Cleanliness Monitoring of Hydraulic Systems

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The extent that solid particles (dirt) affect the performance and reliability of hydraulic systems has been recognized by equipment designers, system builders and users alike, and all are implementing measures to lessen the effects. Fundamental to this approach is the setting of a fluid cleanliness specification and monitoring the achievements of the contamination control measures fitted to the process.

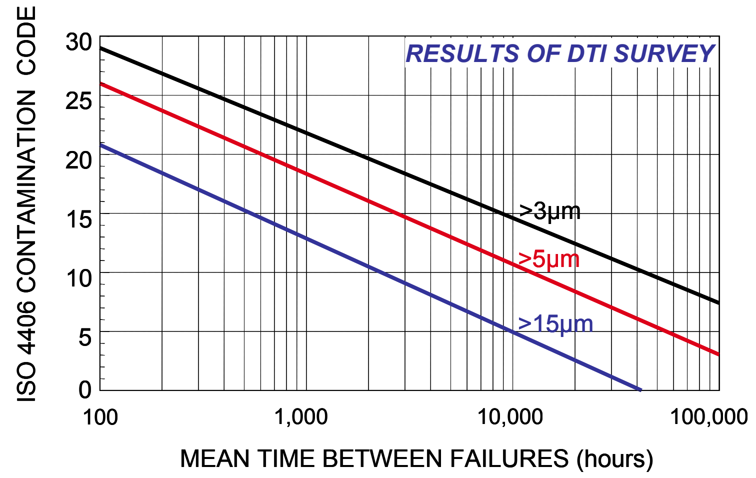
Monitoring the concentrations of particles in the various process fluids is now seen as an essential part of contamination control, whether it is during piece-part production through to maintenance activity in service. Automatic Particle Counters (APCs) are an essential measurement tool as they can quickly and accurately measure the number of particles over a wide size range. It is this accuracy and speed that makes them indispensible in monitoring contamination in service as part of a proactive maintenance regime. APCs are able to detect small but significant increases in the numbers of particles allowing corrective action to be promptly implemented when they rise above a specified level before any serious damage is done to that part of the process. Thus, to reduce the amount of wear experienced by the process or system, the minimum of time must lapse between sampling, the detection of an increase and its correction. This is best done using APCs permanently installed to the system as the data is continuously available.

This paper looks at the requirements for monitoring fluid systems in service and examines the options for integrating APCs into a maintenance regime. It demonstrates the benefits of monitoring on-line with an APC fitted to the system, whether it is with a permanently installed APC or a portable unit. It also gives guidance on how to obtain valid data and detect errors.

Introduction

Research studies (1, 2 & 3) have established that the presence of solid particles (dirt) in the hydraulic fluid is the single most important factor influencing the reliability and life of fluid systems. It has been estimated that between 50 and 70% of failures to plant and machinery were due to dirt in the lubricant. Furthermore the UK's DTI survey quantified the relationship between the level of reliability of systems and the of dirt level in the system as represented by the ISO 4406 Solid Contamination Code [4]. This relationship is seen in Figure 1. Put quite simply, the lower the dirt level, the more reliable the system and the longer its useful service life.

Figure 1 – Relationship between Hydraulic System Dirt Level and Reliability



Note: APC calibration was ISO 4402

Significant improvements in fluid cleanliness has been made in the Fluid Power industry since the DTI survey was carried out some 30 years ago [5] as equipment designers, system builders and users realize the potential benefits to be gained as a result of operating with cleaner fluids. Management of cleanliness has been extended to the manufacturing processes as part of an overall approach to lower the incidence of damage to components during initial operation and so reduce the probability of a failure. This way a long component life is assured. Industry has moved from having to live with contamination to maintaining cleanliness!

It has been stated that cleanliness monitoring is probably the most sensitive of all monitoring techniques [6] and, by virtue of its simplicity, it is probably the most cost effective. For this reason, it is being integrated as a front line technique in fluid management into most operational areas from piece part production through assembly and test, and continued in service. Fundamental to this is the provision of a fluid cleanliness specification and a means of measurement that gives accurate and consistent data so that any significant increase in the level of contamination level is promptly detected and corrected. If the reason is promptly identified and the root cause determined then, the amount of surface wear occurring will be minimized. Thus, the measurement method chosen, should give accurate results in the shortest possible time. Having a succession of false alarms would prove to be both costly and disastrous to the concept of monitoring.

