Oil cleanliness in Wind Power Gearboxes

Elforsk rapport 12:52

Jan Ukonsaari, Hans Møller

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Preface

The purpose of this project is to comprise common knowledge regarding lubrication, components and particle counting for oil cleanliness. Particle counting accuracy was tested with different laboratory methods and filter tests were carried out adding new value to the report.

The work was carried out by Jan Ukonsaari and Hans Møller at Vattenfall as a project within the Swedish wind energy research programme "Vindforsk – III". The report is the final report for project V-367.

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Comments on the work and the final report have been given by a reference group with the following members: Jenny Nilander from Statkraft, Thomas Stalin from Vattenfall, Johnny Pettersson from ITS Transmission and Anders Björck from Elforsk,

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Sammanfattning

Vindkraft är en förnybar energikälla som i ökande omfattning bidrar till den elektriska energiförsörjningen. Den vanligaste vindkraftsturbindesignen använder växellåda i drivlinan för att anpassa varvtal från turbin till generator. Fokus på livslängd på växellådor har ökat de senaste åren i takt med att maskinernas effekt och storlek växt. En påverkande livslängdsfaktor är växellådsoljans renhet. Detta arbete behandlar betydelsen av ren olja, att kvantifiera den, filtermetoder och rekommendationer för att kunna uppnå god oljerenhet. Utöver summerade teoretiska baskunskaper om renhetens betydelse har noggrannhet i metoden ISO 4406:99 praktiskt studerats närmare och off-line filter tester genomförts.

En litteraturstudie visar att oljans renhet har stor påverkan på växellådornas högt belastade kontakter i lager och kuggar. Speciellt viktigt är inkörning. Oljans renhet kan inte kompensera för begångna fel i design, tillverkning, montering eller inkörning. Livslängdens beroende på renheten ger möjlighet till ökning eller minskning med upp till 50 % (dvs. ca 3 ggr ökning från lågt värde). Undantag från detta kan ske i extrema fall. Livslängd i vindkraftsväxellådor är vanligen beräknat till 20 år eller mer.

Den vanligaste metoden att kvantifiera oljerenhet är den enligt standard ISO 4406:99. Enligt den räknas antalet partiklar per milliliter vätska och dessa sorteras i grupper om storlekarna, som enligt standardens definition är, större än 4, 6 och 14 μm. Nästan alla räknade partiklarenligt metoden är större än smörjfilmen i växellådornas kontakter, som normalt är 0,1-1,5 μm i minsta film. Dessa partiklar har därför trots sin ringa storlek i absoluta tal en påverkan på smörjningen. Som jämförelse kan nämnas att ett hår på människan är 17-180 μm tjockt. Gränsen för urskiljning i ett bra ljusmikroskåp är 0,5 μm.

En laboratorieundersökning om noggrannhet vid partikelräkning med olika metoder, och blandningar av olja och utspädningsvätskor genomfördes. För några, av de åtta insamlade växellådsoljorna, visade automatisk partikelräkning variationer på upp till 16 gånger för räknade antal partiklar beroende på vald utspädningsvätska. Jämfört med mikroskopiräkning av filtrerade partiklar var skillnaden ibland än större. Undersökningen i projektet påvisar betydelsen att beakta hur prov är analyserade och utförda vid jämförelse av olika provresultat.

Off-line filtertester på två olika filtertyper visade att de hade olika genomströmmande flöden. Den ena hade högre flöde och renade oljan snabbare. Tester i verklig applikation, som inte genomfördes här, är nödvändiga för att bedöma verklig skillnad mellan filtertyper och dess lämplighet för vindkraftsväxellådor.

Värden på oljerenhet från turbiner i drift funna under detta arbete med bra oljereningssystem visar att renheten motsvarar eller överträffar rekommenderade värden funna i publika material och handböcker. Riktigt ren olja är bra för växellådan, bra för oljan själv och ger bättre förutsättningar för lyckosamma felorsaksanalyser och diskussioner. Ren olja driver utvecklingen framåt. Full inverkan av ren olja har ännu inte setts i vindkraft för att dessa inte varit i drift tillräckligt länge.

Summary

Wind power is a renewable energy source that increasingly contributes to the total electrical energy production. The most common wind turbine designs use gearboxes in the drive train. The focus on the life span of the gearbox has increased during the last 10 years. One potential factor affecting the life span is oil cleanliness. The work presented in this report concerns oil cleanliness in wind power gear boxes with a review on the importance of cleanliness, how to measure cleanliness and filtration methods. Recommendations as to the nature of measures that need to be considered in order to obtain good cleanliness are also included. In addition the ISO 4406:99 cleanliness definition, additional practical methods have been investigated and off-line filter tests have been performed using two different types of filters.

A literature review has revealed that oil cleanliness has a large affect on gearbox EHL (elasto-hydrodynamic-lubrication) component life such as rolling element bearings and gears. Special attention should be addressed to the initial run-in. Oil cleanliness can not fix faults in other stages such as design, manufacturing, assembly or run-in of gearboxes. It is estimated that the oil cleanliness can increase or reduce life up to 50% (or about 3 times from lower value) for an otherwise well functioning gearbox. Exceptions from that interval can appear in extreme cases. Life of gearboxes is normally calculated to 20 years or more.

The most common method to characterize oil cleanliness is the standard ISO 4406:99. The particle contamination is defined by numbers denoting the number of particles per ml fluid for the sizes of particles: particles defined as larger than 4, 6 and 14 μm size respectively. This means that almost all particles noted in measurements are larger than the EHL film thickness, which typically is in the order of 0.1-1.5 μm. The characterized particles therefore all will have an effect of the lubrication even though they are small. A human hair, by comparison, is 17-180 μm thick. The limit for a good optical microscope is a resolution of about 0.5 μm.

A laboratory study was carried out investigating the particle counting accuracy based on the selected counting method and solvent used in the process. For some of the eight tested used gearbox oils, the automatic particle counter method was determined to be solvent type dependent, giving particle count results that were up to 16 times different. The difference was even more noticeable when using the filtration and optical microscopy counting. The study shows the importance of reviewing the laboratory analyse method and procedure when evaluating cleanliness values.

The off-line filter tests performed showed that the two different filter types tested had different characteristics. One had much higher flow and cleaned the oil quicker. Real gearbox long term tests, not performed in this project, are necessary to achieve reliable results for application suitability.

Cleanliness values found in real gearboxes with good oil filter systems meet the cleanliness values found in public material and handbooks. Really clean oil is good for the gearbox, the oil itself and provides a better basis for failure investigations and discussions. Cleaner oil leads the development further; the full potential has not yet been seen due to the short wind power running time.

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1 Introduction

Oil cleanliness is an area where it can be difficult to distinguish between what is actually true and what is the tellers' truth. Often the success of good oil cleanliness will be shown during long term experience spanning over the expected or surpassed life time of a machine. This area risks being down-prioritized if the knowledge of how oil cleanliness affect component life is not up to date. This project examines the importance of oil cleanliness in wind power gearboxes with both a basic and an additional knowledge part:

- A compilation of common knowledge including theory
  - Lubrication, oil properties and general gearbox contact damages
  - The importance of oil cleanliness
  - Filters, layout, particle counting and monitoring, and some hands-on recommendations
- Contribution of additional knowledge by practical investigations
  - Investigation of laboratory procedures and generated faults in particle counting
  - Off-line filter test results and experience of cleanliness values

This study is concluded with a discussion on cleanliness, expected gearbox life and what the filter performance development leads to.

1.1 Background

In wind power, the gearboxes have challenging conditions due to load and environment but also the high expectations of good long term functionality. The demands are based on a design life of at least 20 years and failures prior to this result in economical drawbacks. There is a high focus on subjects affecting service life. One such area is oil cleanliness; the importance of clean oils, how to achieve clean oils and how to measure the oil cleanliness. Knowledge in this area can affect all gearboxes, new as well as old.

Oil cleanliness is often discussed within the scope of filter performance. When oil cleanliness is discussed from a gearbox point of view, the top of the line filters nowadays show results that they remove particles in the range of or even smaller than the lubricated components oil film thickness.

Gearbox life is more than oil cleanliness. It is about design, manufacturing, material properties, assembly, lubrication (oil type, oil quality, oil supply, oil level), running, run-in and environmental conditions (salt, temperature, water), where good (oil) cleanliness is an important aspect. Oil cleanliness cannot fix faults in any of the design and construction stages, but can be a solution for some environmental conditions.

1.2 Objective

The main objective of this project was to state the importance of good oil cleanliness in terms of how contamination affect the gearbox components. This project shall give the reader basic knowledge of how to obtain clean oil, how to continuously monitor cleanliness and secure valid oil analyses both generally and in terms of particles. Finally, the aim was to perform tests and present results that will demonstrate the weaknesses of present methods and some results from oil filter tests and the difficulties in the process.

1.3 Project limitations

One of the project objectives was to give the reader an introduction and basic knowledge within the area of oil cleanliness. The objective was not to point out specific products as top-of-the-line and recommend them, neither to produce exact guidelines on how to do things.

This work report comprises a view of oil cleanliness in wind power gearboxes and hopefully provides a base for further evaluation of important factors and actions into reality. It is not to evaluate what is economically viable in terms of oil cleanliness.

2 Basic lubrication and damages in gearbox contacts

EHL – Elasto-Hydrodynamic-Lubrication

Lubricated gearbox contacts are found in gears and bearings. For gearboxes in wind power rolling element bearings dominate. Lubrication of loaded contacts with surfaces in relative motion requires converging surfaces to generate a lubricate film that separates them. The converging gap enables formation of a hydrodynamic pressure which can carry load. Gear- and rolling element bearing contacts are non-conformal (Hertzian contact) where the pressure becomes high enough to compress the oil, and increase its viscosity to a level that it will stay in the contact for a while. The contact pressure level will locally deform the surfaces. This is called elasto-hydrodynamical-lubrication (EHL, Figure 1). The contact pressure can be more than 1.5 GPa and the lubricating film thickness is 0.1-1.5 μm up to 3 μm (human hair is 17-180 μm thick). Gears are sliding/rolling contacts with pure rolling in the pitch line where the highest loads occur. Rolling element bearings have ideally no sliding between rollers and raceways but within the contact both pure rolling lines and areas of sliding are found. Low or unloaded bearings can have more roller sliding, sometimes called skidding. Bearing life estimations are more accurate under high load conditions and very uncertain when skidding occurs.

Gearbox contact damages

For bearings working under normal operation conditions there are generally three types of surface contact damage that can occur under proper operational conditions: surface distress, fatigue pitting, and fatigue spalling [1]. Other surface damage can occur due to improper mounting or improper operating conditions. Surface distress appears as a smooth surface resulting from plastic deformation in the asperity dimension. This plastic deformation causes a thin work-hardened surface layer (typically less than 10 μm). Pitting fatigue appears as shallow craters at contact surfaces with a depth of, at most, the thickness of the work-hardened layer ~10 μm (Figure 2). Rolling element bearing surface fatigue is normally characterized by spalling, which is 20-100 μm deep. The produced particles are 30-50 μm or larger. Example of damage appearances on component surfaces are shown in Figure 3. There is no definitive difference between pitting and spalling but often pitting is noted for shallower craters than spalling in discussions. It is believed that spalling results from ligament collapse at subsurface crack tips [1].

Apart from damages described above, yielding in the pitch line, gears can have damages called scratching, scoring and scuffing. Scoring may be caused by solid phase welding or abrasion in the direction of sliding. Scratching is minor scoring. Scuffing is characterized by material transfer between sliding surfaces.

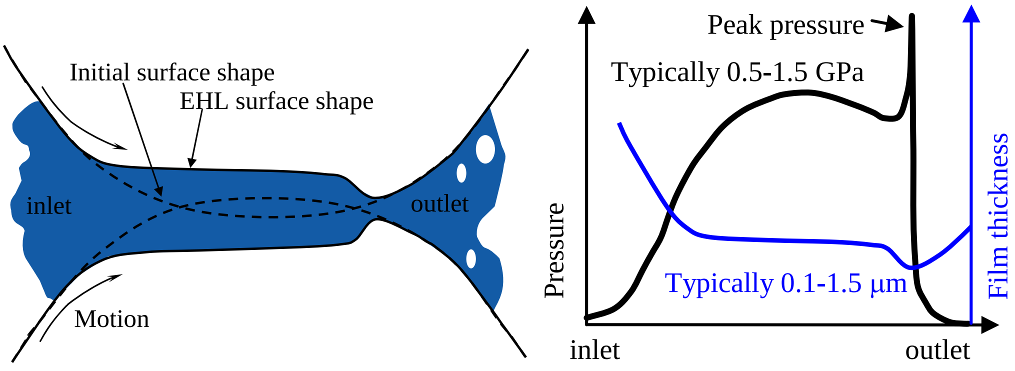

Figure 1. EHL contact illustrating original and deformed surface shape and typical surface pressure and oil film thickness values.

