitor (Q.D.M) which collects debris as a magnetic plug but on the arrival of a particle the in-built sensor produces a pulse proportional to the particle volume. Hence the device can differentiate between size range and the numbers counted.

A novel method where the lubricating fluid is directed against a thin film resistor is available. The Fulmer abrasivity sensor responds to the abrasive qualities of wear debris or other hard particulate. It responds to particles over a wide range of sizes and is sensitive to low concentrations of small particles (down to 1 micron).

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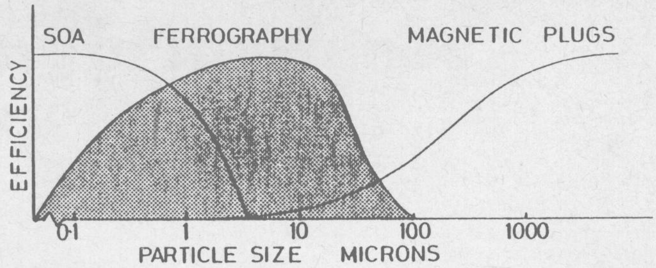

Fig 1 The complementary and inter-relative nature of techniques

Performance monitoring of machines in the chemical industry

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1 SUMMARY

This paper describes ways of monitoring the performance of pumps, turbines and compressors in a Process Industry in the absence of full instrumentation. It also shows how the information obtained can be used to decide on the need for an overhaul and, for more complicated units, which parts to overhaul: monitoring the health of machines is also briefly discussed. It is the author's opinion that when a machine is healthy and its performance unchanged little benefit is derived from dismantling and examining such a machine: indeed it can lead to malfunction if this work is badly done.

2 INTRODUCTION

To be able to make sensible management decisions about how to share the load between various available machines and when to overhaul them it is necessary to monitor the performance of such machines. In theory an accurate flow meter, a detailed knowledge of the substance handled, enthalpy change and the power output or input are sufficient to define the performance of any machine. In practice, most of these measurements are not available and the performance of a machine has to be evaluated from secondary readings. This paper deals with compressors, turbines, pumps and also outlines other observations which should be made to provide high availability.

The measurements required for various types of process machinery differ and hence different machines are discussed separately.

3 DATA RECORDING

Good records are essential if performance monitoring is to be a useful management tool: in the absence of records decisions have to be made without any information on trends and it is more economic to rely on breakdown maintenance. A series of test results allows one to judge the need for action, eg frequently performance falls slowly at first till a level is reached where the drop becomes very rapid and at such a point preventitive maintenance is best applied. Thus good records allow management to evaluate the significance of changes and decide on the action required to maximise production, efficiency and plant life: poor records are at best misleading and at worst very costly.

Changes must be evaluated to allow conclusions to be reached: for example an increase in delivery temperature can be caused by raised suction temperature or delivery pressure, a change in fluid or a drop in machine efficiency. Consequently adequate thought must be given to the parameters which are recorded and how they are to be used.

4 PUMPS

To fully measure the performance of a pump the following parameters must be checked: Inlet pressure, Exit pressure, Flow rate, Pump speed, Density of the liquid handled, and if motor driven, the power taken by the motor.

It is rare that all these parameters are available. Inlet and outlet pressures are usually measured by Bourdon tube pressure gauges, flow rate (if measured at all) with an orifice plate flow meter: flow-meters can achieve accuracies of one percent but in commercial applications the accuracy is usually much worse. The fluid density is usually assumed to be constant which is justified only if water is handled: when salt solutions are being pumped this is not a reasonable assumption. Speed is usually assumed constant at synchronous minus slip. Motor power is only measured on the biggest of the machines: usually only a current reading on one phase is available.