This paper looks at the requirements for monitoring the level of cleanliness in fluid systems, briefly discusses the technique that the authors' consider to be the most suitable and illustrates this with an example. The paper also details the pitfalls to avoid so that the potential benefits of this form of monitoring can be realized.

Philosophy of Cleanliness Monitoring

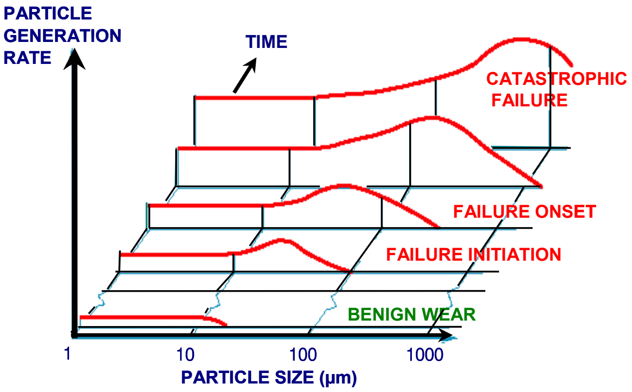
Most modern hydraulic systems, both fluid power and lubrication, are now being designed to operate at a specified fluid cleanliness level. This is called the "Required Cleanliness Level" (or RCL) and its importance cannot be over emphasized. It forms the base level that the system filters must achieve and maintain throughout their useful life. Of equal importance, it also should form the basis of cleanliness specifications for all manufacturing processes e.g. machine coolants and wash fluids, system assembly and the flushing process preceding delivery. Further information about RCLs can be obtained in the paper by Bensch [7].

To fully understand the effect of particulate contaminant on components, some knowledge of the wear process is desirable. As it is beyond the scope of this paper to go into this, the reader is advised to read the paper by Needelman [8]. Briefly, contaminant particles that come into contact with surfaces will cause damage to the surfaces through wear, resulting in loss in performance and, eventually, component failure. This happens during all manufacturing process to a greater or lesser extent, even during component piece part machining operations. Thus the dirt particles should be removed from the process at the earliest opportunity to eliminate or minimize the effects and consequential damage.

In service, hydraulic systems are generally re-circulatory such that any wear debris generated will be circulated through the components to potentially produce more wear. This is called “regenerative wear”. If not corrected there will be acceleration in the components wear rates, substantial amounts of surface material will be removed and component failure will be likely in a short period of time. Under these circumstances operation can be unpredictable and unsafe. Even if failure is not experienced, the surface of the component will be so abraded that it may not operate to it’s design performance and will certainly not achieve the desired service life.

The role of filtration in this process can be appreciated by looking at how components wear up to eventual catastrophic failure (Figure 2). If the filtration level has been correctly selected for the system concerned, i.e., based upon the contaminant sensitivity requirements of the components and the life and reliability expected by the user, then wear rates will be low and under control. Here low numbers of small particles (< 10 µm) will be generated mainly by fatigue i.e. repeated stress of the surfaces. These are termed “fatigue platelets” and are small, almost two-dimensional particles (i.e. very thin) and their shape means that they can generally pass through component clearances without producing other wear particles. Even when they get caught in a clearance, they are generally easily fractured, producing only small amounts of denting to the other surfaces. This wear mode is very mild (“benign”) and this will ensure reliable operation and long component lives.

Figure 2 Particle Generation Rate up To Failure



If either the wrong grade of filter is selected or the existing filter has weaknesses such that its performance is seriously reduced, there will be a rise in the contamination level through three body regenerative wear. This causes an increase in both the numbers and the size of particles generated. The wear mechanism changes very quickly from mild fatigue wear to abrasive wear causing larger amounts of material to be removed from the component. Unless this change is detected and rectified, then this regenerative wear will progressively produce even larger particles and eventually the component will fail, often catastrophically.