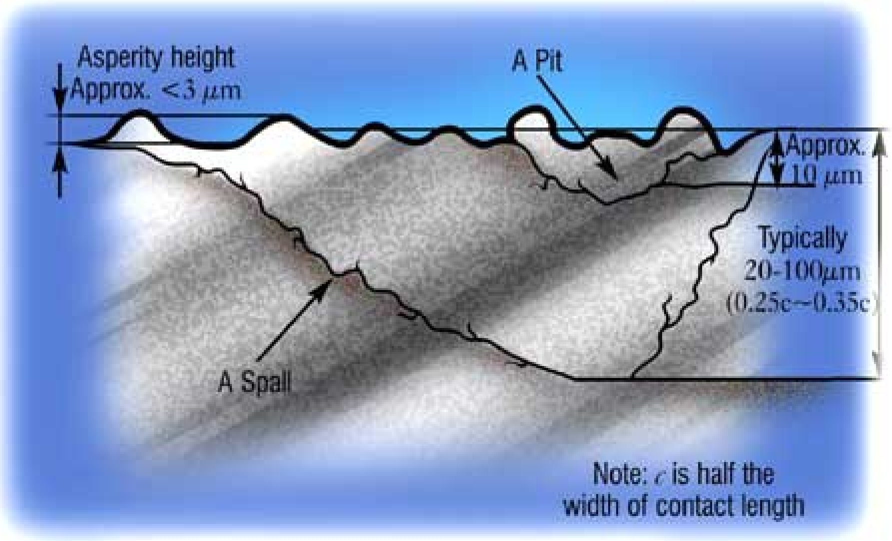

Figure 2. Pitting and spalling [1].

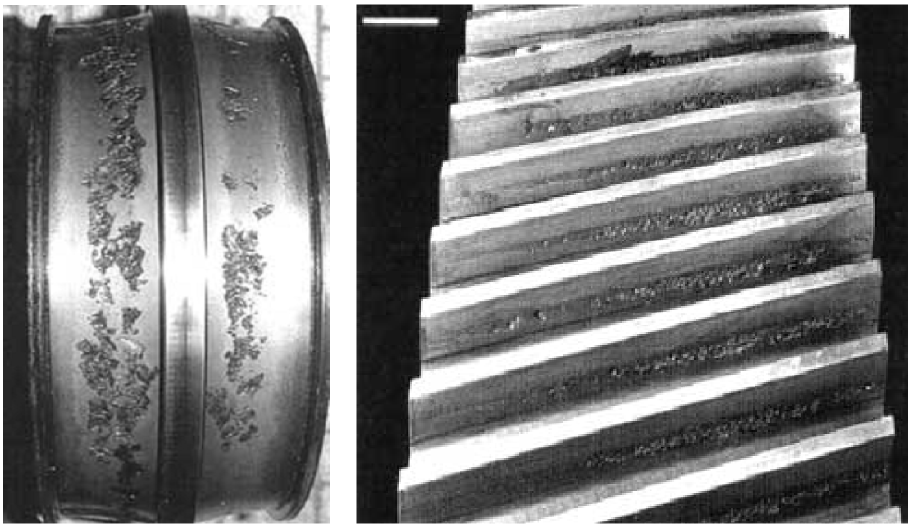

Figure 3. Fatigue spalls on roller bearing inner ring and fatigue pitting (spalling) on pitch line in gear teeth [1].

Figure 4. Example of scuffing of gear [2].

3 Oil properties and analysis

Oil characteristics are important for gearbox component life. For wind power it has to be suitable for the conditions of -40°C - +95°C, hard steel contacts and locally extremely high pressure and long operation time (5+ years) This section will discuss some of the gear oil properties which are also important to the analyse. Other oil properties are discussed in Chapter 3.1 and more extensively and comprehensively in [3].

The most common base oils used in gearboxes are mineral, poly-alfa-olefin (PAO), poly-ethylen-glycol (PAG) and synthetic esters.

Analysis of gear oil has two objectives:

- to assess the condition and properties of the oil
- a tool for condition monitoring, i.e. to assess the condition of bearings and gear

Generally, in-service oil is adequate for further use if it has the specified viscosity, is dry, free of contaminants and contains sufficient concentration of key additives. Below are the main properties and the required analysis:

(It must be pointed out that there will not be only one common analysis program based on the properties here. These properties provide information to enable the user to make a targeted analysis program.)

Viscosity
This analysis is probably the single most important property of any gear oil. Oil film thickness will mainly be determined by viscosity and it will strongly affect losses. OEM (original equipment manufacturer) specifies an ISO Viscosity Grade to be used and it is important to verify, that the oil meet this requirement. Users sometimes confuse viscosity specification with accuracy of the analysis itself. Gear oils are specified according to their ISO Viscosity Grade class. An unused ISO VG 320 shall have a (kinematic) viscosity @ 40°C in the interval 320 cSt (centi Stokes) ± 10%. The analyse is well within 1 cSt interval. The rather wide tolerance band for unused oil reflects mainly, that base oils are blended of various products with different viscosities. Shortly after filling the gearbox with new oil an oil sample should be taken to assess the actual viscosity in this specific gearbox. This value for viscosity serves as a subsequent reference value for evaluating the trend in viscosity.

Moisture and water
Moisture levels should be kept as low as possible due to its detrimental effect on both gearbox components and lubricants. Field experience in well designed systems with off-line filters show that figures < 100 ppm water is achievable. In gearboxes using PAG moisture is normally not an issue as this product is very polar and thus is able to “absorb” high quantities of water molecules without negative effect on performance. Figures up to 20.000 ppm have been reported as acceptable moisture levels, but please note – this limit ONLY

apply for PAG and can vary based on the intended application. Synthetic esters generally have more water content than mineral oil and PAO.

Acid number (AN)
Acid number is normally recommended as part of the testing program of in-service gear oil although interpretation of the results is sometimes ambiguous. Acid number (AN) measures the amount of alkaline (here: KOH) needed to “neutralize” acid components in the oil. The unit for AN is mg KOH/g (of oil). For unused oil the AN will be determined by the type and concentration of additives in the oil. As these deplete the AN will decrease and TAN can be used to evaluate the residual amount of additive. Oxidation of the base oil generally results in degradation products with “acid” behaviour thus affecting the AN.

Additives
Gear oils contain a number of different additives to minimize oxidation of the oil and enhancing the oils AntiWear (AW) and extreme pressure (EP) performance. As the chemistry of these additives are not known (proprietary information) this analysis normally will be limited to assess oxidation inhibitors via analysis of phenol and amine, analysis of sulphur and phosphor (indication of EP and AW) and some elements like molybdenum and zink as indicators for AW-additives.

Cleanliness
Standard ISO 4406:99 target should be established and analysis of in-service oils will provide data to evaluate whether the system is operating satisfactory. High level of particulate (substance consisting of particles) indicate either an increased wear, intrusion of external contaminants (fx caused by damaged breathing filter) or improper function of oil filters in the circuit. Strengths and weaknesses of the ISO 4406 is discussed in Chapter 8 and 9

Wear particles
Analysis of wear particles is primarily used for conditioning monitoring. Trend analysis of wear particles is a very effective tool to track changes of wear patterns.
Analysis of wear particles should comprise of analysis of the individual elements and analysis of ferrous debris (PQ-index or similar). It is often forgotten, that the analyse method used today for measuring wear metals are only able to detect wear smaller particles up to 6 or 8 µm. Presence of larger wear particles, and especially larger than 50 µm, are strong indicators of fatigue failure mode in the gearbox and should be examined further.

3.1 Other important oil properties

There are several properties of oil that are important but not always motivated to test for condition monitoring purposes. More can be read in [3].

VI (viscosity index)
VI is a calculated value of a relationship of oil viscosity at 40°C and 100°C. Higher value means more stable viscosity when temperature changes. Typical

values for mineral oil is VI = 80-120, PAO 140-180, synthetic esters 130-200 and PAGs 200-240. Viscosity at 100°C is sometimes tested.

Filterability
Gear oils shall not contain additives which interact with the type of filters used in wind turbine. For example, foam depressant based on silicone oil tends to be removed by off-line filters.

Viscosity dependence on pressure
Viscosity changes in an oil with pressure. This property depends on the chemistry of the base oil and it influence on the actual oil film thickness and shear stress level in the contact zone.

Limited shear stress
The viscosity in EHL can solidify and appear to have a limited shear stress when being exposed to increasing loads (contact pressure). The friction in the EHL contact eventually stops increasing. Synthetic oils generally have a lower limiting shear stress (Figure 5) compared with mineral base oils. This is regarded as a preferable property.

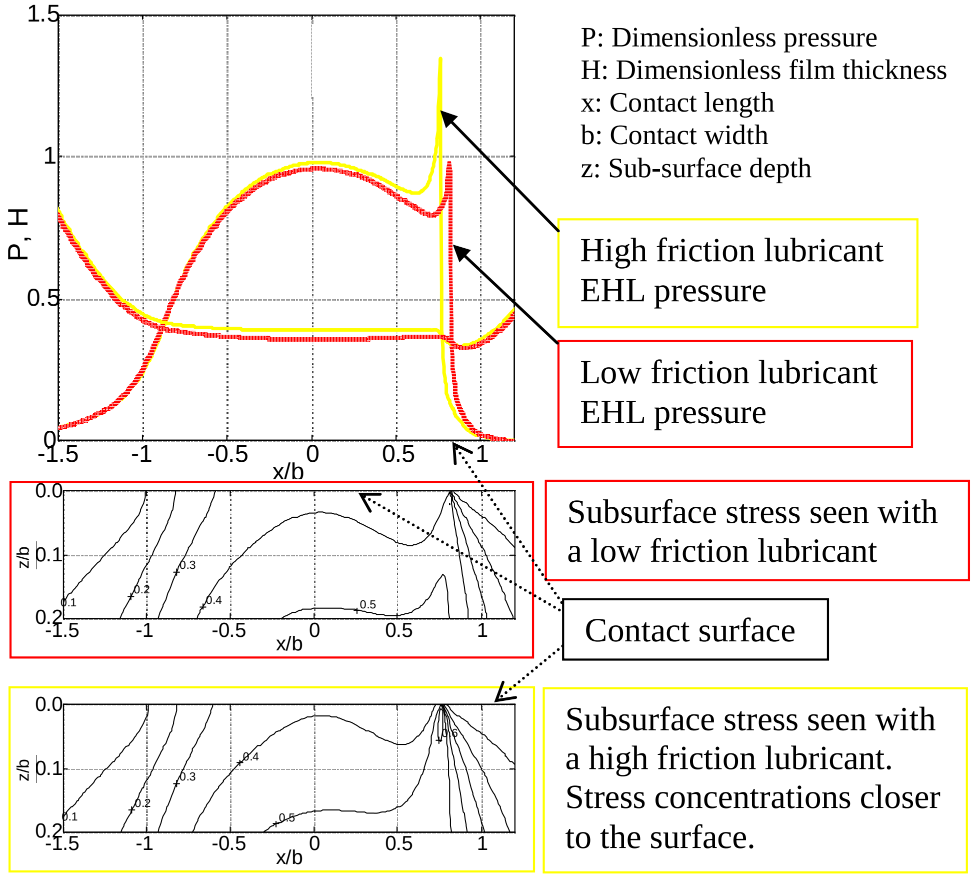

Figure 5. Example of dimensionless pressure and subsurface stress in an EHL contact with a low and high friction lubricant (limiting shear stress).

4 Oil contamination affect on life

Gearboxes with rolling element bearings and gear contacts are dependent on expected levels of oil cleanliness in order to operate correctly throughout their full design life. Some estimations indicate that 80 % of machine wear is particle induced [4]; that figure can very well be true. The importance of oil cleanliness increases in good designs. A “perfect” gearbox with expected life of 25 years might reach 12 years with dirty oil and 25, 30 or 50 years of life with extremely clean oil. However, a poorly designed gearbox might experience 3 years of life with dirty oil and perhaps 3 years and 5 months with extremely clean oil. The cleanliness during run-in can very well also make a difference from 3 to 25 years of life. This chapter will enlighten more on particles, water, gases and the run-in stage of EHL lubricated component.

Particles in oil are well known to significantly affect conditions in gears and rolling element bearings with elasto-hydrodynamic-lubrication (EHL). Particles can directly cause small surface damages, often seen as indentations. Depending on the nature of the particle, the contact indentation will be different [6]. Surface indentations in the contact zone change the material stress and will lead to earlier fatigue.

Wear is increased by particle contamination. Partial wear can change the contact conditions and worsen the EHL contact pressure distribution [7]. Particles in the contacts will give higher peak pressures, higher material subsurface stresses and lower minimum film thickness (coarsely illustrated in Figure 6).

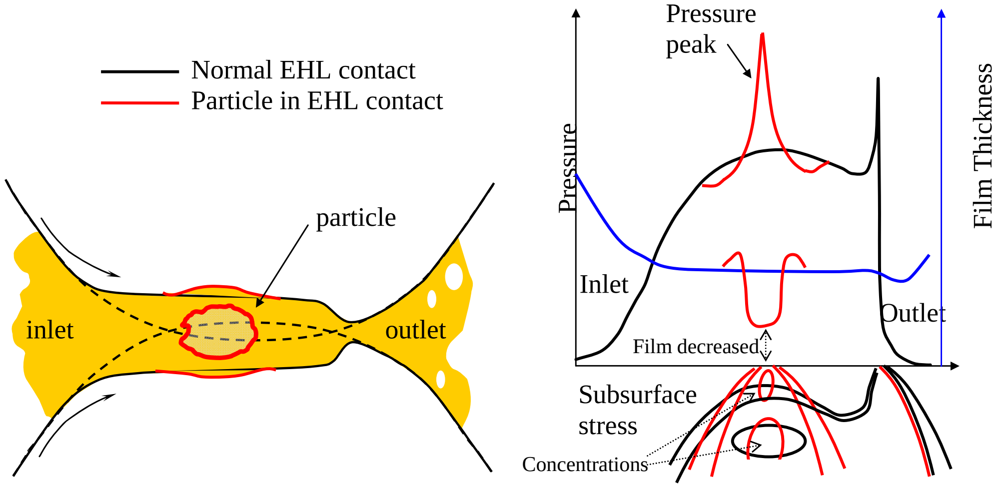

Figure 6. Schematic illustration of particle effect of EHL contact pressure, film thickness and subsurface material stress level.