The result of these limitations is that ordinary plant instrumentation only allows pump performance to be checked within 5-10%. Slight deterioration of the order of 2 or 3% will therefore not be noticed if monitoring is carried out with plant instrumentation and this is made worse by the changes which do occur in pressure gauges and flow meters. Another way to check the efficiency of larger pumps with high heads is to measure the difference in temperature between inlet and outlet in the fluid handled. Because this difference is only a few degrees, measurements must be carried out with calibrated platinum resistance thermometers. For example a pump lifting water a thousand meters (100 bar) with an efficiency of 80% would heat the water by 6°C. This type of measurement only applies with large pumps, when dealing with small pumps (up to say 100 Kw) then complaints of the plant operators are the best guide on the need for an overhaul.

5 COMPRESSORS

5.1 Centrifugal Compressors

The plant manager is only interested in the overall performance of the machine: unfortunately it is not possible to measure overall performance simply on multi-stage machines. To check the performance of a centrifugal compressor it is necessary to measure the performance of each individual stage - which we define as the part of a machine where only mechanical energy is added to (or removed from) the fluid. In compressors this is between inter-coolers.

To be able to characterise each stage the following information is needed:

The inlet and exit temperatures and pressures flow rate, the type of gas handled and its properties, and speed of the machine. From this data the performance of each stage can be calculated. Gas compositions and properties frequently vary, exceptions being air compressors and refrigeration compressors; however, in the latter case if operated near to the critical point large errors may occur due to only small inaccuracies in temperature and pressure measurement.

Gas densities are always assumed and not measured; the same applies to gas compressibilities and to the ratios of specific heat of gases. Even the quantities which are measured are subject to necessary tolerances for example temperatures are usually measured with thermocouples which have tolerances of 1.5 - 2.5°C at ambient temperatures.

It is therefore usual to just measure the inlet and exit pressure, temperature and with the assumed gas properties use them to calculate the polytropic efficiency η and head using the following equation:

$$\eta = \frac{\dot{j} - 1}{\dot{j}} \times \frac{n}{n-1} \qquad (1)$$

$$\frac{n-1}{n} = \frac{\log Tr}{\log Pr} \qquad (2)$$

$$\text{and } H = \frac{zR}{M}\, Ti\, \frac{n}{n-1} \left(P_R^{\frac{n-1}{n}} - 1 \right) \qquad (3)$$

$\dot{j}$ = ratio of specific head
Tr= Temperature ratio
Pr= Pressure ratio
H = Head
n= polytropic index
R= Gas constant
z= Compressibility
M= Molecule weight

Provided that the throughput is reasonably well known, and constant, it is reasonable to use polytropic efficiency, or the polytropic index, as one of the criteria of a machines performance. Plotting the polytropic efficiency of a stage with time will show variations. A steady downward drift shows the operator that something is amiss and the machine requires an overhaul. From these measurements the operator can calculate the polytropic head and again it is advantageous to plot the head with respect to time. Because flow variations effect the head more than stage efficiency an adequate knowledge of flow rate is required before conclusions can be drawn.

For variable speed machines it is necessary to divide the head by the square of the speed to obtain a figure not influenced by the speed. From the head and the polytropic efficiency it is easy to calculate the power consumed provided that the mass flow is known. However, even on larger machines flow metering is usually of a poor quality and is provided mainly to allow the surge control system to work. It is thus not accurate enough for "costing" purposes though the flow indication may be reproducible. It should be noted that neither polytropic stage efficiency nor the polytropic head show up short comings in interstage coolers, but keeping close records of stage efficiency, stage head and heat transfer in coolers allows performance of a machine to be monitored. Other helpful parameters worth noting are changes in the machine speed or control drive position in relation to the plant output or delivery pressure.

Thus one can conclude that decisions on the need for maintenance should be based on changes in the:

1) individual stagepolytropic efficiencies.

2) individual stage polytropic heads corrected for speed and rate.

3) increased power or speed demand for given operating conditions.

5.2 Reciprocating Compressors

The most important measurement for reciprocating compressors is the delivery temperature of each cylinder as measured in each valve chamber. It is this parameter which first indicates most faults and it should be added that again good records are the best tool in diagnosing the cause of such faults. Measuring interstage inlet and delivery pressures and temperatures does allow the condition of the machine to be evaluated specially if the gas composition and the rate are kept constant. On machines with throughput regulation, for example first stage by-pass or clearance volume bottles,interstage conditions obviously vary with the rate going through the machine. More precise monitoring must be carried out by taking indicator diagrams and modern instrumentation permits indicator diagrams to be taken with electronic instrumentation so avoiding use of the string driven recorders of the past.