The aim of more traditional forms of monitoring (vibration, noise, chip detection etc) is the detection of imminent failure so that the component can be taken out of service before failing catastrophically. In most cases the component has to be replaced because it is damaged beyond economic repair. In cleanliness monitoring, the philosophy is completely different. System fluid samples are analysed for any significant increase in smaller particles and actions promptly implemented to correct the situation and bring the wear back into the benign mode in the shortest possible time. This way the aims of reliable operation and long component life will be achieved.

Selection of the Most Suitable Monitor

Planning

The subject of monitor selection is very large as it depends upon the requirements of the user and, to a certain extent, on the end customer(s). Thus selection is beyond the scope of this paper and is reported elsewhere [9]. However the user is advised to spend time evaluating exactly what his requirements are before purchasing a monitor as they sometimes involve considerable capital expense. This may appear obvious, but it is the authors' experience that users often buy a monitor which appears to be suitable initially, only to have problems later. This is tied up in planning and education. The operator must become familiar with the principle of the device, how apply and use it, and how to interpret the data; the unit is as good as the person who interprets the data! Consideration must also be given on how contaminant monitoring can integrate to the existing system management infrastructure.

Requirements for fluid Cleanliness Monitor

Bearing in mind the strategy stated in Section 2, the product requirement for monitoring fluid cleanliness can be summarized as:

- Needs to be able to measure relatively low concentrations of 'small' i.e. < 10 µm
- Needs to measure a wide range of particle sizes and concentrations
- Can present data in an industry acceptable form e.g. to Cleanliness Coding systems such as ISO 4406 or AS4059 [10],
- Is approved by the ISO Committee developing particle counting standards for the Hydraulics industry
- Have proven accuracy and repeatability
- Provides results 'immediately' or at least in a short time period so that corrective actions can be effected with the minimum delay
- Can analyze a wide range of fluid types e g. hydraulic, lubrication, wash and solvent fluids
- Have an 'acceptable' cost

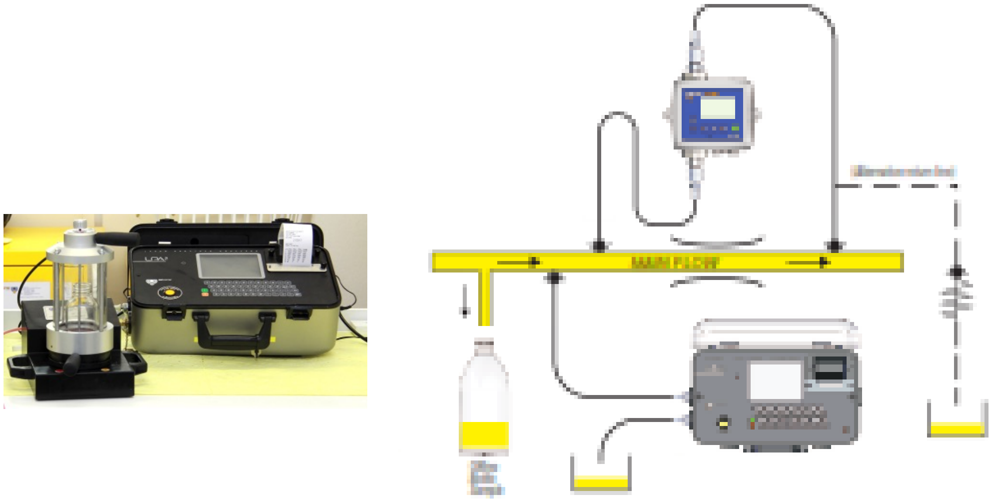
Size range of Interest

This should be self-explanatory and the instrument must be tailored to the users' and perhaps the end customers' requirements. The generally accepted size range of interest in fluid systems is 4 to 70 µm(c) and most Cleanliness Classification systems feature these sizes. However, it should be noted that Component Cleanliness sizes go up to >1,000 µm.