4.1 Particles

Size

Particle size significantly affects component life with EHL contacts, here estimated by SKF using filter size (Figure 7). According to [8] hard particles that are larger than the oil film thickness will damage the contact surface. A lightly loaded bearing can have a reduced life factor of 500 if subjected to heavily contaminated oil instead of clean oil. In a clean system all material stresses are well within the elastic limit and a bearing can operate at load levels just under the threshold for gross plastic flow [8]. Springer [9] says that at heavy loads, the effects of varying debris levels are reduced because the net effect on the general contact material stress level is reduced as opposed to the greater effect on modifying the general stress level at light loads (Figure 8). This is also included in bearing calculations [10]. Tests undertaken in ultra-clean conditions have shown that bearings had a 40 times longer life compared to the calculated values [12, 13]. For the purpose of this test, ultra-clean oil was defined as oil filtered with a 3 µm filter.

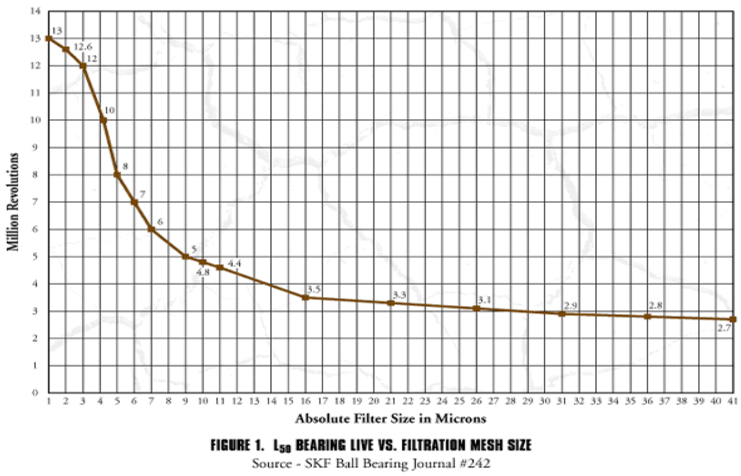

Figure 7. Bearing life vs. filtration mesh size [11].

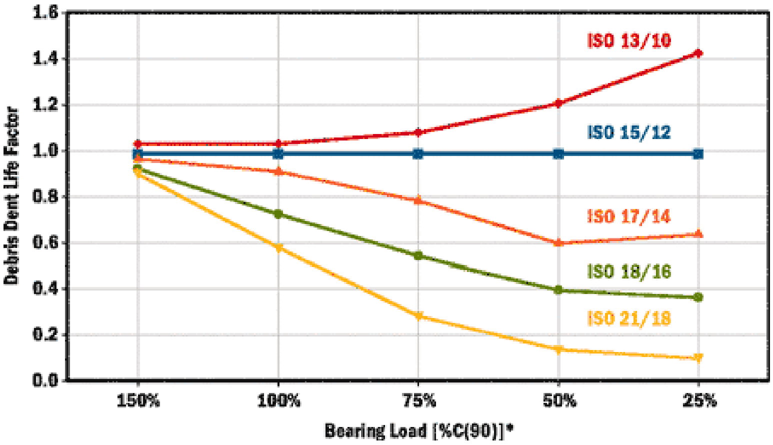

Figure 8. Debris Life Adjustment as a function of load and various ISO 4406:87 Codes for 5 and 15 µm particle size (see Ch. 8 for explanation) [9].

Hardness

With respect to particle content and size; it is also important to consider the hardness. Larger soft particles can be accommodated in the oil film without resulting in surface contact plastic deformation, although very big, soft particles of 50-100 μm size can cause permanent indentation on the surface [8].

Friction and temperature

Shear stress in the EHL contact can also be interpreted as friction i.e. lower shear stress means lower friction. A clean lubricant has a limited shear stress value; a limit where the shear forces overcome the compressed fluid shear resistance. Contact shear stress can be modified by particles in the oil i.e. shear forces are transferred to opposite surface by particles instead of by the shear of oil. This can be one of the reasons why temperature decreases have been seen after high performance filters have been installed i.e. contact shear stresses are modified. It will require more energy to roll over particles compared to a perfectly smooth surface.

A lower temperature leads to decrease of the oxidation processes and extends lubricant life (Arrhenius reaction rate equation). It is not only the bulk oil temperature that affects the oil. The EHD contact temperature is high which together with high pressure activates specific additives protecting the surfaces (anti-wear and extreme pressure additives, AW- and EP-additives). The additive activation can be disturbed by particles causing uneven pressure and temperatures with a following risk of reducing effective lubrication and additive function.

Additives

Several additive types have high polarity which means that they are attracted to material surfaces. If the oil has a high content of particles there is a risk of competition between the surfaces and the particles to attract additives. The consequence of this can be reduced additive function. Metals like iron and copper are also known to act as catalysts in chemical processes, of which the oil oxidation is the most important.

4.2 Water

Water is perhaps the most complex contamination in oil. Water in oil includes various states of coexistence with the oil and chemical and physical effects and transformations during service. Water content will directly affect bearing life (Figure 9), where an increase from 100 to 300 ppm water will reduce the bearing life with a factor of 2. Note that the effect of reducing water content below 100 ppm is not included in Figure 9. The level of how much water can be allowed in oil varies between different lubricant base oils. In Appendix A a compilation written by Fitch [14] regarding water enlightens the complexity more.

Water can lead to a reduction of the viscosity and in the high pressure EHL contacts it will not increase and stay in the contact the way oil does. There is a high risk of poor lubrication. Water can also cause emulsions and thereby increase the oil viscosity dramatically.

Free water in oil can act as a particle when small water drops are surrounded by oil in the contact. Consider all chemical effects related to water [14] in combination with high local energy boosting the processes. Free water in oil can easily cause the component life to be reduced by a factor of 100.

Oil can contain more soluble water at higher temperatures (higher saturation point) and it is important to consider the conditions in wind power. The gearbox can have standstill for a long time which will reduce the temperature. A potential consequence of this is that free water separates from the oil depending on the water concentration during in-service operation. Warm moisture air will circulate within the gearbox and condense on cold surfaces. These surfaces can now be exposed to high water content.

Water is a natural accelerator of oil oxidation. High water content in combination with metals such as copper will increase the oxidation rate by several times [15].

Considering water content it is preferred to keep the content as low as possible. Acceptable levels must be evaluated for different types of oil. Note that water content in the oil will have seasonal variations where winter is a dryer period.

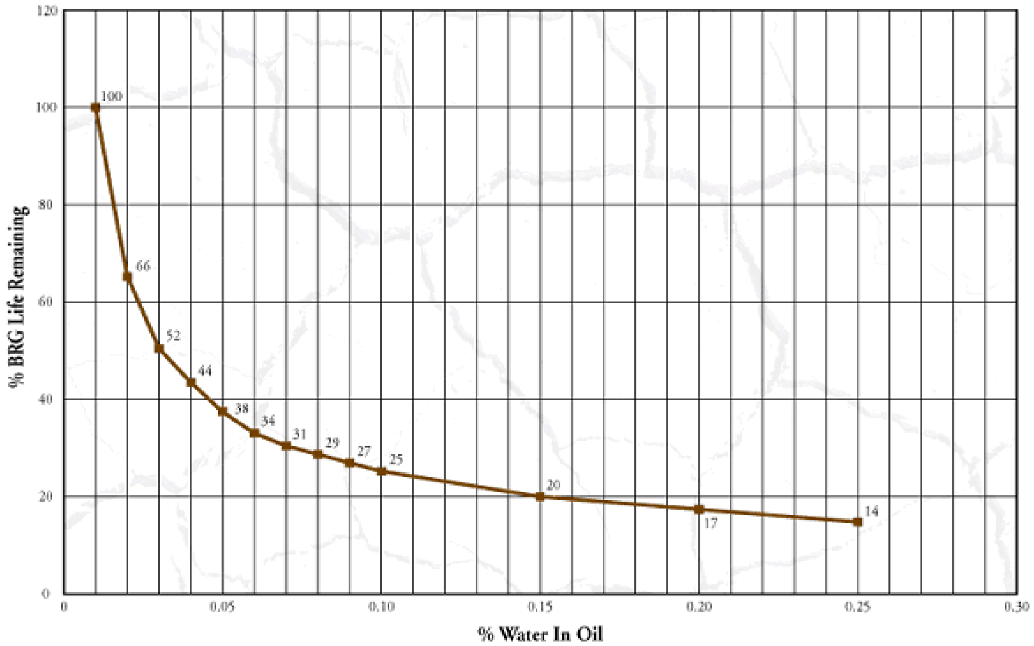

FIGURE 2. WATER CONTAMINATION VS. BEARING LIFE

Figure 9. Water contamination vs. bearing life [16].

4.3 Gases

Air contamination can have negative effects on the machine and the lubricant [17]. Air can damage lubricating oil by increasing the rate of oxidation and thermal degradation, depleting additives, reducing its heat transfer coefficient and reducing its film strength. Oil can oxidize when its molecules come into contact with oxygen. This problem is exasperated when the bubbles move into high-pressure environments where the volume change causes a drastic temperature increase. The process, sometimes called microdieseling, causes thermal degradation of the oil as well.

Machine wear can be generated by air contamination by several mechanisms. Air is readily compressible compared to oil. In order for the oil to create the appropriate lubricating film thickness, it must be more incompressible. When the oil is heavily contaminated with entrained air, its film strength can be reduced to the point where the film breaks down, allowing mechanical friction between interacting surfaces. Depending upon the type of machine, this effect could be rapid.

In machine environments where dramatic pressure changes occur, such as a hydraulic pump, the dramatic and instantaneous volumetric change causes bubbles to implode violently, which leads to erosion of machine surfaces. In hydraulics, entrained air can create other problems as well, such as spongy operations, loss of control and an increased likelihood of surface deposits in valves.

In wind power gearboxes the oil generally has high air content due to the high oil circulation and viscous oil with rather slow air release properties. The resident time in the oil sump is generally insufficient to allow the entrained air to escape from the oil. During the air release, foam may forms. Foam is seldom a root cause for failure if the foam does not fill up a volume space (hard foam) and inhibit oil from lubricating contact surfaces. To the uninitiated, foam causes a visual effect of something bad, but in most cases it is the air/gas in the oil causing the component deterioration.

Gas content can be affected by other contamination such as water or possibly too much or too little anti foam additives. Cleaner oil decreases the gas content.

4.4 Run-in

The running in process is very important. During the run in of the components the surface material becomes hardened by the plastic deformation caused by the EHL contact pressure. If the initial hardening process is disturbed by particles causing surface indentations this will cause exaggerated sub-surface stresses and stress gradients and significantly lower the life of the component. There is no benefit of using oil filtration if cleanliness was unacceptable during run-in i.e. poor run-in cleanliness cannot be adjusted by replacing the oil or fitting finer filters afterwards [13].

A figure of time that is mentioned as critical for surface indentations during run-in is the first half hour of running [13]. The bearing surfaces will be more resistant to particle contamination after the run-in. There is no standard in wind power today describing a good running in process [18] but run-in procedures are applied by several gearbox manufacturers.

5 Filter types

There are several different filter types using different technology that can clean oil. This compilation provides a brief introduction to some of the different types and main performance properties. The efficiency of a certain filter depends on both technique and design. Some filters can combine a number of different techniques.

Conventional filters

Conventional filters can be made in several materials: paper, cellulose, fibre glass and metals. Some materials can absorb water. The fluid flows through the material mostly arranged as a grid not allowing particles of a certain size to pass. Mechanical, adsorptive and absorptive function can be used for removal of contamination. Often a β_x–value notes the filter performance by the number of particles larger than a certain size x (μm) entering the filter divided by the number leaving it. The filter performance is tested in a multi-pass test (ISO 16889). Cleanliness using these types of filter will include discussions of filter flow, higher flow - higher cleanliness. Filter efficiency, E is:

$$E = \frac{\beta_x - 1}{\beta_x} * 100 \ (\%)$$

Fine or sub-micron filters

Sub micron filter (deep filter) differs from the conventional filters due to the ability to capture particles smaller than about 1 μm, which can be the case for a β_3 -200 filter. These can be manufactured from several materials. Most common is cellulose, but other materials are also used. These can be similar to conventional filters but can also be designed differently. For instance flow can be through a fine fibre structure or along the fibres. As for conventional filters; mechanical, adsorptive and absorptive function is seen. Sub micron filters are not always classified in patch test for a β-value. The filter systems are normally a total unit including pump and valves for controlled flow or pressure. Compared to conventional filters discussions regarding the sub micron filters are more about contamination capacity (in weight) and cleanliness according to gravimetric definition and not only the ISO 4406 standard. Normally these types have higher contamination capacity and water removal capacity than conventional filters and a system cleaning effects from varnish for long term use might be found.

Electrostatic filters

Electro static filter uses high voltage potential surfaces where the oil can flow through and polar particles will be attracted to the surfaces. The majority of contamination particles can be captured as well as oil oxidation products and during long term use also accomplishes a varnish removal effect from system surfaces. The electrostatic filter suppliers have a similar type of recommendation for cleanliness definition as sub-micron filter suppliers have.

Electrostatic filters are more commonly used in hydraulic systems compared to gearboxes. Water cannot be removed. Electrical static phenomena for discharge of sparks in oil can occur in several types of filters; however this does not happen with electro static filters.

