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Using contamination control in condition based maintenance of a hydraulic system

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Abstract: Hydraulic systems are continually improving, resulting in higher power and faster response rate while at the same time preserving the use of energy. This claim is based on the facts such as: advancements in hydraulic drives and control, understanding mechanisms of failures, and condition based maintenance (CBM) approach in terms of contamination control. Contamination control is a broad subject with a purpose to provide hydraulic system functionality. Contamination control program consist of all activities needed to assure efficient and reliable production of force or torque at the hydraulic actuators. CBM is regaining popularity through last decades, in aerospace, automotive and construction industry, which are utilizing hydraulic control systems. Purpose of this research paper is to develop and discuss about contamination control program as a part of CBM approach with a goal to preserve and prolong hydraulic system lifespan. Therefore, this study represents groundwork for engineers and scientific community focused on hydraulic system maintenance.

Keywords: maintenance, CBM, contamination control, oil hydraulics, particulate contamination

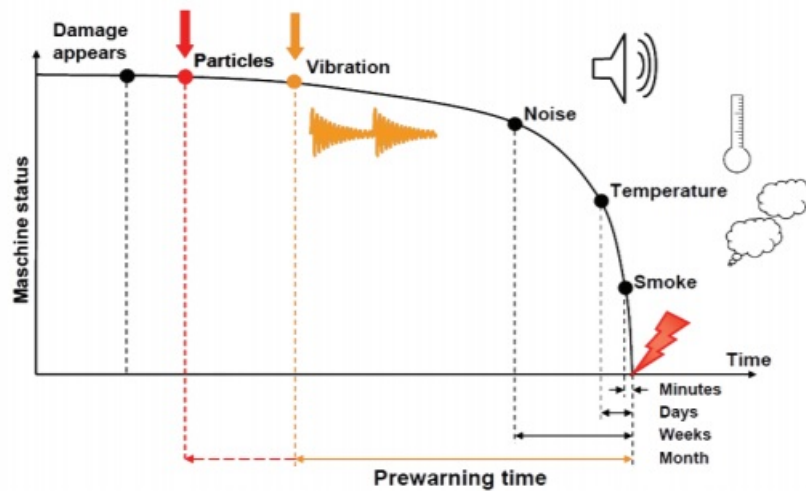
INTRODUCTION

Contamination of hydraulic control system has long been recognized as one of the major causes of components wear due to oil degradation. In addition to increased internal leakage (in pumps and actuators), it also decreases the ability of valves to control flow and pressure accurately, thus wasting input energy and generating heat /1/. Particle contamination is unquestioned the major cause of failures in hydraulic systems /2-6/. This type of contamination directly leads to machine breakdown, downtime, and maintenance expenses. It has been shown that 70 - 85% of hydraulic component' failures resulted from particulate contamination, with root causes of abrasive wear /6,7/. Servicing and maintaining system cleanliness is a key issue in the operation of hydraulic system. Some have stated that research into service and maintenance system development attracts little interest in scientific community, and furthermore, this limited research tends to only focus on aerospace sector /8/. However, other industries, utilizing hydraulic control systems, with high data transactions and maintenance costs (automotive, construction machines, wind turbines, and off-road heavy machinery), should also benefit from preventive maintenance schemes driven by real time data acquisition and processing /4/.

This paper has dealt primarily with condition based maintenance approach utilized in preserving the integrity of hydraulic system. There are numerous studies conducted concerning contamination control, which will be discussed in the paper. However, these studies are mainly focused on understanding the notion of solid particle contamination and lubrication degradation mechanisms in the sense of reducing wear and increasing reliability of a system /9/. Lubrication degradation promotes mechanical interaction of surface asperities, which is a known cause of increasing friction, wear and, consequently, vibration. In comparison with vibration based monitoring techniques, Poley /11/ claims that oil condition monitoring provides approximately 10 times earlier warnings for machine malfunction and failure. The reason oil condition monitoring technique is appropriate lies in the fact that failure can be detected months before

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system is damaged (picture 1) /12/. This is very important for machines that operate around-the-clock, under difficult operating conditions, and away from professional maintenance staff, where constant monitoring of equipment status is required /13/.



Picture 1. Pre-warning times for different CM methods /12/

A comprehensive discussion on factors that influence oil degradation: water, aeration, and chemical reaction, are beyond the scope of this paper. However, this research study deals with condition based approach, monitoring techniques to determine the current state (diagnosis), and techniques to predict future state of the system (prognosis).