Mode of operation

There are two methods of measuring the cleanliness of the process fluid, ***off-line*** and ***on-line*** and these are seen graphically in Figure 3

Figure 3– Modes of Sampling and Analysis



a) Off-line is where a sample of the fluid is taken from the system and collected in a suitably cleaned container for subsequent analysis either at the work place or, as is more usual, in a laboratory. The process is time consuming and delays are incurred between sampling, the receipt of the data for examination and then possible corrective action. This can range from hours if the analysis is performed in-situ, to weeks if sent to an external laboratory. This will not be a problem if the process is under control, but it could be disastrous if the contamination level is changing rapidly.

Another problem associated with off-line analysis is that contamination is added in the sampling and handling processes. This can generate substantial errors, give variability in data and, perhaps of greater concern, cause unnecessary corrective actions. The cleanliness levels of modern filtered systems are so high (i.e. very clean) that this extraneous dirt can completely masks the dirt levels in the system [11]. This makes interpretation of trended data almost impossible. Thus, current bottle sampling techniques are no longer satisfactory for cleanliness monitoring.

The benefit of this mode of sampling is that there are a much wider range of techniques and instruments available to the user should they need to find out more about the contaminant profile of the sample to find the root cause of any increase in the contamination level as part of a Proactive Maintenance regime. Examples of these are: Microscopic analysis, Spectrographic Analysis, Infra-red analysis, Wear Debris Analysis etc.

b) On-line is where the instrument is connected directly to the system or process, either to a main flow line or the reservoir, and so eliminates the errors associated with taking bottle samples. It also ensures that the time between sampling and acting on the data is mimimised. There are two forms of this: *portable and permanently mounted*.

The portable units offer the advantage that one unit can monitor a number of systems at a site and could offer a cost effective solution where a large number of systems need to be monitored, say > 5. However, they do have the following disadvantages:

- The unit has to be flushed every time a connection is made to remove the connection debris that is generated otherwise errors will result and the sample is not representative of the fluid in the pipe. This can take as long as 40 minutes [12].
- A significant fluid volume may be 'lost' if the outlet hose is not directed back to the reservoir.
- Cross contamination of fluids may occur if the unit is used on a number of systems with different hydraulic fluids.
- The analysis process is not 'immediate' because of the need to go to the location, connect, and flush adequately, and then confirm that the data is correct and consistent.
- The result may not be truly representative of the fluid in the system.

The permanently mounted unit is the preferred option it overcomes the disadvantages of the portable unit namely:

- The data is continuously available so any increases in contamination can be noticed instantly and corrective action can then be promptly implemented.
- Flushing the unit prior to measurement is unnecessary.
- This outlet can be connected back to the system so there in no loss of fluid.
- Sampling times can be easily be increased to reduce variability when monitoring either clean fluids (particle count statistics) or variable generation rates, with no waiting penalty

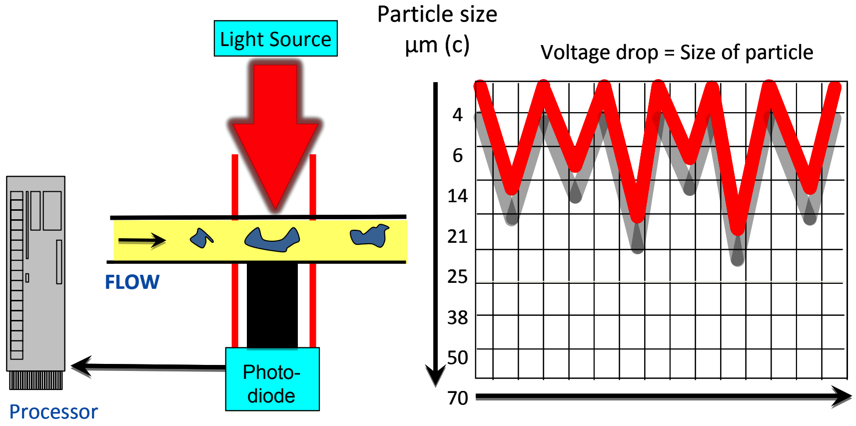
This method of analysis does demand one instrument for each system. In the past this may have been beyond the resources of most users and a single portable unit was used to monitor numerous systems on a planned inspection routing. However, the advances in technology have resulted in a dramatic reduction in the cost of these devices so that such investment is no longer prohibitive.