Cyclone filters
Cyclone filters uses centrifugal force to separate more dense particles from the fluid. Even free water can be removed depending on the properties of the lubricant. This type of filter is not common in wind power gearboxes. The potential of this filter with respect to cost, maintenance and performance is not known.

Air breathers
A good quality breather with a 1 µm filter will remove a large percentage of the airborne particles. In fact, a standard spin-on filter will perform effectively as a breather (Figure 10). If in a moist environment, then the use of desiccating breathers is recommended [19].

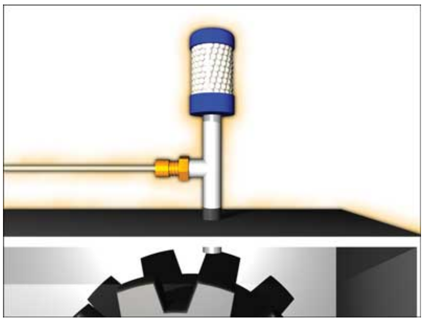

Figure 10. Spin-On filter [19].

6 Filter system layout

System layout using different filters can be arranged in a few different ways with in-line filters and off line filters. Figure 11 shows in-line, on-line and off-line position examples and filter scheme. It is a common knowledge that a combination of in-line filters and off-line filters is the most effective means of achieving cleaner oil.

In-line filter

The whole lubricant flow passes the in-line filters before entering the gearbox at different positions (bearings and gears). The main filter task is to make sure that larger particles are stopped before entering the EHL contact. The in-line filter is often selected to 10, 20 or 30 µm size capable of high flow. A better filter type will result in both safer gearbox and overall cleaner oil, but pore size less than 10 µm is normally not feasible due to unacceptable pressure drop across the filter. Conventional filters are preferred but the β-values will seldom or never be as good as promised due to the harsh environment with air, vibrations and flow changes.

Off-line filter

Gearboxes often have a small oil flow passing through an off-line filter for achieving better cleanliness than the in-line filters alone are capable of. The off-line filter system can be optimized for the gearbox and oil, resulting in very clean oil. Temperature, pressure and flow are normally quite stable giving rather good filter function. There are several filter types to select from. 3 µm filter with β-value of 200 is a common standard today. The off-line filters available can also be of a type that does not specify their β-values but can still achieve good cleanliness.

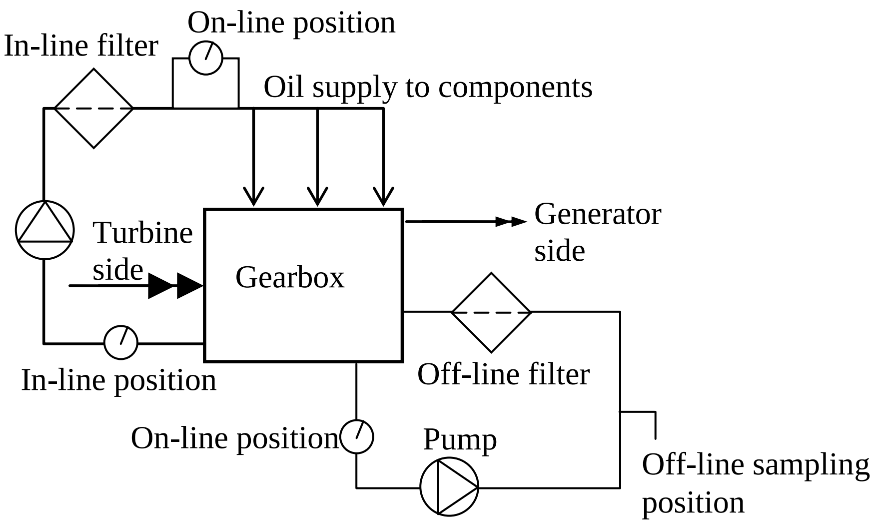

Figure 11. In-line, on-line and off-line position examples and filter scheme.

7 Methods for real time particle counting

There are basically two different objectives for on-line counting of particle content to get real time values; to control the status of the oil cleanliness and gearbox condition. These factors are often co-dependent.

Oil cleanliness

There are several particle counters for oil cleanliness control available on the market. Monitoring wind power gearbox oil conditions during running can be a challenge for cleanliness sensors to show correct results due to the harsh environment; foremost air content in oil and also properties for additives. For particle content in the oil it is common to use an automatic particle counter (APC, Figure 12) sensor configured to quantify them according to ISO 4406:99. The challenge here is to not count the air bubbles in the oil. There are a few sensors on the market which can cope with this. The sensor can be placed on-line in parallel to the in-line oil supply flow or off-line. An APC ISO 4406:99 sensor is normally not an early detection sensor, but can still indicate faults with increasing levels. These types of sensors are effective tools when running in a gearbox and for investigating filter performance vs. the contaminant production.

Gearbox condition monitoring

Oil particle counting can be used for monitoring gearbox status (condition monitoring). Large hard particles are likely to origin from more severe surface damages (see Chapter 2). Light blockage, magnetic technology (Direct Reading ferrography, Particle Quantifier), Fulmer (wear of sensitive film) or image analyse by CCD sensors can be used to detect metals on-line and other large particles. Depending on rated flow, several sensors are capable of detecting particles >50 μm at a decent flow. For an in-line sensor coping with an oil flow of 120 l/min, the limit can be about 100 μm. For flows less than this, the sensors will be capable of detecting particle sizes closer to those required for monitoring oil cleanliness.

Experience of effectiveness and sensor placement

In [18] is a discussion of sensor effectiveness and placement. Sensor effectiveness has demonstrated cost savings due to early damage detection in other more mature industries. Machine owners in wind power tend to rely on CM suppliers and might believe that they will detect all problems in wind power. For instance, CM on oil can only detect damage and not where and if it is critical. Different views on sensor mounting can be met but similar trends in wear debris can be obtained from several positions if the sensor mounting location is appropriate.

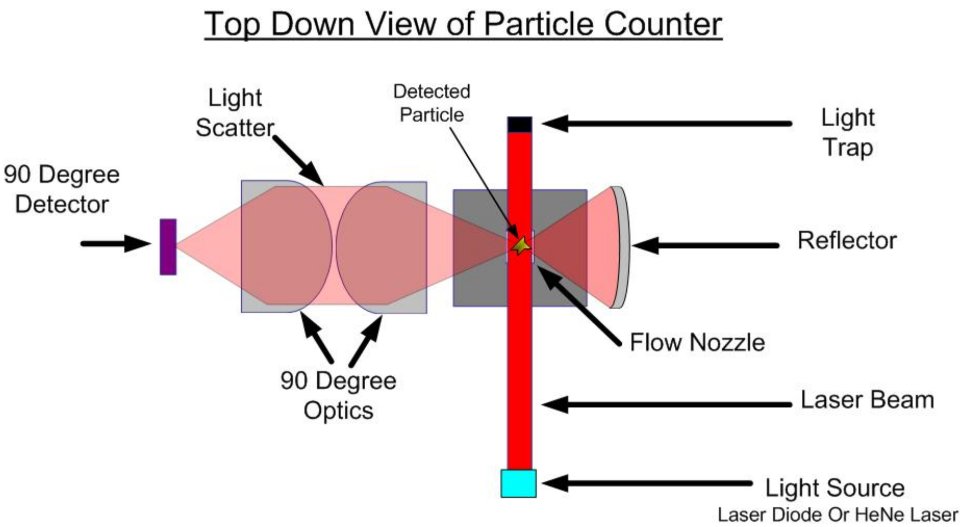

Figure 12. APC (automatic particle counter) with light blockage principle.

8 Particle characterisation according to standard ISO 4406

ISO 4406:99 is the main standard method used today for stating the particle content. Particles are detected and defined in sizes of 4, 6 and 14 μm equivalent diameter size. Cleanliness figures are for example noted: ISO 4406:99: 18/17/11. This means that the oil contains per ml (Table 1):

1,300-2,500 particles larger than 4 μm,
640 – 1,300 particles larger than 6 μm and
10 – 20 particles larger than 14 μm.

Various methods are used for measuring cleanliness of gear oils (optical sensors, filter blockage and microscopy with CCD-systems). The results from the different methods are not directly comparable. Air, solvent, temperature and equipment technology will give a spread of the results as well as lubricant properties and sometimes also oil additives.

Table 1. ISO 4406 codes in Number of particles per ml fluid.

Number of Particles per ml		ISO Code
More Than	Up to & Including	
80,000	160,000	24
40,000	80,000	23
20,000	40,000	22
10,000	20,000	21
5,000	10,000	20
2,500	5,000	19
1,300	2,500	18
640	1,300	17
320	640	16
160	320	15
80	160	14
40	80	13
20	40	12
10	20	11
5	10	10
2.5	5	9
1.3	2.5	8
0.64	1.3	7
0.32	0.64	6
0.16	0.32	5
0.08	0.16	4
0.04	0.08	3
0.02	0.04	2
0.01	0.02	1
0.005	0.01	0
0.0025	0.005	00

The ISO 4406 standard has been revised in 1999 at which time the definition of the size of a given particle was changed from its length to an equivalent area derived from the 2 dimensional area of the particle (Figure 13). This led to optical particle counter re-calibration when the new standard was used [21]. Particle monitors counting according to the old standard (ISO 4406:87) were calibrated according to ISO 4402 standard. For this calibration an AC Fine Test Dust was used. This methodology had a numbers of shortcomings and they were resolved when a new NIST (National Institute of Standards and Technology) calibration product was developed. This product contains very homogeneous spherical particles enabling calibration to be made which reflect the area of the particles. ISO 4402 standard has been replaced by ISO 11171 standard which is the current (mandatory) standard to be used for calibration of optical particle monitors.

Table 2 compares the particles sizes for the old and new method. It should be noted that the ISO 4406:99 standard at 4 μm will count particles down to about 1 μm size according to the former ISO 4406:87 standard. ISO 4406:87 2/5/15 μm is about ISO 4406:99 4.6/6.4/13.6 μm. Considering the particle size compared to the EHL film thickness in gearboxes it is rather large particles that are counted (Figure 1).

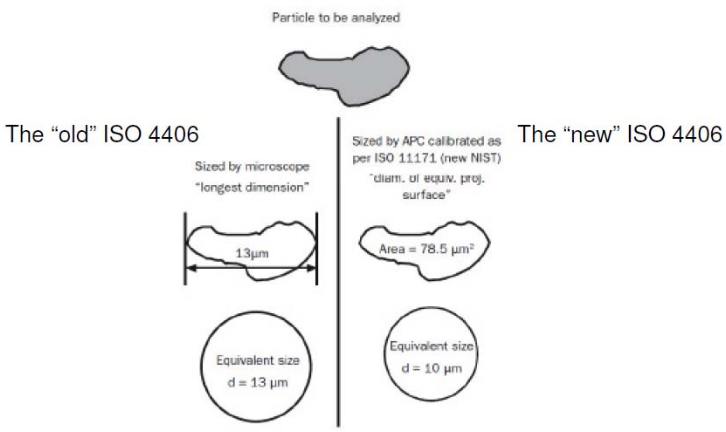

Figure 13. Older ISO 4406:1987 standard compared to the newer ISO 4406:1999 standard for the same particle.

Table 2. Comparison of particle size for older ISO 4406:87 standard vs. ISO 4406:99 standard.

ISO 4406:1987	ISO 4406:1999
Size (μm) according to ISO 4402:1991	Size (μm) according to ISO 11171:1999
<1	***4***
1	4.2
2	4.6
3	5.1
4.3	***6***
5	6.4
7	7.7
10	9.8
15	13.6
15.5	***14***
20	17.5
25	21.2
30	24.9
40	31.7
50	38.2

8.1 Oil sampling

There are several challenges in taking a representative oil sample. Some complicating issues include; the contamination is not visible to the naked eye, oil sample bottles may not be laboratory clean and the location of the sampling point might not be optimal. The oil sampling is in many cases the cause for huge spread in the analyse results. A valve that is not a proper sampling valve might need 100-1000 litre flushing before constant contamination level prevails.

There are a few methods to take oil samples where the first one is preferred [22]:

1 From a suitable sampling valve (see method in Appendix E).

2 From an unspecified valve.

3 Reservoir sampling

4 Bottle dipping

8.2 Alternative contamination definition

Even if ISO 4406-99 standard registers small particles there are methods to define even smaller particles. One such method is gravimetric measurement of fine filters before and after passing of an oil sample (ISO 5885:1987). Common gravimetric test filter grid size is 0.8, 0.45 and 0.22 μm. The result is total mass of contaminants and a visual inspection/photo of the filter sample can complement the result. Although it can be a delicate task to define weight loss for rather clean oils this method can be effective for visual appearance of filter performance as a complement to standard ISO 4406. Filters can be used for optical microscopy studies including ISO 4406:99 standard with automatic image analyse.

Suspected contamination in oil can also be colouring, often brown, grey or black. Black oil can be rather clean according the ISO 4406 definition, but the colour can still be an indicator of system or oil changes. An alternative method (MPC – Membrane Patch Calorimetry) uses the colour of a filter after oil passage to evaluate risk of varnish formation from oxidation products [23]. This technique is more commonly used in turbine or hydraulic oil applications, where the primary focus is on long oil life.

8.3 Particle size distribution in gearbox oil

Investigations on particle size distribution in used oil have shown that the majority of insoluble contaminants are below 5 μm size (according to ISO 11171 definition), in some cases up to almost 90 % weight of total contamination.

The particle size distribution will depend on several things. During the run-in of a gearbox, particles will enter the oil from surfaces being worn in and hardened and remains from the manufacturing process. Larger particles will be milled and crushed in the EHL contacts into smaller and smaller particles. Wear particles after run-in will also go through the same procedure. The hardest remains from the manufacturing materials will not be milled into smaller particles. Good filtration and cleaning procedures will reduce both particle crushing and wear.