HYDRAULIC OIL CONTAMINATION AND MONITORING

System failures caused by contamination may be classified into the following three phases /1/:

- degradation,
- transient or misuse, and
- catastrophic.

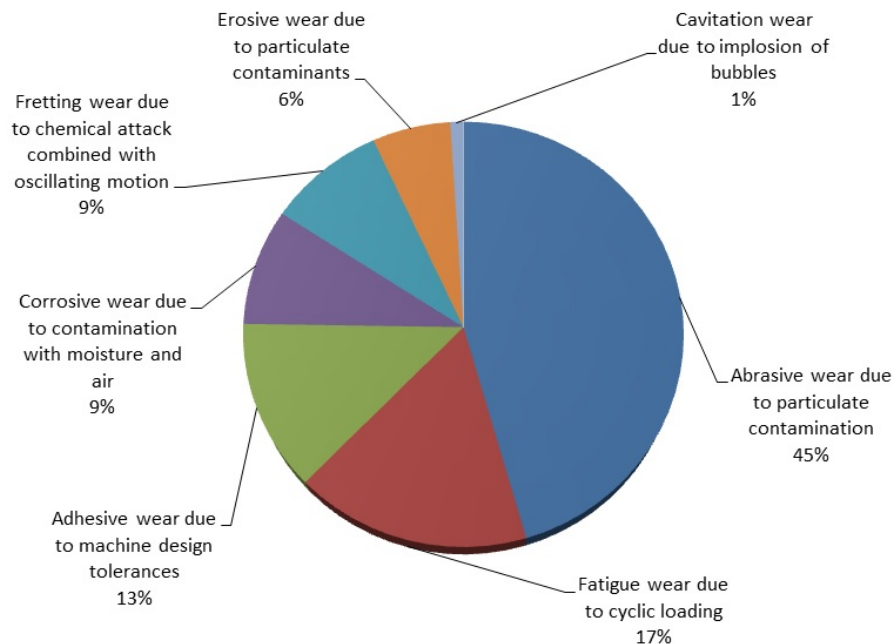
Degradation can be classified as gradual changes in system parameters over time (e.g. pump flow rate, valve leakage, wear of cylinder barrels, cylinder speed decline, etc.). As this type of malfunction continue to degrade, it can easily and rapidly lead to catastrophic failure. Therefore, corrective actions must be undertaken. Transient or misuse failure can be classified as intermittent failures such as power loss or wrong maintenance actions (e.g. wrong hydraulic oil). While, catastrophic failures can be classified as complete failure of the system or a component (e.g. jamming of the valve due to contamination). All of the above system failures could result from one of the following type of contamination or combined:

1. Built-in contamination. This can be splitted into two sub-categories:
 - contamination of a new hydraulic system – particulate, pieces of welding slag, dirt, etc., which can be found in the system when it was assembled;
 - contaminated new oil – contaminants entered the new oil during manufacturing, handling, or during the storage period.
2. Ingressed contamination. This type of contaminants can enter the system usually through breather cap of a reservoir, dirt sticking on cylinder rod, or anytime a hydraulic line is disconnected for maintenance, failure, or any other reason, there is a potential for particles ingression.
3. Internally generated contamination. This type is the most dangerous one, because particles are removed from inner surfaces due to wear processes (abrasion, adhesion, fatigue) and circulated throughout the system.

Garvey et al. /7/ listed the seven basic wear mechanisms present in hydraulic system, shown in picture 2. In addition, knowing categories of system malfunctions caused by contaminants within the system can be a good basis for prognostic, but also diagnostic procedure. By understanding mechanisms of faults and failures, one can map the information obtained from systems behavior from past and based on the

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mapping process can create so called pattern recognition. However, drawback in creating pattern recognition is that it requires expertise in the field, highly trained and skilled personnel. Therefore, automatic pattern recognition is desirable. This can be achieved through classification of signals based on the information extracted from signals in the system with malfunctions. Various methods are discussed in the field of hydraulic failure analysis, particularly FMEA /14-17/, artificial intelligence (AI) e.g. fuzzy or neural nets /18,19/, modeling and simulation /20,21/.