It is the author's opinion that indicator diagrams are mainly of value in establishing if a design is correct rather than as a measure of machine condition. Piston ring wear would have to be extreme to be detected by changes in interstage temperature or pressure. On the rare machines using reciprocating steam engine drives indicator diagrams are essential if the setting of the engine is to be optimised.

6 STEAM TURBINES

To monitor the condition of a turbine measurement of the power output, steam input, and speed are quite adequate. Unfortunately there is seldom provision for measuring the power output, nor are accurate flowmeters provided, and in the case of condensing turbine, it is difficult to measure the steam condition at the exhaust end. With all of these difficulties how can one effectively monitor the condition of steam turbines? Two of the most useful measures are the first stage (wheel chamber) pressure and valve positions. Inlet steam pressure is usually kept constant and at a constant temperature. Therefore measurements will be undertaken at similar inlet steam condition. On the other hand the condition of the exhaust steam varies greatly depending on the load on the machine as well as the condition of the machine. On turbines with a dry exhaust (most back pressure turbines) a measure exhaust condition can be derived readily since only the exhaust temperature and pressure need to be known. This is not so on condensing turbines whose exhaust wetness must be known: process plant condensing turbines are not usually equipped with sample points which allow the exhaust steam wetness to be measured thus preventing proper evaluation of performance.

On larger plants with high pressure boilers operating on fully demineralised water (not softened) build up of deposits inside a turbine does not occur and it is possible to use the wheel chamber (first stage) pressure as a measure of steam quantity passing through the turbine.

This measurement was originally provided to allow the degree of fouling to be estimated for an accurately known steam flow. By keeping a record of the wheel chamber pressure the steam inlet conditions, and the valve position changes in the turbine performance can be estimated in the absence of accurate flow measurement.

7 Power Balance

It is often useful to carry out a power balance because it permits a simple check on the accuracy of the obtained data and highlights gross inefficiencies. On most electrically driven machines a relation between amps and power must be obtained from the circle diagram tests; on large machines watt meters are commonly fitted. The power of a compressor is obtained by adding the power of each stage ie the sum of a mass flow times the stage head divided by the stage efficiency.

A reliable torque meter has recently become available and its use will both reduce effort required to obtain a power balance, and pinpoint which item is causing change in energy consumption.

On one installation of two turbine driven compressors it was found by plotting total power generated as measured on two torque meters against interstage pressure that an optimum existed, needing 2% less power than the customery operating point. A saving of that magnitude is well worth having on a multi-megawatt installation, it soon pays for the torque meter and could not have been made by relying on standard instrumentation.

8 MACHINE "HEALTH"

Besides performance, the "Health" of machines must be monitored and the importance of keeping a machine "healthy" cannot be overstressed. Under "Health" many more parameters than vibration which is commonly used, must be evaluated. For example are there any oil leaks, what is the shaft axial position, what is the bearing temperature, are there any steam leaks, has the consumption of seal oil gone up on machines where sealing is achieved by floating rings, has the consumption of purge gas changed, is the seal steam on condensing turbine adjusted properly? All these items come under the general heading of health of a machine though they currently get little attention because many operators consider that vibration measurement will tell all about a machines condition.

Another aspect to be considered under health is the condition of the lubricating oil. For large oil systems it is advisable to take a monthly sample of the oil and have it analysed for the level of anti-oxidant, water content and acidity. Short comings in the anti-oxidant can be remedied by "spiking" the oil ie introducing additives to prevent oxidation to occur which in turn would lead to the acid level rising so high that an oil change is required.A less frequent analysis for metal particles is also desirable and if positive points to undesirable wear which must be investigated. Forsmaller units changing the oil annually or bi-annually is the best solution.