Contamination will also be produced during the lubricant and additive oxidation and degradation process producing “soft contaminants”. Surface attraction can lead to coloured layers found within the system. Several adhered oxidation products can lead to formation of larger particles, large enough to be captured by filters or to generally clog filters in high concentration or be seen as thicker layers at some positions. Contamination by oxidation products can increase the particle content found in lab tests; this is sensitive to the used lab method where temperature and solvent affects the result [Appendix B].

9 Laboratory investigation on ISO 4406 particle counting

Purpose
This investigation [Appendix B] was to enlighten some shortcomings or difficulties in the ISO 4406:99 standard particle counting. It will lead to better understanding of the measurements and results in terms of technique, method and solvent used.

Test description
Samples from 8 in-service gear oils from units with in-line and off-line filtering systems in Sweden were collected. All machines were rated over 1 MW. No attention was taken to machine or oil age. The following analyse procedures have been examined:

- Optical measurement (using PAMAS model XX)
  - × Heating the test sample to 60 °C to reduce the viscosity
  - × Diluting the test sample using different solvent and different sample:solvent dilution rates.
- Microscopy (using Olympus microscope with CCD-camera and Olympus SIS-software)
  - × The analysis included the following steps:
    - Filtration of 50 g sample through a 1 µm membrane patch using sufficient solvent (petroleum benzene) to remove all trace of oil from the membrane.
    - Scanning of the filter surface (1150 mm^2) and classification of the particle size according to its equivalent area.

Five different solvents were used and pre-filtered with a 0.45 µm filter. Optical instrument PAMAS accuracy was controlled with a reference oil in heated and two different dilluted states. The reference control result showed acceptable accuracy.

Results
Diluted and no-diluted samples from the same oil gave in one case up to 4 ISO 4406:99 standard codes difference which means a factor of 16 in particle number difference. Different solvents resulted in 0 to 2 ISO code variations. The optical automatic particle counter gave higher counts for smaller particles than the optical microscopy method. The latter uses a 1 µm membrane and depending on particle shape some small particles can pass the membrane. For larger particles one example of opposite results was found. A possible cause of this may be that particles where blocking each other.

Conclusion

By utilising more specific procedures with optical instruments, better absolute values can be obtained using ISO 4406:99 standard. This allows for a more meaningful comparison of results between different laboratories. Note that changes in the procedures used can disrupt the relative follow up from historical values. The most secure values for not counting air bubbles are obtained by counting in microscopy which is one cause why it is considered to give more accurate values compared to the optical measurement. This study has shown that a spread of values can be expected and that the laboratory method and procedure must be reviewed when evaluating oil cleanliness results.

10 Results from off-line filter tests

Off-line filter tests were conducted twice; first in a full scale high speed shaft (HSS) bearing test-rig [Appendix D] and later on in a lab with used gearbox oil [Appendix C].

10.1 Full scale test-rig off-line filter test

Purpose and test procedure
The purpose of the test was to compare two off-line filter performances in a full scale high speed shaft (HSS) bearing test rig under controlled conditions. During the test the off-line filter was the only active filter. The filter was run for six days. The first four 24 hour periods were undertaken without test-rig running. During the following two 24 hour periods the test-rig was operational for three 8 hour shifts. Oil samples were taken prior to off-line filter start and at the end of the test-period. The bottles were flushed twice before each sample was taken.

Test-rig
The test-rig has the following specifications (Figure 14):

Oil volume: 200 litres Mobil SHC 320 XMP.
Oil flow through test bearings during testing: 27 l/min.
Test-rig bearings: Complete HSS bearing setup for a 2 MW gearbox.
Mean oil temperature during testing: ~60°C.
Test-rig performance: Capable of simulating real gearbox conditions: speed, load, oil flow and temperature.
Tested filters: CJC HDU 15/25 PV (insert GV 1525) and Europafilter.
Contamination monitoring: On-line ISO 4406:99 oil cleanliness sensor.

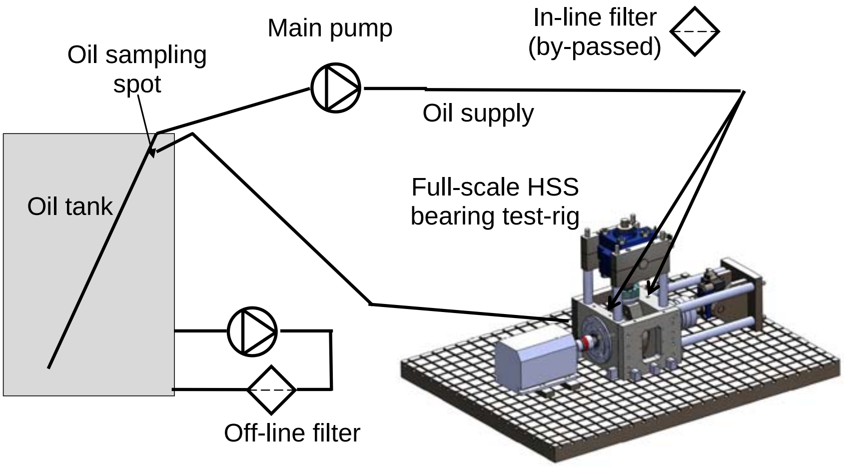

Figure 14. Off-line filter test setup principles in HSS test-rig.

Results

The results showed that the CJC filter cleaned the oil from ISO 4406:99 class 20/17/12 down to 14/12-13/8-10 measured by the on-line sensor (Figure 15). Corresponding values from laboratory analyses using automatic optical microscopy image analyse on 0.22 μm filter showed starting values at 16/14/12 and at the end 13/13/11.

For Europafilter the cleanliness of the oil changed from ISO 4406:99 class 22/18/13 down to 16-17/14-13/10 measured by the on-line sensor (Figure 16). Laboratory microscopy results showed 18/17/14 and at the end 14/14/11.

Gravimetric tests (according to ISO 5885, dubble membrane method) were performed but showed inconsistent results in terms of contamination weight loss during the off-line filter tests (Figure 17). Photographs of the gravimetric filters indicated a shiny plastic like layer, but the layer composition has not been confirmed. See Appendix D for microscopy photographs of the filters at high magnification.

Comparing the two filters showed that CJC filter had a higher flow and the total oil volume that passed the filter was about 35 times the system oil volume. Corresponding value for Europafilter was about 1200 litres or 6 times the oil volume. Higher flow normally leads to faster steady state for cleanliness values and can also affect the steady state cleanliness depending on contamination production.

Conclusions

The off-line filters had not reached steady state in terms of contamination production and filter contamination removal. The test indicates that the CJC filter was closer to establish steady state compared to the Europafilter. Off-line tests require time for getting reliable results, especially when contamination is produced in the system. The test time was clearly too short for the Europafilter, not reaching steady cleanliness, or that the filter capacity was too low for the test-time. The Europafilter start level of oil contamination was higher than that for the CJC filter which reduces the comparison value when steady state was not reached. The contamination level difference was caused by test-rig oil leakage, minor oil volume change and test-rig running.

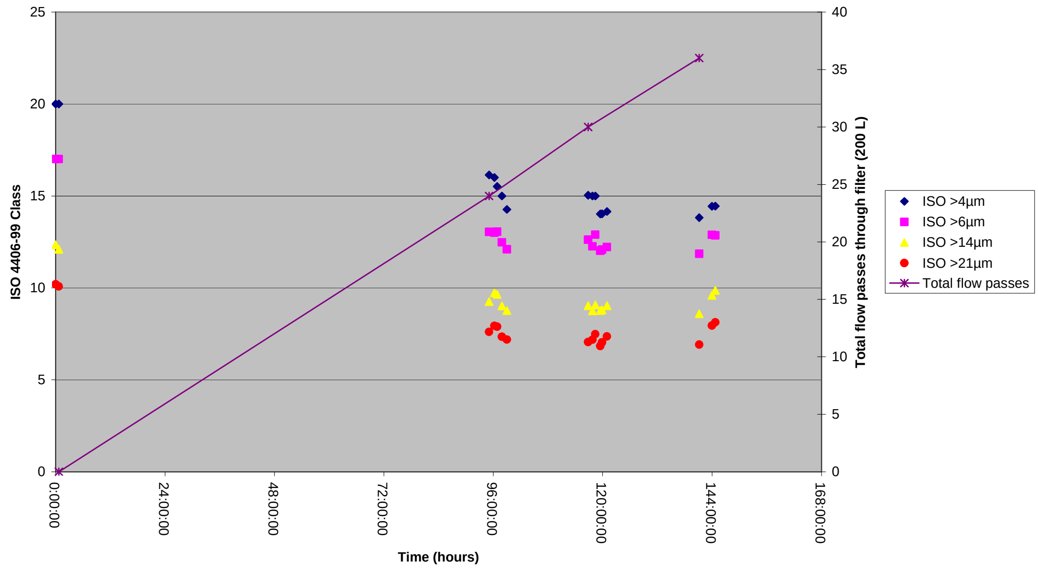

Figure 15. ISO 4406-99 on-line counting results for CJC.

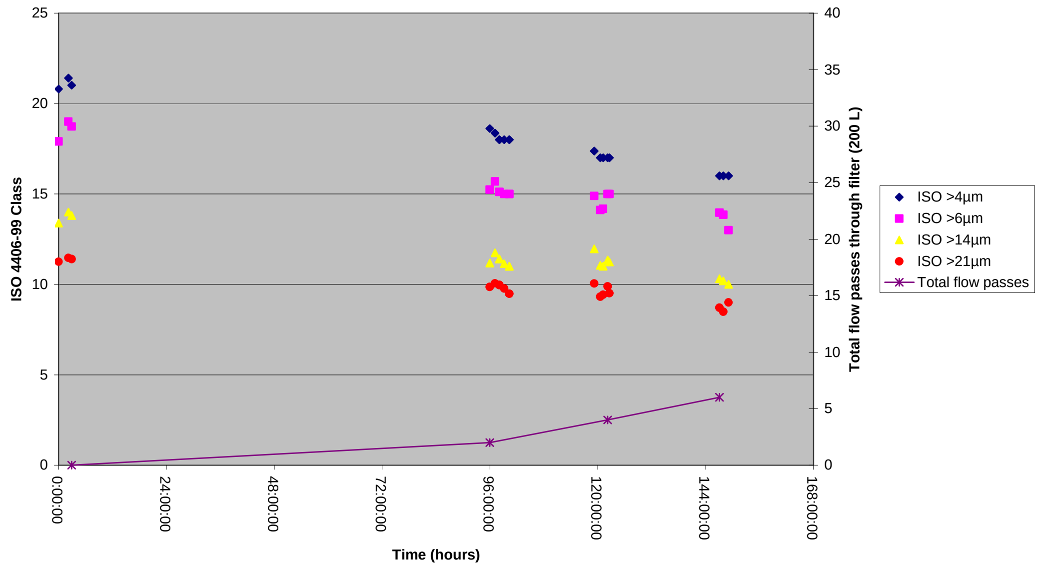

Figure 16. ISO 4406-99 on-line counting results for Europafilter.

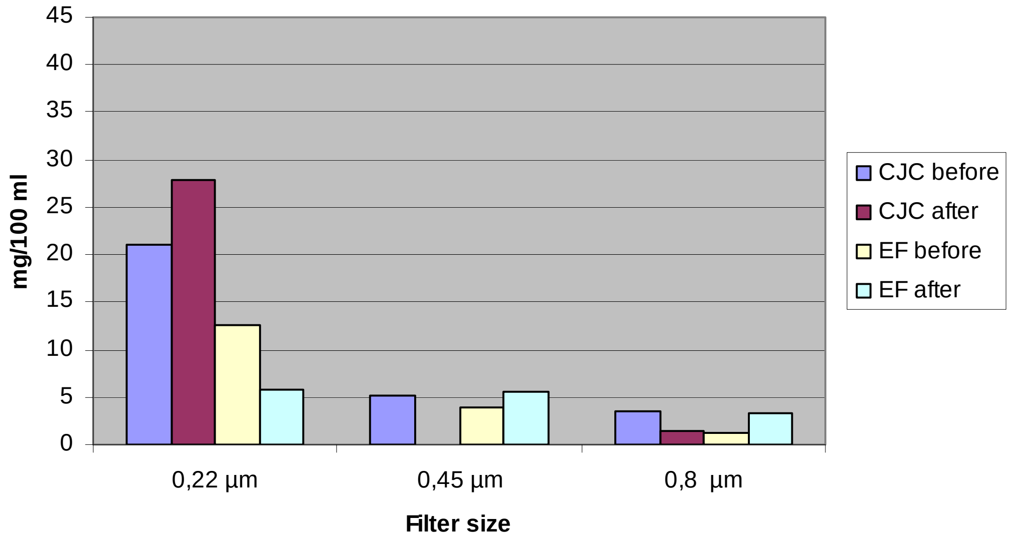

Figure 17. Gravimetric results from oil samples before and after (at the end of) off-line filter test. Double filtration method was used, upper filter minus lower filter weight difference. The results are inconsistent.

Figure 18. Plastic like shiny layer formed on gravimetric filters.

10.2 Filter test with used gearbox oil

Purpose
This test was initiated due to the fact that the full scale test rig filter test was not producing results from which clear conclusions could be drawn. Filter performance of identical filters were tested again (see Chapter 10.1 and the test setup in Appendix C).