Picture 2. Basic wear mechanisms present in hydraulic system

Oil analysis is complex, sensitive, and expensive, hence professional staff of engineers and laboratory technicians should conduct it. On the other hand, it is also time consuming because sending samples to laboratories for analysis and waiting for results may take for weeks, even months. Even so, some percentage of such tests turns out to be normal. Generally speaking, Wilson et al. /22/ claim that 50% of the analysis find no problems and only 5% detect serious problems, while the remaining 45% of cases indicate imminent problems or increased trends, which might require further testing. The best way to reduce time and costs by oil analysis is to use a real-time on-site instrument with appropriate on-board equipment /22,23/. Therefore, professional staff of engineers and technicians should carefully choose the appropriate apparatus for oil diagnosis. The underlying reason is that every instrument has its level of quality. For example, Tic et al. /6/ conducted a research comparison analysis of Automatic Particle Counters (APCs) and high-precision laboratory instrument, namely Internormen CCS2. Results from their experiment showed significant discrepancies in results ranging from $\pm \frac{1}{2}$ ISO /24/ class. Besides, while using APCs, one must not forget to include environment conditions, oil sampling points, disturbances, fluctuations in fluid temperature and system pressure, etc. There are numerous instruments used for oil contamination analysis besides APCs, such as ferrographs, spectrophotometers, etc. Thus, procedure of sampling and conducting diagnostic and prognostic analysis of oils is by no means an easy task.

CONDITION BASED MAINTENANCE (CBM)

There are a hundreds of definitions of maintenance, but in summary, maintenance should be considered as: ensuring the required reliability, availability, efficiency, and capability of a physical product /25/.

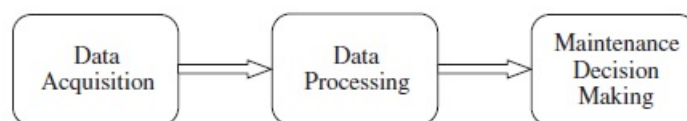
Maintenance costs are a major part of the operating costs of all manufacturing or production plants. Depending on the specific industry, maintenance costs can represent between 10% and 40% of goods produced /26/. Benefit of CBM is the automatic ability to monitor the mean time between failures (MTBF). This data provides the means to determine the most cost effective time to apply maintenance activities, rather than continually absorbing high maintenance costs. CBM will automatically display the reduction of

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MTBF over the life of the machine. When the MTBF reaches the point that continued operation and maintenance costs exceed replacement cost, the machine should be replaced /26/.

Namely, CBM is a maintenance program that recommends decisions based on the information collected through condition monitoring. It consists of three key steps: data acquisition, data processing and maintenance decision-making step (picture 3). Oil analysis is considered to have diagnostics and prognostics aspects (which are the two most important /27/) of CBM in hydraulic systems. Diagnostics deals with fault detection, while prognostics deals with fault prediction before it occurs. In terms of event analysis prognostics is prior, while diagnostics is posterior. It is clear that prognostics is superior to diagnostics in the sense that prognostics can predict and prevent failures before they occur. However, prognostics can not function as an individual aspect of CBM, and the reason is that there are always some faults or failures which are not predictable. For comprehensive understanding of decision aspects in CBM reader is referred to /28/. Fundamental steps of CBM in the context of contamination control in hydraulic systems are:

1. Data acquisition. Collecting useful data from targeted mechanism. Data can be categorized into two main types, namely event data and condition monitoring data. From a hydraulic system point of view, event data collects information about what happened (e.g. installation, breakdown, overhaul) and what was done (e.g. repair, oil change, stoppage). Condition monitoring analysis can be numerous data (e.g. particle contamination, acoustic, vibration, temperature) which can be monitored by different instruments: automatic particle counters (APCs), spectrogram, accelerometer, infrared camera, and results can be demonstrated as value data (ISO code level /24/), signals to waveform data, or multidimensional data for IC camera. Authors emphasize that event data and condition monitoring data are equally important. Even though, in practice sometimes, event data can be overlooked.
2. Data processing. The first step of data processing is data cleaning. Data cleaning includes isolating errors and removing them. Data errors are caused by many factors, including the human error, which is unavoidable, especially in the situation if the data is inserted manually. The next step is data analysis. Data analysis in condition monitoring data falls into three categories: value type (e.g. pressure, temperature, flow), waveform type (e.g. vibration, acoustic), and multidimensional type (e.g. IC image).
3. Maintenance decision making. Third, and last step, presents a crucial step in order to reduce or overcome faults or failures in the future. Techniques of decision support consists of: prognostics and diagnostics. Prognostics as mentioned earlier, attempts to predict faults before they occur, while diagnostics works on a pattern recognition.