For reciprocating compressors operating dry under very difficult conditions a run out gauge is a useful indicator of wear but this applies only to horizontal machines which are not as well suited to these conditions as vertical machines.

9 THE FUTURE

Microcomputers capable of monitoring various parameters, calculating an overall efficiency and power absorbed by a multi-stage centrifugal compressor are available now. However at present they are rarely used and even then only on the largest installations. Their upkeep is expensive and the results obtained will depend on the ability of the primary instruments namely the transducers used to measure the prime quantities. Increasing use of digital instruments will encourage their use. Ref (1).

Gathering data by hand and evaluating it at monthly or quarterly intervals will therefore continue to be the most common way of monitoring the performance of machinery in the process industry - except on the very largest machines where dedicated instrumentation may be employed.

10 EXAMPLE:

RECORDS FOR TURBINE DRIVEN AIR COMPRESSOR SET

To illustrate the above policy the readings taken and the use made of them as shown on the example of an air compressor on an ammonia plant. The unit delivery 40,000 NM^3/H at about 40 bar, and operates at 8000 rpm. The arrangement is shown in Fig 1.

The set is driven by a condensing turbine with inlet steam conditions of 40 to 350°C.

Table 1 shows the routine readings taken on this compressor ("Inputs"). Note that for this one compressor 26 readings are taken! Under the heading "Outputs" the parameters which have been calculated are given.

Fig 2 is a plot of the calculated efficiency against time of the 2nd stage. The plot illustrates a) the accuracy of the method (efficiencies do not improve with running time) and b) that an overhaul becomes desirable in 1981.

11 CONCLUSION

Simple data available from standard instrumentation can successfully be used to monitor the performance of machinery, provided the right use is made of the readings. Changes observed are a useful guide to machine deterioration and the need for overhauls. In the absence of deterioration of the performance routine strip downs of "healthy" machines - which show no change in performance - should be avoided.

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12 Ref (1) The Impact of Digital Logic on Control and Monitoring Philosophy; W Wong, K J Hultgren.

TABLE 1 THE READINGS TAKEN ON ONE DAY AND THE VALUES CALCULATED

AIR COMPRESSOR SURVEY

DATE: ....
SPEED: 8050 rpm
RATE: 37800 M^3/h

INPUT	1	2	3	4	5	6
P_1 psig	0	2410	45	69	105	145
P_2 psig	25	46	76	106	151	520
T_1 °C	5	45	43	64	75	44
T_2 °C	129	110	112	130	93	222
Cooling t_1 °C	15	15	15	15	15	-
Water t_2 °C	24	22	23	23	-	-
OUTPUT						
	77.5	70.5	74.4	72.9	79.7	74.3
Head kJ/kg	9280	4240	3940	3640	3300	13140
Rate	37.600	16400	10550	8020	5800	3850
(actual) M^3/h						
Head % Design	97	84	78	90	99	101
Power Kw	2130	1070	940	890	740	3160
Cooler UA $KJ/M^2/°C$	81	14	6	6	-	-

