Using contamination control in condition-based maintenance of a hydraulic system

Marko Orošnjak, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia*
Tamara Peković, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia
Mitar Jocanović, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia
Velibor Karanović, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia
Amalija Horvatić Novak, Faculty of mechanical engineering and naval architecture, Ivana Lucica 5, 10000 Zagreb, Croatia

Abstract: *Hydraulic systems are continually improving, resulting in a higher power and faster response rate while at the same time preserving the use of energy due to advancements in hydraulic drivers and control. At the same time, the degradation of these drives and control valves are exposed to wear which are primarily caused by the degradation of the fluid influenced by contamination of the same. Understanding the mechanisms of contamination failure, root causes and consequences can result in higher energy efficiency, precision and response of the hydraulic system. As such contamination control has been widely disseminated topic in the previous decades dedicated to maintaining the system cleanliness through condition monitoring, diagnostic and prognostics, encapsulated in Condition-Based Maintenance (CBM) approach. Moreover, to help assess the hydraulic system, especially on a lower layer of abstraction where concrete maintenance activities are conducted to preserve the system functionality, we propose contamination control program for efficient and reliable production of force or torque at the hydraulic actuators.*

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

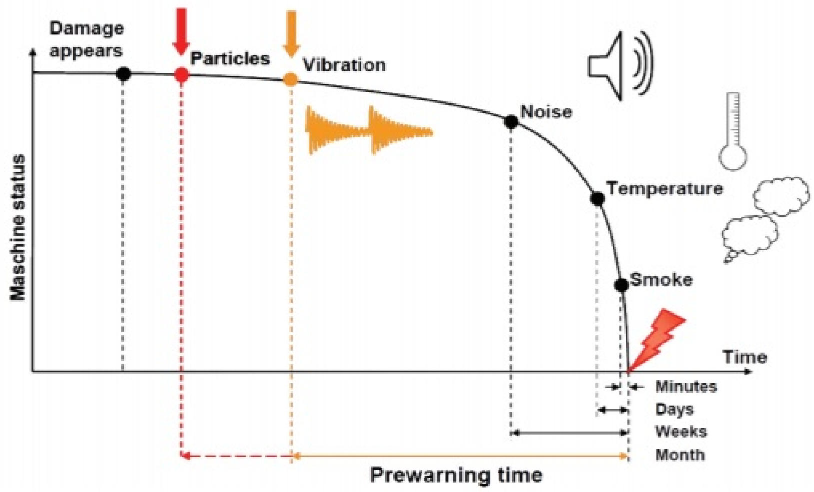
INTRODUCTION

Contamination, in general, in hydraulic systems, 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 a hydraulic system. Some have stated that research into service and maintenance system development attracts little interest in the scientific community, and this limited research tends only to 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 condition-based maintenance (CBM) schemes driven by real time data acquisition and processing /4/.

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 the 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 the system

* Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovića 6, 21000 Novi Sad orosnjak@uns.ac.rs

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 a condition-based approach, i.e. condition monitoring techniques to determine the current state (diagnosis), and techniques to predict the 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.

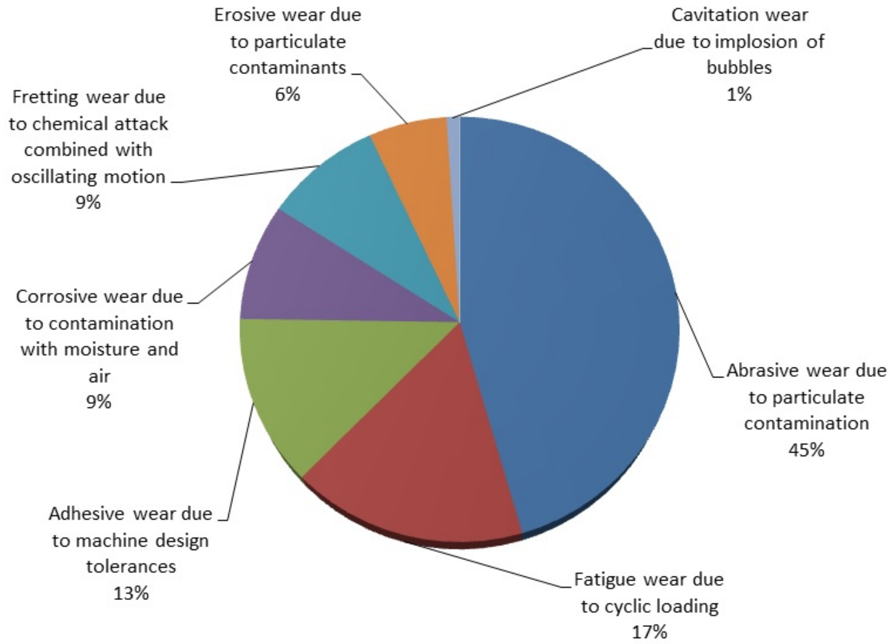
Degradation can be classified as gradual changes in system parameters over time (e.g. pump flow rate, valve leakage, wear of cylinder barrels, cylinder speed decline, etc.). As this type of malfunction continues to degrade, it can easily and rapidly lead to catastrophic failure. Therefore, corrective 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 the 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 types of contamination or combined:

1. Built-in contamination. This can be split 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 the hydraulic system, shown in picture 2. Besides, knowing categories of system malfunctions caused by contaminants within the system can be a good basis for prognostic, but also diagnostic procedure. By understanding the mechanisms of faults and failures, one can map the information obtained from systems behaviour from the past and based on the

* Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovića 6, 21000 Novi Sad orosnjak@uns.ac.rs

mapping process can create so-called pattern recognition. However, a 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 the 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 Networks (NN) /18,19/, and modelling and simulation /20,21/.



Picture 2. Basic wear mechanisms present in the 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, a small percentage of such tests turns out to be normal. Generally speaking, Wilson et al. /22/ claim that 50% of the oil analysis finds 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, the 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 $\pm$ ½ ISO class /24/. Besides, while using APCs, one must not forget to include environmental conditions, soil 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, the procedure of sampling and conducting a diagnostic and prognostic analysis of oils is by no means an easy task.

CONDITION-BASED MAINTENANCE (CBM)

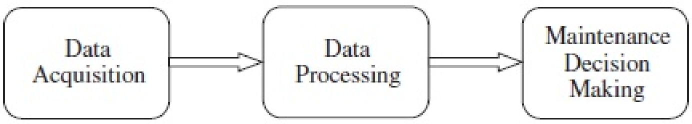
There are hundreds of definitions of maintenance, but in summary, maintenance should be considered as ensuring the required reliability, availability, efficiency, and capability of a physical product /25/.

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/. The 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

* Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovića 6, 21000 Novi Sad orosnjak@uns.ac.rs

reduction of 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 the event, analysis prognostics is prior, while diagnostics are posterior. 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 a 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 a 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 collect 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 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 the last step, presents a crucial step to reduce or overcome faults or failures in the future. Techniques of decision support consist of prognostics and diagnostics. Prognostics, as mentioned earlier, attempts to predict faults before they occur, while diagnostics work on pattern recognition.



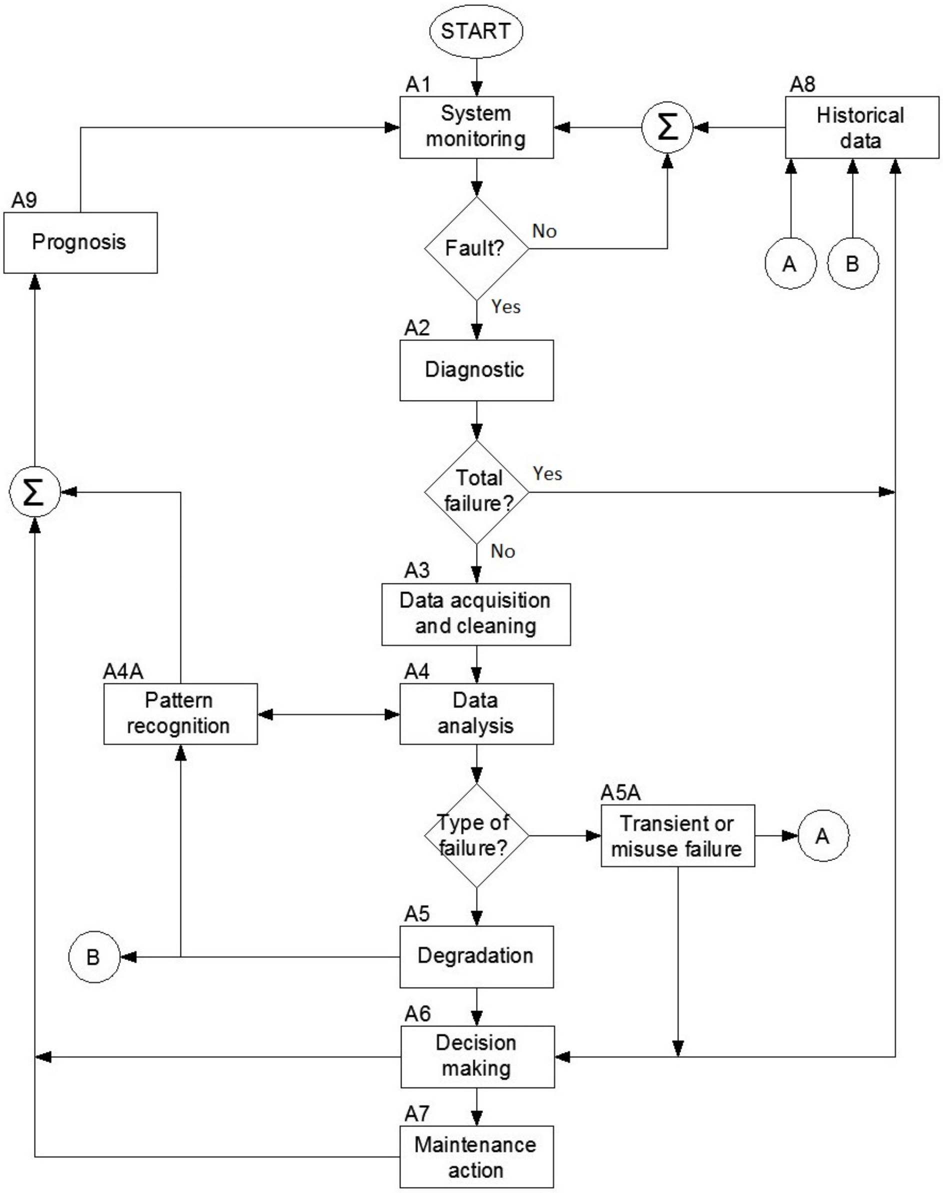
Picture 3. Three steps in CBM /35/.