General description

The tested oil was a Mobil SHC 320XMP which has been in use for 12,458 hours in a 2MW turbine located in south of Sweden. The oil was taken out 2012-03-15. The accumulated production since the previous oil change was 8,598 MWh. The gearbox was under investigation for damage.

The oil was put into 50 kg barrels (oil volume about 50 litres) and heated to about 60°C (Figure 19). Initial oil samples were taken after filling the barrels and before reaching 60°C. Oil filtration was started and oil samples was taken at different times throughout the test. The CJC filter test was run twice due to the significant start value for APC ISO 4406:99 particle counts. A new filter insert was installed for all tests. All results from the tests are presented here.

APC (model PAMAS SBSS-C) with ISO 4406:99 standard was used to investigate the particle content. The identical procedure was used to improve the relative counting value accuracy. The oils were diluted 50/50 with one solvent. Gravimetric tests were conducted using 0.8 and 0.45 μm filter pore size. Filters were cleaned and weighed before and after filtering of 100 ml oil. The oil was not diluted prior to filtering.

ICP (inductive coupled plasma) test before and after the tests indicated no filter affect on additive content (Fe, Na, P, Si, Zn).

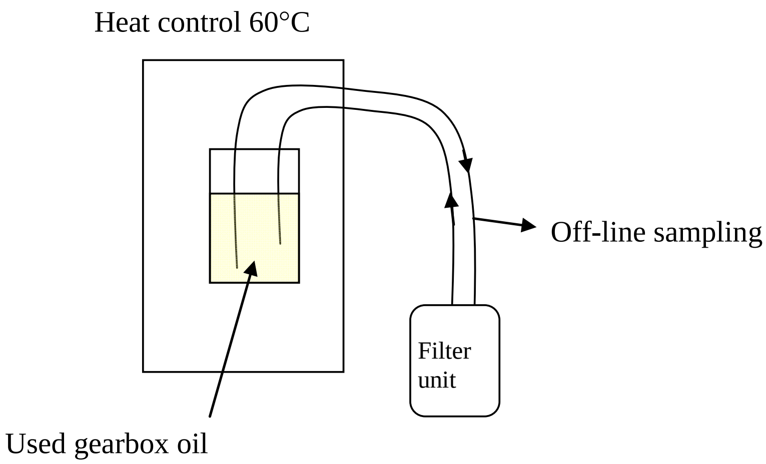

Figure 19. Principle for off-line filter test with used gearbox oil.

Results

The test [Appendix C] indicated that the CJC filter has a higher flow and will quicker reach steady state compared to the Europafilter (Figure 20-Figure 22 and Table 3). The particle content for the Europafilter was lowest for the last sample. Both the CJC test runs showed a less counted particles in the samples prior to the last sample. The flow for the CJC filter tests were totally about 7,000 litres during 70 hours. The total flow for the Europafilter test was about 940 litres during 117 hours.

Gravimetric tests were conducted for 0.8 and 0.45 μm filter pore size. The filters weight showed weight loss for Europafilter between sample S0 and S5. Sample S6* could not be guaranteed from contamination and also showed a weight gain. For CJC filter test samples the gravimetric filter weights was inconsistent showing both weight losses and gains. Gravimetric filters showed more colour change before compared to after Europafilter and CJC oil filtration (Figure 24-Figure 25). This gravimetric filter colour change indicated removal of substances or particles that colours the filter.

Conclusion

The filter tests showed a decreasing particle content according to standard ISO 4409:99 using the APC. The CJC filter showed faster particle content decrease but more inconsistent trends compared to Europafilter. The Gravimetric test results showed colour changes indicating that the oil filters had cleaning function but the gravimetric filter weight changes were not consistent.

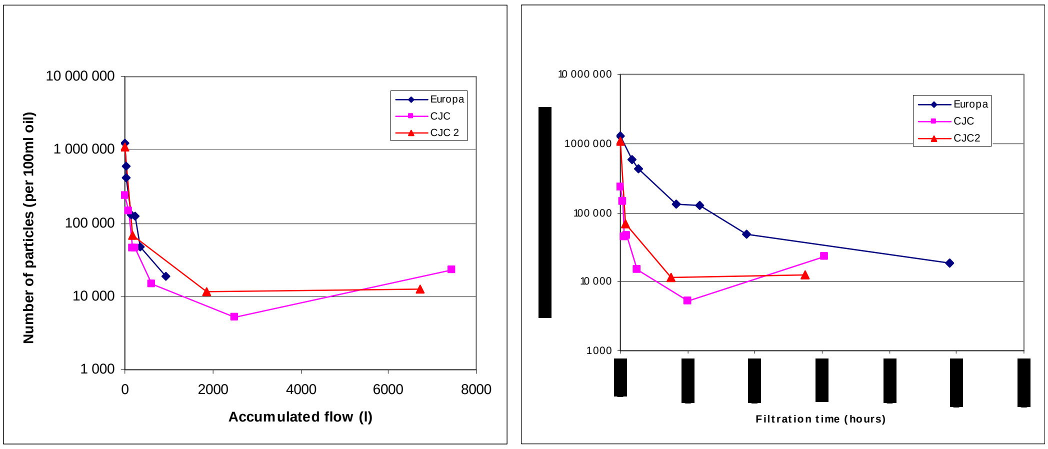

Figure 20. Europafilter vs. CJC ISO 4406-99 particles size 4 μm and larger.

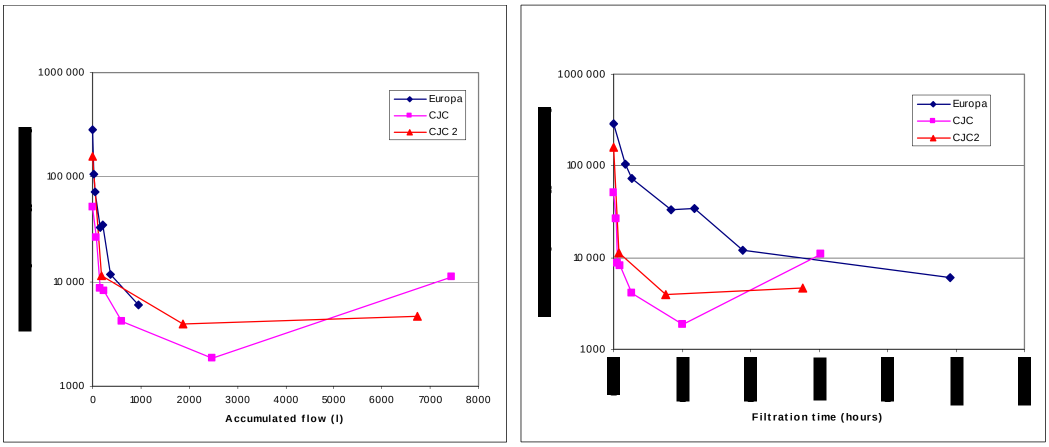

Figure 21. Europafilter vs. CJC ISO 4406-99 particles size 6 μm and larger.

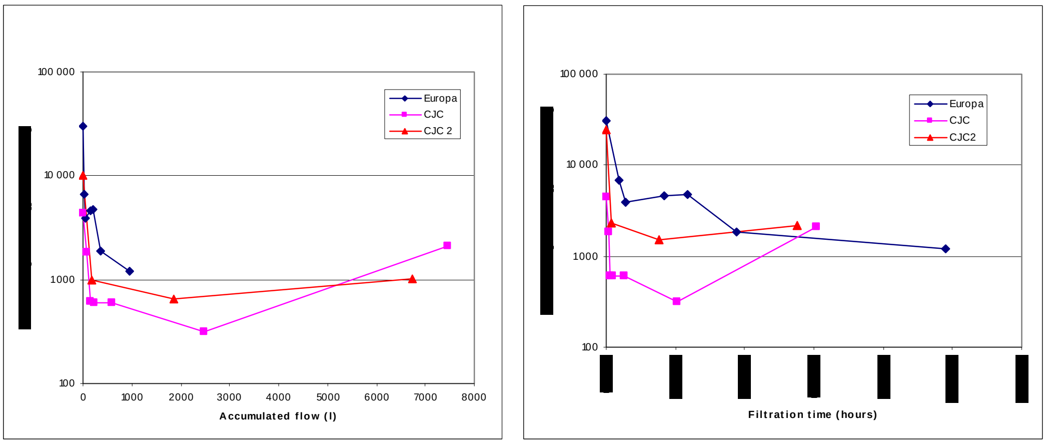

Figure 22. Europafilter vs. CJC ISO 4406-99 particles size 14 μm and larger.

Table 3. Europafilter and CJC ISO 4406-99 codes, sample time and flow.

Test time (hours) EF	Acc. flow (l) EF	ISO 4406:99 EF	Test time (hours) CJC	Acc. flow (l) CJC	ISO 4406:99 CJC	Test time (hours) CJC2	Acc. flow (l) CJC2	ISO 4406:99 CJC2
S0. 0:00	0	20/18/14	S0. 0:00	0	18/16/13	S0. 0:00	0	21/18/14
			S1. 0:45	80	17/15/11			
			S2. 1:33	160	16/14/10	S1. 1:45	177	17/14/10
S1. 4:16	22	19/16/12	S3. 2:21	242	16/14/10			
S2. 6:34	41	18/16/11	S4. 6:11	600	14/13/10			
S3. 19:58	152	17/15/12				S2. 18:07	1867	14/12/10
S4. 28:08	219	16/15/12	S5. 24:23	2490	13/11/9			
S5. 45:08	361	15/13/10	S6. 72:49	7450	15/14/12	S3. 66:10	6730	14/13/11
S6. 117:43	943	14/12/10						

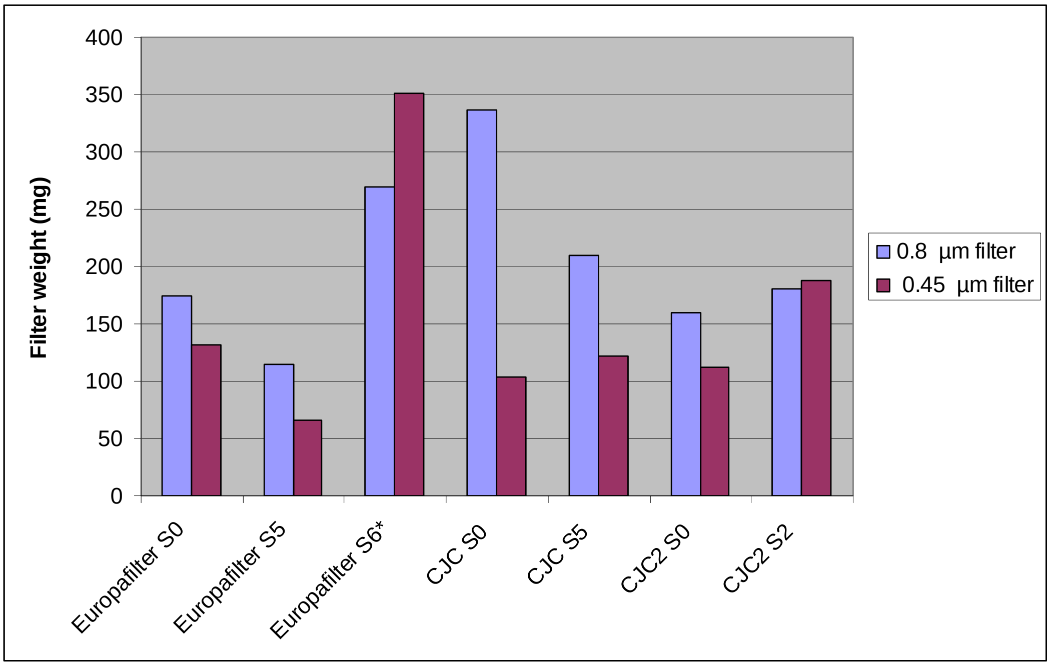

Figure 23. Gravimetric test filter weight for 0.8 and 0.45 µm filter pore size, for Europafilter S6* the sample cleanliness for this test was uncertain.

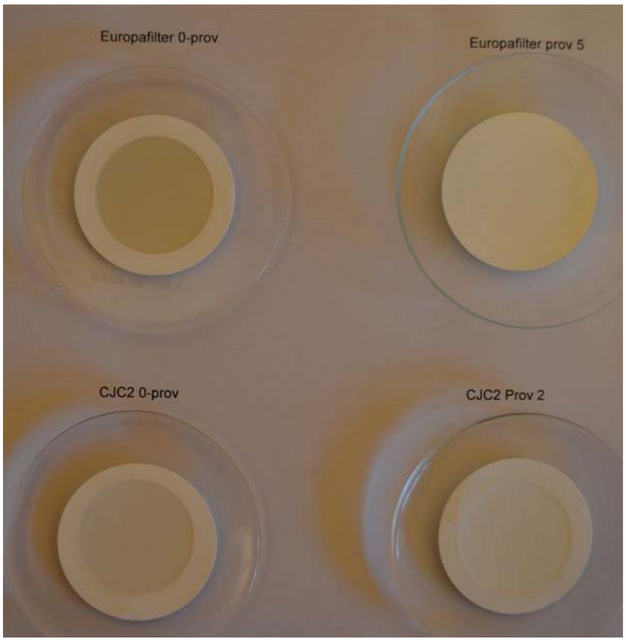

Figure 24. Gravimetric filters 0.8 μm; upper left Europafilter S0 and upper right Europafilter S5, lower left CJC2 S0 and lower right CJC2 S2.