Optimum Means for Monitoring Fluid Cleanliness Levels

Reviewing the requirements for a cleanliness monitor stated in Section 2, it is the authors' opinion that on-line particle counting with Automatic Particle Counters (APCs) is the technique that satisfies these requirements. Without the development of APCs, much of the research into contamination control over the last 35 years would not have been possible. When used within their limitations, they have demonstrated both accuracy and economy of operation. However, like all particle counting techniques, they are subject to certain limitations and, if not used correctly, can give erroneous counts [11].

APC's work on the light extinction principle where the particles contained in the fluid interact with a beam of light shining across a narrow sensing passage to reduce the intensity of light received by a detector, (Figure 4). This is achieved by either using light scattering or adsorption principles. The reduction in intensity is related to particle size by calibration. The APC can cater for a wide particle size range, from 0.5 to over 2,000 µm depending on the type of instrument and its application, and they can work directly on-line, in the 'sip' mode from low pressure sources or off-line from bottle samples extracted from the system. The ability of these instruments to count and size individual particles quickly and with a high degree of accuracy has meant that they have proved to be indispensable in contamination studies. Such fields of application include filter testing, component contaminant sensitivity testing, monitoring the progress of flushing and general condition monitoring.

Figure **4 Principles of APCS**

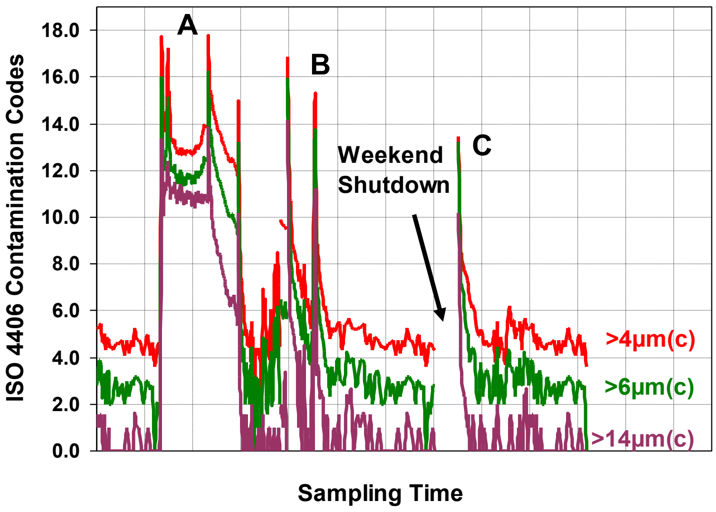


Example showing the Benefits of On-line Monitoring

This example shows how continuous on-line measurement enables 'immediate' detection of an out of control situation and the prompt implementation of corrective actions meant that the amount of extra wear was minimized. The system studied is the hydraulic system of a machine tool that has a single 6µm filter fitted in the pressure line and operates at 120 bar (1,750 psi). The on-line results of a 3-day period have been extracted.

Very low particle counts are experienced initially (ISO 5/3/1) until the system was topped-up with oil during the night shift (A). The oil was poured in and not dispensed through a filter, and proved to be very dirty. This caused the filter to go into partial bypass. Unfortunately, the blockage indicator failed to function and the increased contamination was only spotted the next morning when the on-line monitor was inspected. A new element was fitted and the system cleaned up very rapidly.

Figure 5 Example of Continuous On-line Monitoring



Other increases were evident during the study. The next increase (**B**) was eventually traced to the presence of air in the system, caused by the pressure line filter being located above the reservoir level, such that the oil could partially siphon out of the filter assembly during periods of inactivity. On start-up, at low pressure, a slug of air was circulated around the system until it was removed by a combination of floatation to the surface and being forced into solution when the system was operated at pressure. This was overcome by fitting a spring-loaded check valve to the downstream side of the filter to prevent siphoning and was performed at the weekend shut down. The next peak (C) was noticed immediately after start up and reflected the dirt that ingressed into the system following the breaking-in of the system to fit the check valve. The APC showed that the filter quickly removed this maintenance debris.