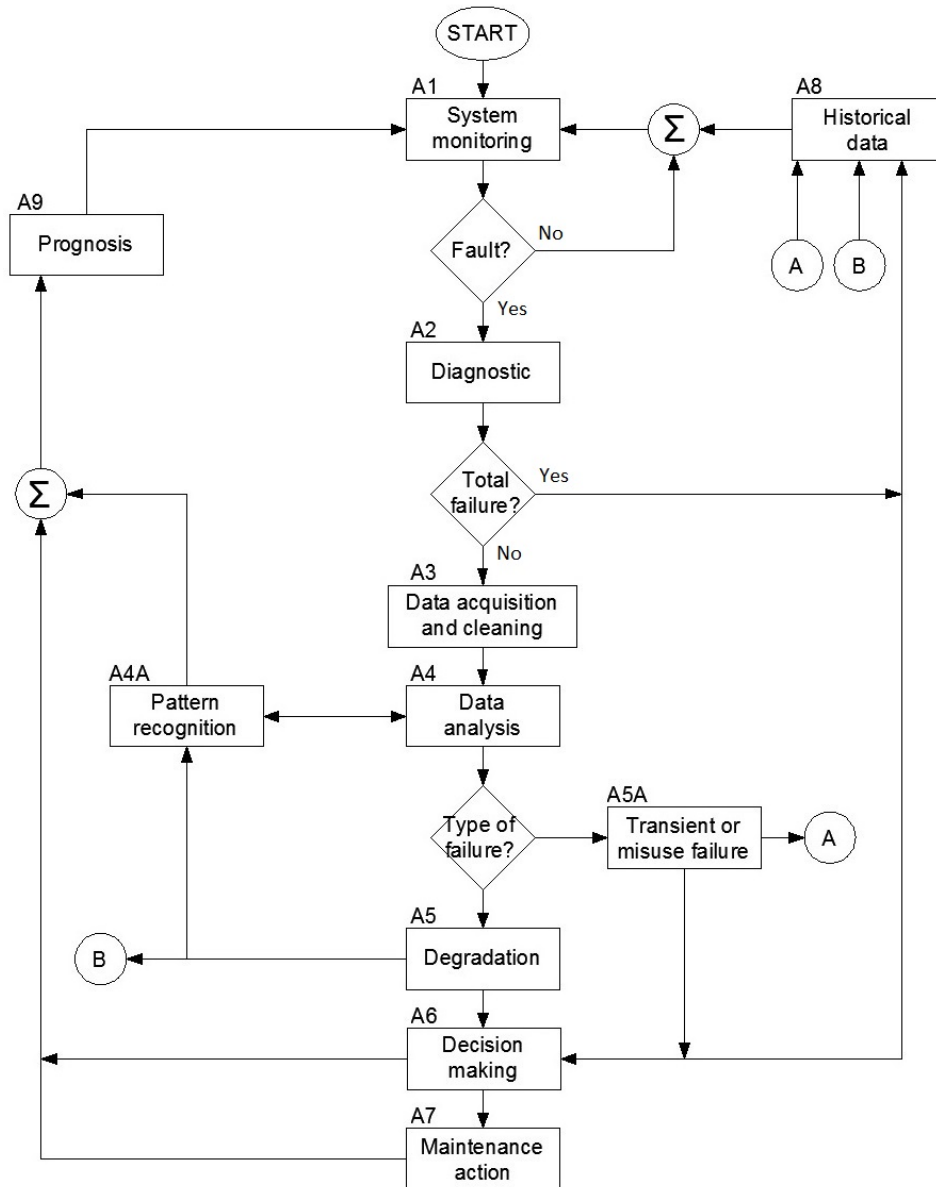
Picture 3. Three steps in CBM /35/.

CONTAMINATION CONTROL PROGRAM DESIGN AND DISCUSSION

Designing a contamination control program requires thorough understanding of hydraulic system performance, working environment, and system maintenance procedures /28/ (diagnostics and prognostics). The reliability of diagnostic and prognostic procedures depends on multiple interrelated factors, such as: staff expertise, commitment, experience, maintenance program, instruments, methods, techniques, etc. From algorithm presented in picture 4, authors propose contamination control program for better comprehensive understanding of perseverance and steadfastness of hydraulic system maintenance. Accordingly, defining the required fluid cleanliness level, or system quality control boundaries, maintenance technicians' main task should be maintaining the system performance within defined boundaries. Aforementioned should not be confused with around-the-clock monitoring the system performance approach, but rather defining "time-to-check" periods through sampling. Likewise,

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maintenance engineers and technicians could use data from sampling and failures as information to improve current program or enhance fault detection points. Following the statement, maintenance personnel can avoid unnecessary maintenance tasks by taking actions only when there is abnormal behavior of hydraulic system. The algorithm presented in picture 4 presents closed loop algorithm, following with information feedback after every cycle on potential error, or fault detection. Algorithm steps are listed, explained, and discussed.