TOTAL 8930 Kw

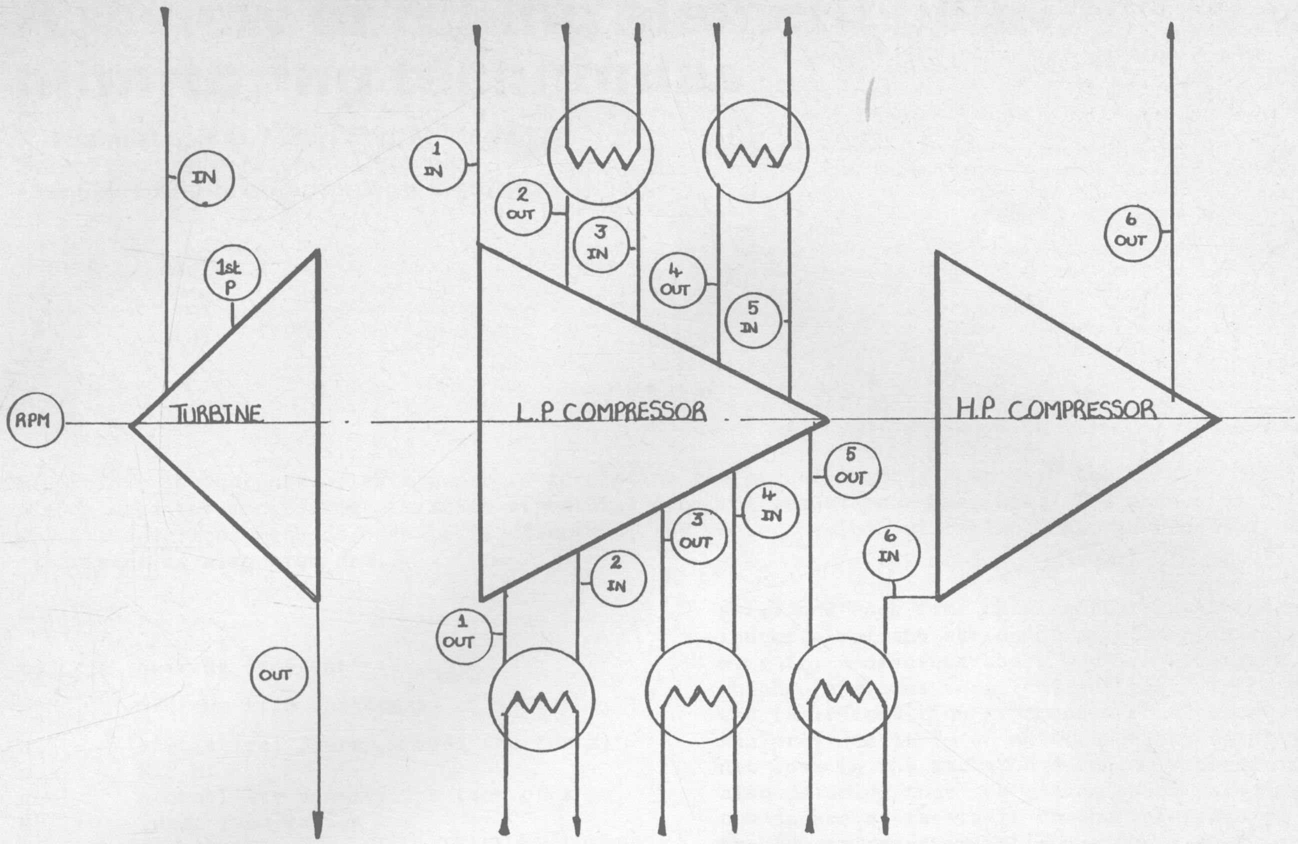

Fig 1 Air compressor

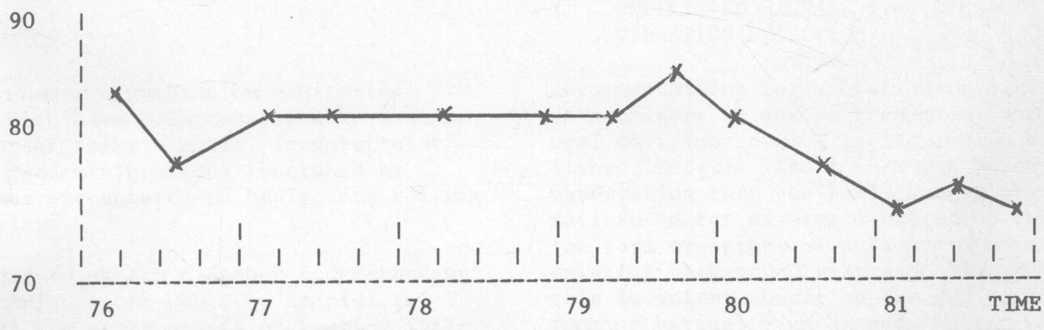

Fig 2 Change in stage efficiency against time