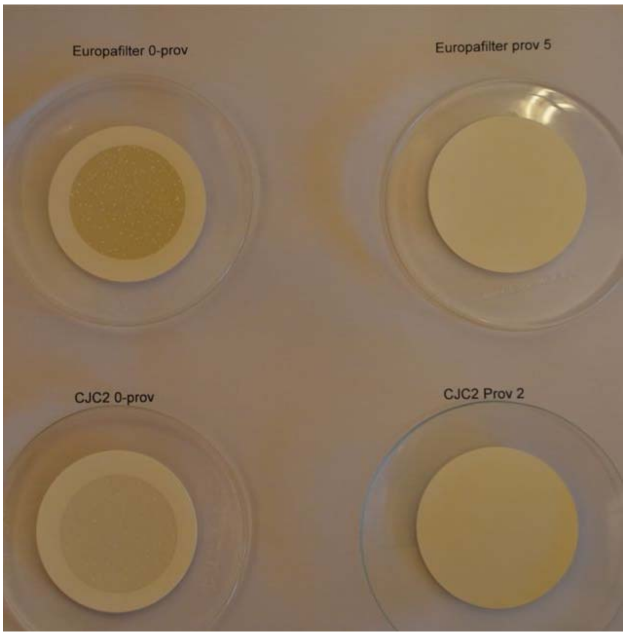

Figure 25. Gravimetric filters 0.45 μm; upper left Europafilter S0 and upper right Europafilter S5, lower left CJC2 S0 and lower right CJC2 S2.

11 Additional oil cleanliness examples

During this work a number of observations and experiences regarding oil cleanliness have arisen.

Real application oil cleanliness
Experience from lab analyses has shown that combined in- and off-line filter systems are able to generate good oil cleanliness when the systems are properly designed together with air breathing filters. One such example is from a large Vattenfall operated off-shore wind farm, where general oil cleanliness is between ISO 4406 code 16/14/11 and 13/12/9. This is better than maximal ISO 4406:99 code 18/16/13 recommended during service [20] Examples of exceptions can show values around ISO 4406 code 23/23/10 and can possibly be explained by sampling contamination and analyse method (see Ch 9). Other but similar wind farms of identical machines have shown values of ISO 4406:99 codes 17/15/12 to 14/12/10 using secured analyse. The examples above are using 10 μm in-line filters and β_3 200 off-line filters.

Oil cleanliness seen in full scale HSS test-rig
During the testing in the HSS test-rig a few different experiences regarding oil cleanliness were noted. When the filter insert was accidently not mounted during the initial commissioning, the cleanliness values was worrying (Table 4). Employing an in-line Hydac β_3 – 200 full flow (without off-line filter) in the test-rig showed cleanliness values down to 9/6/0 on the on-line sensor (Figure 14). More normal values were 10/7/4 and higher values 12/10/8 during testing. The filter flow was about 27 litres per minute. The conditions for the in-line filter are good when compared to the prevailing conditions in an operational gearbox. As earlier written (Ch 10.1) the off-line filters alone didn't manage to match the in-line filter cleanliness values.

Table 4. Examples of oil cleanliness with different filter systems.

Filter type	Application	Flow (l/min)	Typical ISO 4406:99 code
No filter	Full scale test-rig	27	22/19/14*
Off-line	Full scale test-rig	0.1-1.5	14/12/10*
In-line 3 μm	Full scale test-rig	27	14/12/10* - 9/6/0

* Limited running time, possibly not final values

Continuous particle counting for condition monitoring
Combinations of optical and metal sensors are available, in a Vattenfall machine and very early results for samples collected in an off-line position indicate similar particle counting values to those obtained in the laboratory for particles > 40 μm in an oil sample.

12 Acceptable cleanliness and procedures to obtain it

Oil cleanliness never exceeding the recommended values can in practice be difficult to achieve, but it is definitely possible. Here are some simple discussions describing aspects of the system that should be considered. In [20] suitable oil cleanliness values are identified for a number of different stages of the machines life (Table 5).

Table 5. Required oil clenaliness for wind turbine gearboxes [20].

Source of Oil Sample	Required Cleanliness per ISO 4406:99
From new oil before adding to gearbox	16/14/11
From gearbox after factory testing	17/15/12
From gearbox during service	18/16/13

Filtration
Filtration is the most important process for getting clean oil. It can be a difficult job to evaluate filter performance when studying specifications from material available from manufacturers. Every supplier will present the performance of their product in such a way to show that it is superior to the competition. If possible, setup a test that will guide you. Remember to chose filters and filter systems for both good gearbox life and lubricant life. Filtration system including 10 μm in-line filters and 3 μm off-line filters might be good enough? It is the cleanliness that is important, not the filter specification.

Maintenance of filters
In order to keep the oil clean during long term machine operation it is important to adjust service for filter performance or adjust filter performance for service. The oil cleanliness level will be the guide to verify the success in that work. Experience from filter suppliers is often a start that eventually will lead to a suitable goal. One minimum requirement during operation is shown in Table 5.

Re-establish cleanliness
Re-establish cleanliness after service by running the oil though the off-line filter system before starting up the machine again. Service or repairs will contaminate the gearbox, less if you are careful and more otherwise. In some cases the off-line filter system is supposed to run for 48 hours before starting up. Extra filtering capacity is one means of reducing that time before starting up. Sometimes devices include particle counters. An oil change will hopefully bring fresh and good oil into the gearbox but new oil is seldom really clean. Filling the gearbox through the off-line filter system can be a process of several hours (Figure 26), but this can still reduce the time until start up. Special oil fill filters can also be used. Pre-filtering of the oil can assure clean oil, arrangements can be setup for reducing the time for getting clean oil (Figure 27). A long time between oil fill and start-up will increase gravity

effect to separate more dense particles to sink towards the bottom of the oil. Where possible, the use of clean spare parts such as hoses and bearings will enhance cleanliness.

Please note that a bearing change means that the bearing should be run-in properly. Good oil cleanliness is one key here to accomplish long EHL component life.

Air ventilation filters
Air ventilation filters or breathers are also important to control the cleanliness. In and outgoing air affects the cleanliness in terms of particles and water content. There are air filters for controlling both. The air filters control one source of contamination entering the gearbox and it is generally 10 times more expensive to remove a particle compared to preventing it from entering the oil [19]. In most cases, upgrading the vent to a proper contaminant-exclusion breather should minimize the ingestion of hard particles and moisture.

A short guide:

- Use good filters for in-line (high flow catching of larger particles) and off line (removing small particles, water and oxidation products).
- Dimension the filter system for the gearbox in terms of flow, oil type and other requirements such as filter change interval, total cost and finally oil cleanliness and its stability over time.
- Make sure that the off-line filter has a good power supply and secure that it is never shut down. Try to arrange an installation for a low vibration environment.
- Setup careful procedures for oil change, filter change, oil test, and component change. An EHL lubricated component change (bearing, geared shaft) will have a run-in stage when the gearbox is running again during which the cleanliness affects life significantly.
- Fill up with clean oil and use filters when filling the gearbox. Get the oil to a sufficiently clean level before start up. The cleanliness of the oil should be validated according to the requirements of the given application.
- Use good air ventilation filters for both moisture and particles. It is far more expensive to remove contamination compared to adding them.

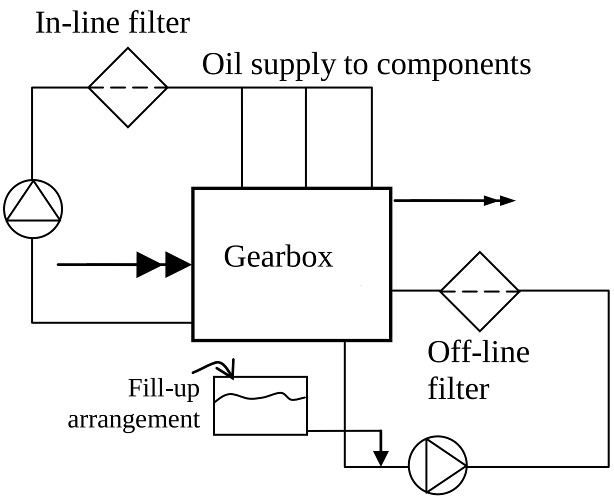

Figure 26. Oil fill-up through off-line filter system.

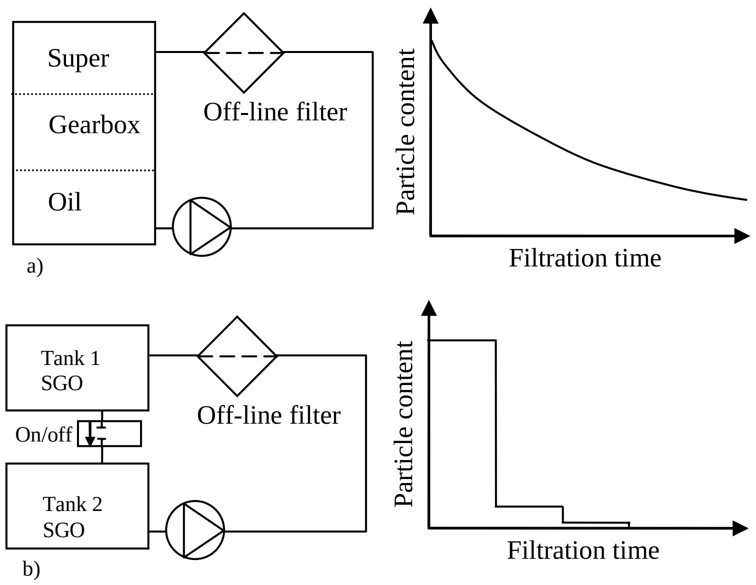

Figure 27. Pre-filtering of oil before filling; a) costant filtering and b) filter from tank to tank.

13 Conclusions

Optimal oil cleanliness and how to obtain it must be evaluated by the machine owner. This study recommends how to set a cleanliness goal and to how to perform real application tests and follow ups.

Oil cleanliness is important in wind power gearboxes. For well designed, manufactured and well run-in gearboxes good cleanliness will make a significant difference in terms of long gearbox and lubricant life. The machine life can be affected by a factor of approximately three, or ±50 % from estimated life.

Almost all particles counted according to the most common ISO 4406:99 standard are larger than the EHL contact oil film thickness. Depending on particle properties (size, hardness, shape) these will affect the lubrication contact conditions and lubricant and in the end component life. Water and gases in the oil also should be seen as contamination. Low concentrations of water can significantly reduce life. However, the effect is lubricant type dependent. Gas content will generate negative long term effects.

Filter development is constantly improving and top-of-the-line off-line filters performance is capable of removing particles almost equally sized or as small as lubricating contact film thickness. This will give longer gearbox life and, longer lubricant life.

This study contributes to method accuracy for defining particles according ISO 4406:99 standard. Different methods give result variations depending on the method and solvent used. For some oils this results in significantly exaggerated particle content. The most reliable method for larger particles is to use filtering and microscopy counting. Using the same specified method improves relative comparison and follow up gearbox oil cleanliness. For smaller particles gravimetric filter analyse is a complementing alternative, but a delicate test for the laboratory to perform, especially with viscous gearbox oils that can have difficulties passing the fine filters without solvent dilution.

Off-line filter tests shows performance of two different filters that clean the oil significantly. The main differences between them seen in the tests are flow rates and the time to reach steady state cleanliness. Higher flow enables a preferred faster reestablishment of steady state oil cleanliness. The test do not show total contamination removal capacity (in weight) and water removal or long term function. Real gearbox tests are the only way to get reliable answers.

The cleanliness values seen here in real gearboxes using in-line and good off-line filters can provide for long gearbox life when comparing them to official values and modern component life calculations. However, life dependent on cleanliness is only truly significant for components working under conditions where life can be calculated.

14 Discussion

Oil cleanliness is much more than filter β-values for removing a certain size of particles. It is about setting up a system that ensures long term clean oil and that is suitable for service efforts. Cleaner oil will reduce the production of oil contaminations due to less wear, oil oxidation and additive depletion.

The impact on life from oil cleanliness increase in designs where the bearing function is normal and the life theories coincide with the actual experience. The difference between a calculated life of 30 years and “infinite” life is very small. An improvement of oil cleanliness can very well be that difference. In a design where bearings and gears are not fully functioning as expected, the life theories will differ from actual life. Cleaner oil also here makes life longer, but the difference between different oil cleanliness levels will be minor.

No specific products have been pointed out as “the best”. There are several suppliers of filters and condition monitoring equipment for oil who evidently have good products. Perhaps for some suppliers, an adjustment of the characteristics of their products is required before the full potential is seen with respect to wind power gearboxes.

Testing of off-line filters is a low risk activity even in real gearboxes as long as the cleanliness is monitored regularly. The value of real tests is higher compared to lab tests performed here, but screening tests are effectively executed in lab. The primary difficulty lies in evaluating filter performance on really small particles and its subsequent long term effect on gearbox and oil life. The smallest particles are too small to be visually analysed one by one in an optical microscope.

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Appendix A: Water in oil

Selected text from: Jim Fitch, How Water Causes Bearing Failure, Noria Corporation, Machinery Lubrication (7/2008).

Hydrogen-induced Fractures. Often called hydrogen embrittlement or blistering, this failure mode is perhaps more acute and prevalent than most tribologists and bearing manufacturers are aware. The sources of the hydrogen can be water, but also electrolysis and corrosion (aided by water). There is evidence that water is attracted to microscopic fatigue cracks in balls and rollers by capillary forces. Once in contact with the free metal within the fissure, the water breaks down and liberates atomic hydrogen. This causes further crack propagation and fracture. High tensile-strength steels are at greatest risk. Sulfur from additives (extreme pressure (EP), antiwear (AW), etc.), mineral oils and environmental hydrogen sulfide may accelerate the progress of the facture. Risk is posed by both soluble and free water.