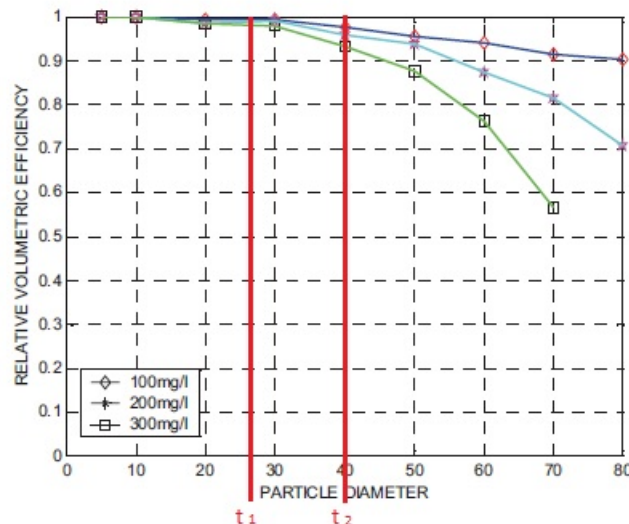
Picture 4. Contamination control program

A1. System monitoring. By system monitoring information is not just collected from condition monitoring data (oil analysis, vibration, acoustic), but also from event data (potential breakdown, installation). All information in this step depends on previous historical data (7b) provided by maintenance personnel and technicians. Based on the data, planned monitoring procedures, time-to-check, and critical failure points are directly proportional to historical data, staff commitment, and expertise. System monitoring includes activities of following the current state of the system performance. However, if those performances go out of defined boundaries then monitoring shows fault and algorithm activates diagnostic step.

A2. Diagnostic. One of the most important steps is commitment of maintenance sector towards constantly achieving continual improvement. The underlying reason is that constantly improving maintenance policy leads to higher performance results, such as cutting costs, reducing MTBF, etc. For example, looking at results from Jing et al./30/ research (picture 5), one can define the time (t_2) from diagnostic results (e.g.

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drop of efficiency, trend, wear) to conduct maintenance activities (e.g. filtering, replacing worn component, oil, etc.). While, on the other hand some may conduct activities earlier (t_1). Therefore, based on personnel expertise, defining time-to-act, equipment and technology, and other activities involved in preserving and prolonging the system lifespan, quality of maintenance policy will depend. Hence, quality of system monitoring approach and diagnostic procedure are result of that policy. The following step is detecting whether the fault is catastrophic or whether it needs further analysis. In a case of catastrophic failure, maintenance professionals must react fast by removing the error, replacing component, and return the system in working condition. Therefore, in case of catastrophic failure next step will be maintenance action (A7) and collecting data for history input data (A8). Otherwise, program will continue to the next step.



Picture 5. Influence of particle contamination

A3. Data acquisition and cleaning. Data acquisition is collecting useful data from targeted process for the purpose of data analysis. Reasons for data cleaning are getting accurate and precise data, which is important for data analysis, decision making, and prognostic procedure. Factors that contribute to data error can come from various sources: human error, non-calibrated instruments, aged equipment, avoiding statistical analysis from collected data, etc. For example, instruments can give different data results as was found in Tic et. al /6/. Therefore, data cleaning step is crucial before data analysis. Following data analysis without data cleaning can lead to incorrect data, misleading conclusions, and non-robust decision making.

A4. Data Analysis. This step in contamination control program is important in a way that it can be used to trace the underlying causes of failure, detection of performance degradation, or modeling of contamination in hydraulic system. For example, based on data several models can be developed via reliability theory /9, 32/, artificial-intelligence /19/, or complex non-linear programming for replacement strategies /33/.

A4A. Pattern recognition. Results from data analysis are performance degradation, causes of failure, or misuse. Information collected from performance degradation will lead to affirmation that failure is caused by degradation itself, but it will also provide clear data to identify patterns and detect faults. Identifying patterns or pattern recognition is procedure of mapping the information obtained from measurements. Graphical tools such as power spectrum graphs, spectrograms, wavelet scalograms, and similar usually do pattern recognition. These data can be useful information in prognostics, but also as a comparison tool in future data analysis. If data analysis shows information about system misuse type of failure (A5A), maintenance professionals are making decisions to remove fault and return system in working condition.