CONTAMINATION CONTROL PROGRAM DESIGN

Designing a contamination control program requires a 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 the algorithm presented in picture 4, authors propose a contamination control program for a 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,

* Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovića 6, 21000 Novi Sad orosnjak@uns.ac.rs

maintenance engineers and technicians could use data from sampling and failures as information to improve the 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 behaviour of the hydraulic system. The algorithm presented in picture 4 presents a 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 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 the 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 at picture 5, one can define the time (*t*) from diagnostic results (e.g. drop of

* Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovića 6, 21000 Novi Sad orosnjak@uns.ac.rs

efficiency, trend, wear) to conduct maintenance activities (e.g. filtering, replacing a 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 the diagnostic procedure is the results 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 a component, and return the system in working condition. Therefore, in case of catastrophic failure, the next step will be maintenance action (A7) and collecting data for history input data (A8). Otherwise, the program will continue to the next step.

Picture 5. Influence of particle contamination (own source)

A3. Data acquisition and cleaning. Data acquisition is collecting useful data from a targeted process for 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, a 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 the 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 modelling of contamination in the 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 the 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 the 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

* Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovića 6, 21000 Novi Sad orosnjak@uns.ac.rs

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 the form of valuable data, waveform, or image data. Although value data may look simpler than waveform or image data, complexities may exist when several variables are large. Trend analysis techniques such as regression analysis and time series models have commonly used techniques for value type data analysis /27/. All three forms of data can show the process of degrading performance. For example, value type data can represent degradation performance through the change of oil ISO class level, temperature rise, pressure drop, through different periods. For waveform data, performance degradation can be seen through a change in waveform of structural acoustics (i.e. vibroacoustic) data. For multidimensional type data, performance degradation by infrared image processing through a 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 the human factor. Special attention should be dedicated towards the exact assembly of the system i.e. adjusting performance, placing components inappropriate position (e.g. valves, filters), appropriate hydraulic oil for a 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 to the breaking of the lubricating layer, which can lead to catastrophic failure. Inappropriate filter placing at the suction line (pump intake) of a gear pump can reduce the service life a pump by at least 50 per cent/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. Besides, decision-making concerning prognosis can also affect re-establishing system monitoring approach, but also a reconstruction of maintenance policy.
A7. Maintenance action. Although it is a last step in the 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 to overcome misunderstanding in the information. After all, every step before maintenance action is built 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 includes statistical approaches, AI approaches, and model-based approaches. Prognosis aims to provide decision support for maintenance decision-making, maintenance policy development, and to determine condition monitoring intervals. The 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 the significant economic impact on the machines' life cycle costs. Most important ones are an 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 the extension of oil life also prolongs the time for buying a new oil and reduces the cost of disposing of the used one, which improves environmental protection and safety level.
However, notwithstanding advancements in maintenance approaches, there are still two common antitheses present in the industry. The first one is the run-to-failure (RTF) policy, while the second one is the around-the-clock maintenance policy. Although RTF may sound like a 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 of the deterioration of the component internal surfaces and mathematical modeling of such phenomenons depending on the wear mechanisms to better predict

* Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovića 6, 21000 Novi Sad orosnjak@uns.ac.rs

incipient failures. Even though the 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 a 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 year's 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 the serious groundwork for engineers and technicians using high-tech equipment, and especially in the Industry 4.0 and cloud based monitoring systems for better and fast diagnosis and prognosis of system states.

REFERENCES

/1/ Battat, B. & Babcock, W., (2003), Understanding and reducing the effects of contamination on hydraulic fluids and systems., The Amptiac Quarterly, Vol. 7, Num. 1, pp.11-15.

/2/ Norvele, F.D. (1984) Contamination control – the key to reliability in fluid power systems, Wear. Issue 94, pp.47-70.

/3/ Frith, R.H., and Scott, W., (1993), Control of solids contamination in hydraulic systems – An overview, Wear, Vol.165, pp.69-74.

/4/ Ng, F., Harding, J.A, Glass, J., (2017), Improving hydraulic excavator performance through inline hydraulic oil contamination monitoring, Mechanical Systems and Signal Processing, Vol.83, pp.176-193.

/5/ Huang, Y.Q., Nie, S.L., Ji, H., (2014), Identification of Contamination Control Strategy for Fluid Power System Using an Inexact Chance-Constrained Integer Program, Journal of Applied Mathematics, pp.1-19. DOI: 10.1155/2014/146413

/6/ Tic, V., Lovrec, D., Edler, J., Operation and Accuracy of Particle Counters for Online Condition Monitoring of Hydraulic Oils, Annals of Faculty Engineering Hunedoara – International Journal of Engineering, Vol. 10, Iss. 3, pp.425-228.

/7/ Garvey, R., and Fogel, G., (1998), Converting tribology based monitoring into measurable maintenance results, Computational Systems Inc., Knoxville, TN.

/8/ Madenas, N., Tiwari, A., Turner, C.J., Woodwad, J., (2014), Information flow in supply chain management: a review across the product lifecycle, CIRP Journal of Manufacturing Science and Technology, Vol. 7, Iss. 4, pp.335-346.

/9/ Orošnjak, M., Jocanović, M. & Karanović, V., (2016), Quality analysis of hydraulic systems in function of reliability theory, Proceedings of the 27th International DAAAM Symposium "Intelligent Manufacturing & Automation", Mostar, BiH. pp569-577. DOI: 10.2507/27th.daaam.proceedings.084.

/10/ Girdhar, P. and Scheffer, C. (2004), Practical Machinery Vibration Analysis and Predictive Maintenance, Elsevier, Oxford.

/11/ Poley, J., (2012), The metamorphosis of oil analysis, Machinery Failure Prevention Technology (MFPT) Conference, Condition Based Maintenance Section 1, Conference Proceedings, Dayton, Ohio, April 24-26, 2012.

/12/ Kuhl, A., (2011), Condition monitoring – many options, one goal, Proceedings of OilDoc 2011, Rosenheim, Germany, February 2011.

/13/ Lovrec, D. and Tich, V., (2012), On-line condition monitoring systems for hydraulic machines, Facta Universitatis, Series: Mechanical Engineering, Vol. 10, No.1, pp.81-89.

/14/ Bull, D. R., Stecki, J. S., Edge, K. A., and Burrows, C. R., (1997) Failure modes and effects analysis (FMEA) of a valve-controlled hydrostatic drive, Fluid Power Engineering: Challenges and Solutions, Tenth Bath International Fluid Power Workshop, Research Studies Press, Ltd. pp.131-143.

* Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovića 6, 21000 Novi Sad orosnjak@uns.ac.rs

/15/ Hawkins, P. G., Atkinson, R. M., Woollons, D. J., Bull, D. R., Edge, K. A. and Burrows, C. R., (1996), An approach to failure modes and effects analysis using multiple models, *International Functional Modelling and Application Association. Proceedings of the Fourth International Workshop on Functional Modelling of Complex Technical Systems*, 1996-06-01.

/16/ Stecki, J. S., Condrad, F., & Oh, B., (2002), Software tool for automated failure modes and effects analysis (FMEA) of hydraulic systems, Fifth JFPS International Symposium on Fluid Power, Nara, Japan.