Two aspects are highlighted here. The first is the need to check the cleanliness of the system more regularly as it cannot be assumed that if samples are acceptable from one period to another, the period in between is consistent. It is likely that if either off or on-line analysis using a portable unit had been used the short term increases may be missed altogether and the more long term events (like the above problem of the filter bypass) only picked up after a significant period. If the high contamination level is allowed to remain unchecked, the amount wear and subsequent damage will accelerate. The second is that continuous measurement leads to a better understanding about the dirt generation profile of the system so that improvements in the design or operation can be made when convenient to do so. This is an essential part of a Proactive Maintenance regime.

Factors Affecting the Validity of Cleanliness Data

It was stated earlier that to avoid 'false alarms', the data from the unit must be representative of that of the fluid in the system and there are a number of factors that influence the validity of cleanliness data. These are detailed elsewhere [11] but are briefly re-examined in relation to permanently installed APCs:-

Sample Bottle Cleanliness: Not applicable.
Sampling Technique: Not applicable as permanently installed units have a continuous flow, but portable units will require flushing after connection.
Location of sampling point: Not applicable as permanently installed units have a fixed location. Cleanliness levels vary around all systems, so the same location should be used for general monitoring.
Flushing of sampling point: Not applicable to permanently installed units.
Calibration method: Not applicable as a common method is used - ISO 11171 [13].

Coincident particles: Where two or more particles are counted as one and may increase the counts of the smaller sizes. This is a function of dirt concentration and should not be frequent with modern cleaner systems. See also finely divided contaminant.

Saturation of APCs: Caused by high particle counts and is not a problem nowadays as the saturation level of APCs is substantially higher than say 15 years ago and systems are much cleaner.

Duty cycle: Like location, the cleanliness will vary as the system operates. To average out these variations, a large volume should be analysed e.g. 1 litre for ISO 10/8/6.

Other fluids (air, water in oil, oil in water, tramp oils etc): APCs require clear, homogeneous liquids and some fluid contaminants will give erroneous results. The nature of the data with these fluid contaminants is such that these should be easily identified as errors. For instance, water contamination can give a profile of ISO 22/21/21 in an otherwise clean system. Identification of these forms of contaminant is down to the experience of the operator. Note that such contaminants are usually a result of poor housekeeping and a lack of education.

Finely divided contaminant: contaminants that are very small, < 4µm(c) and present in large numbers like products of oil oxidation, spent additives and fatigue particle from some gearbox application, will give unrepresentatively high particle counts through the mechanism of coincidence. These can be identified by large differences in the 1st & 2nd cleanliness scale or code numbers e.g., ISO 18/11/08. Generally the 2nd & 3rd code or scale numbers are not significantly affected. Some non-soluble additive materials e.g. Silicone Anti-foam Additive have a similar effect.

Analysis procedures used: On-line counting provides a consistent analysis process and is not affected by such errors.

Extent of knowledge in the technique: As with any technique, the interpretation of the data is critical to the success of the monitoring function as correct interpretation will lead to correct decision making and vice versa. Therefore it is essential that the operator is correctly trained in both the use of the APC and the interpretation of the data.

Conclusions

The following conclusions are drawn:

- The life and reliability of hydraulic systems is greatly affected by the presence of particulate contamination in the lubricant. The cleaner the fluid, the more reliable the system or process and the life of the components will be greatly increased.
- Cleanliness monitoring of hydraulic fluids is probably the simplest and most cost effective monitoring technique and should be front a line technique in any maintenance regime.
- To achieve optimum system performance, a fluid cleanliness specification should be developed based upon the components' contaminant sensitivity requirements and the life and reliability required by the specific user.
- The system should be monitored regularly, the data compared to the specification and corrective actions promptly implemented if the specification is exceeded. This will ensure trouble free operation, leading to improvements in productivity, product quality, profitability and customer satisfaction.

- Of the techniques available, it is continuous on-line automatic particle counting using a permanently installed APC that can best achieve these requirements and is an essential tool in any Proactive maintenance regime. This method of monitoring has less pit falls than similar instruments used in other ways. It also assists in understanding the dirt generation profile of the system so that improvements in the design or operation can be made when convenient to do so.
- The success of the application of APCs is greatly dependent of the knowledge and experience of the operator and training should include both use of the instrument and interpretation of the data.

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