A5. Degradation failure. Degradation implies continual deterioration of system performance out of specifically defined work range. Deterioration data can be obtained via data acquisition in form of value data, waveform, or image data. Although value data may look simpler than waveform or image data, complexities may exist when number of variables is large. Trend analysis techniques such as regression analysis and time series models are commonly used techniques for value type data analysis /27/. All three forms of data can show process of degrading the performance. For example, value type data can represent degradation performance through change of oil ISO class level, temperature rise, pressure drop, through

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different periods. For waveform data, performance degradation can be seen through change in waveform of structural acoustics (i.e. vibroacoustics) data. For multidimensional type data, performance degradation by infrared image processing through specific time interval can be represented by temperature change.

A5A. Transient or misuse failure. Most of the causes of transient faults and failures lead back to human factor. Special attention should be dedicated towards exact assembly of the system i.e. adjusting performance, placing components in appropriate position (e.g. valves, filters), appropriate hydraulic oil for hydraulic system with respect towards original equipment manufacturers (OEMs) requirement of oil quality level, etc. Disrespecting any of the requirements can lead to system stoppage. For example, using inappropriate hydraulic oil with different viscosity can lead towards breaking of lubricating layer, which can lead to catastrophic failure. Inappropriate filter placing at suction line (pump intake) of a gear pump can reduce the service life a pump by at least 50 percent /31/.

A6. Decision-making. Sufficient and efficient decision support would be crucial to maintenance personnel's decision support /27/ before taking action. Decision making will affect the quality of actions taken, reliability of the system, and prognosis of future faults and failures. In addition, decision-making concerning prognosis can also affect re-establishing system monitoring approach, but also reconstruction of maintenance policy.

A7. Maintenance action. Although it is a last step in contamination control program, it is important as much as previous steps. By conducting maintenance actions, maintenance engineers must provide exact information to technicians and personnel in order to overcome misunderstanding in information. After all, every step before maintenance action is build upon the information collected through system monitoring. Providing accurate and consistent information maintenance personnel are avoiding unnecessary tasks, saving time and reducing maintenance costs.

A9. Prognosis. Similar to diagnosis, prognosis also include statistical approaches, AI approaches, and model-based approaches. The aim of prognosis is to provide decision support for maintenance decision-making, maintenance policy development, and to determine condition monitoring intervals. Idea of prognosis incorporating maintenance policies is to optimize CBM involving risk, cost, and reliability.

CONCLUSION

Advancements in contamination control as an integral part of CBM are significant economic impact on the machines' life cycle costs. Most important ones are extension of components life, reduction of unscheduled downtime, and reduction of maintenance costs, due to failures caused by contaminated oil. It should not be forgotten that, extension of oil life also prolongs the time for buying a new oil and reduces the cost of disposing the used one, which improves environment protection and safety level.

However, notwithstanding advancements in maintenance approaches, there are still two common antithesis present in industry. The first one is run-to-failure (RTF) policy, while the second one is around-the-clock maintenance policy. Although RTF may sound like reluctant approach, there are some examples where it can be used (e.g. cost of RTF approach is lower than the cost of production halt). Either of the two can be used to some extent. Nevertheless, CBM is certainly the better choice, especially in the case where faults and failures are highly time consuming and expensive. Further progress hinges on establishing a better understanding on the process of component wear out and contamination modeling/17,20,21/. Contamination control developments are seen through modeling via fuzzy programming/18/, artificial neural networks/19/, and statistical analysis techniques to diagnose or predict faults and failures/9/, etc. Despite the fact that all of the previous studies are concerned with contamination control, most of them focus on a single-system component. The reason is that underlying mechanisms of particle generation and removal are very complex and depend on multiple interrelated factors. Difficulties in reflecting the influence of contaminated oil from whole system perspective, as well as analysing the economic effects of system maintenance, will lead to superficial understanding by engineers and maintenance personnel in practice. In fact, throughout the years maintenance sectors kept neglecting these complexities, which led to information losses and slow pace advancements in maintenance policies. Continually improving the contamination control program as an integral part of CBM can be serious groundwork for engineers and technicians using high-tech equipment, and especially in scientific community whereas state-of-the-art research Industry 4.0 and Internet-of-Things (IoT) are currently evolving.

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