/17/ Chao, L., Stecki, J. S. Stecki, and Dransfield, P., (1990), Dynamic contamination control model for fluid contamination, Proceedings of the international conference on fluid power control and robotics, Chengdu, China, pp.342-347.

/18/ Ji, H., Nie, S., and Huang, Y., (2014), An Interval-fuzzy two-stage stochastic programming method for filter management of hydraulic systems, Proceedings of Institution of Mechanical Engineering Part C: Journal of Mechanical Engineering Science, Vol. 0, Iss. 0, p.1-22, DOI: 10.1177/0954406214563737

/19/ Yong, X, Xuezhi, W., Jie, W., Jun, L., (1997), The application of fuzzy neural network for contamination control of hydraulic oil, IEEE International Conference on Intelligent Processing Systems, 1997. ICIPS '97. Beijing, China. pp.322-324.

/20/ Stecki, J. S. and Chao, L., (1990), Simulation of contamination control systems, The bulletin of the centre for machine condition monitoring, Vol. 2, No.1, pp.10.1–10.6.

/21/ Ma, G., Ning, S., Hu, J. & Gao, J., (2016), Dynamic balance analysis of contamination control for hydraulic systems based on dynamic filtration ratio, Industrial Lubrication and Tribology, Vol. 68, Iss. 1, pp.-45 – 51.

/22/ Wilson, B.W., Hansen, H. H., & Shepard, L.C., (1999), Development of a Modular In-Situ Oil Analysis Prognostic System, International Society of Logistics (SOLE) 1999 Symposium, Las Vegas, Nevada, August 30 – September 2, 1999., pp.1-7.

/23/ Mačužić, I. & Jeremić, B., 2004, Proactive Approach to Oil Maintenance Strategy, Tribology in Industry, Vol. 26, No.1&2, p.27-31.

/24/ ISO 4406:1999, Hydraulic fluid power — Fluids — Method for coding the level of contamination by solid particles.

/25/ Kumar, U., Galar, A., Stenstrom, C., Berges, L., (2013), Maintenance performance metrics: a state-of-the-art review, Journal of Quality in Maintenance Engineering, Vol. 19 Issue: 3, pp.233-277, doi: 10.1108/JQME-05-2013-0029.

/26/ Cheng, H., (2007) Implementation Strategies and Tools for Condition Based Maintenance at Nuclear Power Plants, International Atomic Energy Agency, Wagramer Strasse 5, Vienna, Austria.

/27/ Jardine, A. K. S., Lin, D., & Banjević, D., (2006), A review on machinery diagnostics and prognostics implementing condition-based maintenance, Mechanical Systems and Signal Processing, Vol. 20, pp.1483-1510. doi: 10.1016/j.ymssp.2005.09.012

/28/ Stecki, J. (2009). Contamination Control and Failure Analysis. Lubrication and Maintenance of Industrial Machinery: Best practices and reliability. ed. Rober, M. G., and Totten, G.E., CRC Press LLC, Taylor & Francis Group, Boca Raton, Florida, USA.

/29/ Wang, W. & Gu, F., (2000), Modeling Condition Based Maintenance Decision Support, Proceedings of the 33rd International MATADOR Conference, pp.159-164. DOI: 10.1007/978-1-4471-0777-4_25.

/30/ Jing, B., Yang, L., & Lu, S., (2009), The Research of Contamination Abrasion on External Gear Pump, Chinese Control and Decision Conference (CCDC 2009), 17-19. June., pp.3090-3093.

/31/ Ingvast, H., (1993), Diagnosing Tyrone Gear Pump Failures, The Third Scandinavian International Conference on Fluid Power, Vol. 2, pages 535-546.

/32/ Jocanović, M., Šević, D., Karanović, V., Beker, I., Dudić, S., (2012), Increased Efficiency of Hydraulic Systems Through Reliability Theory and Monitoring of System Operating Parameters Strojniški Vestnik - Journal of Mechanical Engineering, Vol. 58, Iss. 4,pp.281-288.

* Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovića 6, 21000 Novi Sad orosnjak@uns.ac.rs

/33/ Nie, S. L., Li, Y. P., Shi, X. Y., Huang, G.H., and Hu, B., (2009), An IPINP model for the assessment of filter allocation and replacement strategies in a hydraulic contamination control system under uncertainty, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Vol. 223, Iss. 4, pp,999-1015.

* Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovića 6, 21000 Novi Sad orosnjak@uns.ac.rs