Corrosion. Rust requires water. Even soluble water can contribute to rust formation. Water gives acids their greatest corrosive potential. Etched and pitted surfaces from corrosion on bearing raceways and rolling elements disrupt the formation of critical EHL oil films that give bearing lubricants film strength to control contact fatigue and wear. Static etching and fretting are also accelerated by free water.

Oxidation. Many bearings have only a limited volume of lubricant and, therefore, just a scintilla of antioxidant. High temperatures flanked by metal particles and water can consume the antioxidants rapidly and rid the lubricant from the needed oxidative protective environment. The negative consequences of oil oxidation are numerous but include corrosion, sludge, varnish and impaired oil flow.

Additive Depletion. We've mentioned that water aids in the depletion of antioxidants, but it also cripples or diminishes the performance of a host of other additives. These include AW, EP, rust inhibitors, dispersants, detergents and demulsifying agents. Water can hydrolyze some additives, agglomerate others or simply wash them out of the working fluid into puddles on sump floors. Sulfur-phosphorous EP additives in the presence of water can transform into sulfuric and phosphoric acids, increasing an oil's acid number (AN).

Oil Flow Restrictions. Water is highly polar, and as such, has the interesting ability to mop up oil impurities that are also polar (oxides, dead additives, particles, carbon fines and resin, for instance) to form sludge balls and emulsions. These amorphous suspensions can enter critical oil ways, glands and orifices that feed bearings of lubricating oil. When the sludge impedes oil flow, the bearing suffers a starvation condition and failure is imminent. Additionally, filters are short-lived in oil systems loaded with suspended sludge. In subfreezing conditions, free water can form ice crystals which can interfere with oil flow as well.

Aeration and Foam. Water lowers an oil's interfacial tension (IFT), which can cripple its air-handling ability, leading to aeration and foam. It takes only about 1,000 ppm water to turn your bearing sump into a bubble bath. Air can weaken oil films, increase heat, induce oxidation, cause cavitation and interfere with oil flow; all catastrophic to the bearing. Aeration and foam can also incapacitate the effectiveness of oil slingers/flingers, ring oilers and collar oilers.

Impaired Film Strength. Rolling element bearings depend on an oil's viscosity to create a critical clearance under load. If the loads are too great, speeds are too low or the viscosity is too thin, then the fatigue life of the bearing is shortened. When small globules of water are pulled into the load zone the clearance is often lost, resulting in bumping or rubbing of the opposing surfaces (rolling element and raceway). Lubricants normally get stiff under load (referred to as their pressure-viscosity coefficient) which is needed to bear the working load (often greater than 500,000 psi).

However, water's viscosity is only one centistoke and this viscosity remains virtually unchanged, regardless of the load exerted. It is not good at bearing high-pressure loads. This results in collapsed film strength followed by fatigue cracks, pits and spalls. Water can also flash or explode into superheated steam in bearing load zones, which can sharply disrupt oil films and potentially fracture surfaces.

Microbial Contamination. Water is a known promoter of microorganisms such as fungi and bacteria. Over time, these can form thick biomass suspensions that can plug filters and interfere with oil flow. Microbial contamination is also corrosive.

Water Washing. When grease is contaminated with water, it can soften and flow out of the bearing. Water sprays can also wash the grease directly from the bearing, depending on the grease thickener and conditions.

The obvious solution to the water problem is a proactive solution; that is, preventing the intrusion of water into the oil/grease and bearing environment. The only water that doesn't cause harm is the water that doesn't invade your system. Contaminant exclusion tactics are always a wise maintenance investment.

Be a long-term thinker by controlling risk factors today, while the bearing still has remaining useful life (RUL). The cost of removing water and/or remediating the damage it causes will far exceed any investment to exclude it from entry. So please, don't skimp when it comes to "proactive" contamination control.

Appendix B: Particles in gear oils

Hans Møller, Vattenfall A/S, Denmark.

Assessment of cleanliness in gear oil is a very important parameter, and measurement of particulates is included in nearly every in-service oil analysis. However, it is important to realize that the different methods used to establish the cleanliness can give quite different results depending on the properties and composition of the used oil sample.

As mentioned previous in this report analysis of particulates based on optical sensors and microscopy of a filter patch with CCD-systems are the most often used techniques. The optical sensor technique is the far most used method, as this method can be automated and thus be a cost-effective technique.

The optical sensor system uses the concept “one particle counting” thus requiring a narrow capillary to ensure, that only one particle passes the optical path at a time. These laboratory instruments were originally developed for analysis of hydraulic and turbine oils with a viscosity in the range ISO VG 32-46. Gear oils in wind turbines typically have viscosity of ISO VG 320 and to reduce the viscosity of the test sample to be analyzed the fluid is either heated or diluted with various solvents. The end user of the analyse results rarely has any ideas about the specific analyse method used. But it’s important, as the cleanliness levels do depend on the method used and especially if you want to compare results across different laboratories knowledge about the analyse procedure is absolute necessary.

The cleanliness of gear oils from 8 different wind turbines in Sweden have been analyzed to illustrate the potential difference in results when different analyse methods are used. The following analyse procedures have been examined:

- Optical measurement (using PAMAS model XX)
  - Heating the test sample to 60 °C to reduce the viscosity
  - Diluting the test sample using different solvent and different sample:solvent dilution rates.
- Microscopy (using Olympus microscope with CCD-camera and Olympus SIS-software)
  - The analysis included the following steps:
    - Filtration of 50 g sample through a 1 µm membrane patch using sufficient solvent (petroleum benzene) to remove all trace of oil from the membrane.
    - Scanning of the filter surface (1150 mm^2) and classification of the particle size according to its equivalent area.

As solvents we have used polar as well as non-polar solvents comprising N-heptane, 2-propanol mixed with toluene (1:1) and petroleum benzene. The dilution ratio varied from 1:1 to 1:3 (sample:solvent). Not all combination of solvents and dilution rates were tested to reduce the over-all number of analysis. All solvents were filtered through a 0,45 µm membrane filters to insure a very low level of particulates and thus not causing any contamination of the oil samples.

Assessment of the accuracy of the analyse methods

Initially, the accuracy of the PAMAS measurement, both on un-diluted as well as diluted samples, was assessed by analysis of a certified reference fluid with a cleanliness ISO 4406 code of 20/18/14. The follow results were obtained:

- Analysis on heated, un-diluted oil:	ISO 19/18/15
- Analysis on diluted (1:1 with petroleum benzene)	ISO 20/19/14
- Analysis on diluted (1:3 with petroleum benzene)	ISO 20/19/14

All solvents used in this project to dilute the gear oils have been pre-filtered through a 0,45 µm membrane filter to reduce any contaminant. The cleanliness of the solvents was:

- N-Heptane:	ISO 12/10/07
	ISO 10/09/06
	ISO 10/08/04
- Petroleum benzene:	ISO 12/10/04
	ISO 12/09/04
	ISO 12/10/05

The cleanliness of the solvents is fully satisfactory for this comparison of analyse methods.

Type of gear oils

The eight oils used in this project were supplied from various wind turbines in Sweden. They cover different manufactures and type of oils (mineral oils and poly-alpha olefins) and thus - to some extend - are representative for in-service oils in the current fleet of wind turbines.

Six of these oils seemed to be incompatible with the polar solvent consisting of a mixture of 2-Propanol and Toluene. After dilution these samples had a hazy appearance and some of them divided subsequently in separate phases. Thus only two data-set exist with this solvent.

Results & comments

The analyse results expressed as ISO 4406 code numbers and the actual counted particles in the three size classes are summarized in Table 6 and Table 7 respectively. The results (ISO classes) also appear graphically in Figure 28 to Figure 30.

The results of this experiment clearly document that different analyse method for assessment of cleanliness of gear oils can result in quite varying results, especially for the minor particle size classes (i.e. > 4 µm and > 6 µm). The reason for this scatter of data is caused by the fact, that there is no unique definition of "a particle".

Analyse methods based on deflection of light (as the PAMAS) is the most sensitive technique. It will detect all wear particles and eventually external contaminants but also "particles" formed by degradation of the base oil or additives (often referred to as "soft contaminants") might become counted as particles. Entrained air bubbles will also be counted as particles which of cause will lead to a biased result. To reduce presence of air bubbles in the test sample in the measuring cell to minimum different techniques are used (reduction of the pressure in the measuring cell etc). In oils with a very high level of particulates (> 21 ISO classes) there is also the risk that more than one particle passes the measuring point at a time, thus giving rise to a low counting number.

From a user perspective it is very difficult (nearly impossible) to verify the analyse result from a monitor based on deflection of light. Generally, this type of monitors are used widely and they normally function satisfactorily but it is virtual impossible to assess to what extend "particles" like oil degradation product or air bubbles are included in the final analyse result.

In this experiment the effect of using different solvents has been examined. Solvent reduces the viscosity and reduces the concentration of "real" particles and thereby minimize the risk that more than on particle will pass the sensor at a given time. Secondly, the solvent tends to dissolve oil degradation products and thus reduces the risk of counting "soft contaminants" in the final result.

Five different solvent typically used to dissolve gear oils have been used. It appears that only two oils (V2 and V6 both mineral oils) were miscible with solvent B (2-propanol and toluene) whereas the synthetic based PAO´s gave a non-homogeneous appearance.

Comparing PAMAS data from no-diluted and diluted samples typically the differences varies from 0 to 2 ISO units but for oil no. V2 the difference is 4 units. This is an unacceptable high difference as 4 ISO units equivalent a difference in particle number of $2^4 = 16$.

Particle counting based on filtration of a test sample through a membrane filter and scanning the surface for particles eliminates the problem with air bubbles and "soft contaminants". However, this method tends to underestimate the amounts of small particles and this is clearly to see in the data (Table 6 and Figure 28-Figure 30). For the coarser particle (> 14 µm) the optical method and filtration/microscopy give comparable results. Note, that the latter sometimes gives higher results than PAMAS.

Table 6. Classes for > 4µm, > 6µm and > 14µm included in ISO 4406;1999.

	PAMAS (optical, light deflection measurement)						**Olympus** (filtration & microscopy)
Sample No	**Undiluted**	**Diluted the sample with solvent**					
		Solvent A	Solvent B	Solvent C	Solvent D	Solvent E	
V1	17/15/11	16/14/11	-	16/14/10	16/14/11	16/14/11	13/12/10
V2	17/16/11	-	17/16/15	-	-		15/14/11
V3	15/13/09	19/15/11	-	19/15/11	18/16/11	19/16/12	13/12/10
V4	17/14/09	17/15/11	-	17/15/09	18/16/10	18/15/12	16/14/11
V5	20/17/12	20/17/12	-	20/17/12	19/17/13	20/17/12	17/16/12
V6	19/15/11	18/15/12	18/16/12	18/15/12	18/16/12	18/16/12	14/13/10
V7	19/15/10	20/17/13	-	20/16/12	20/17/14	20/17/14	16/14/10
V8	18/15/11	19/16/11	-	19/16/12	19/16/12	19/16/14	16/14/11

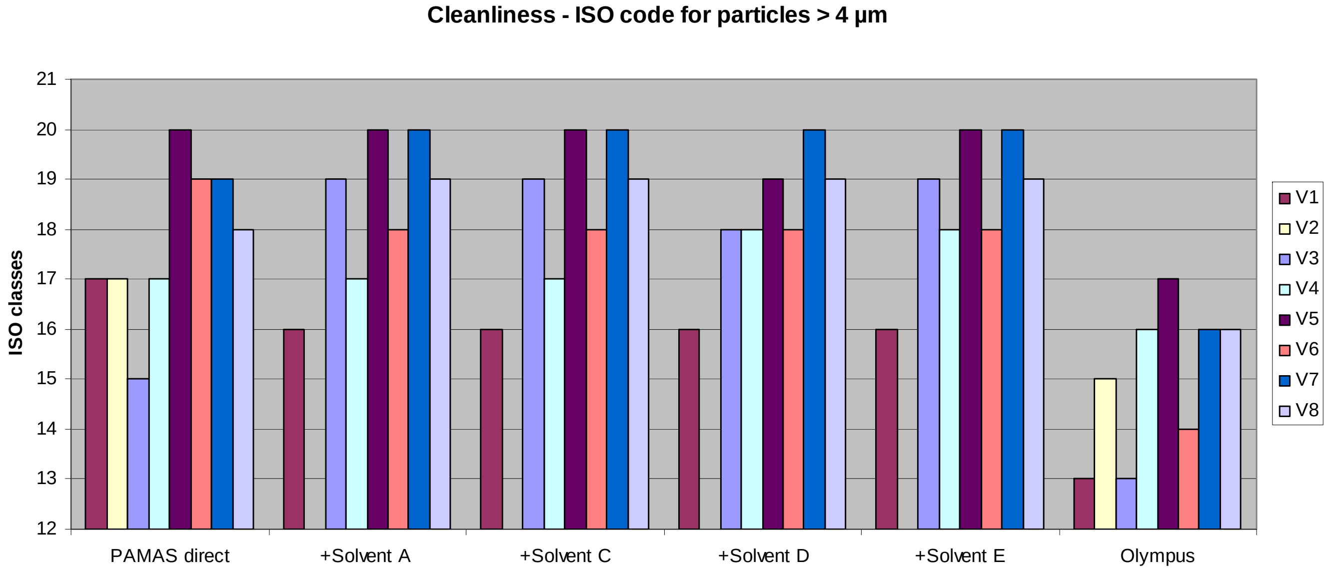
Solvent A: N-Heptane 1:1 Solvent B: 2-Propanol + toluene 1:1 Solvent C:Petroleum benzene 1:1

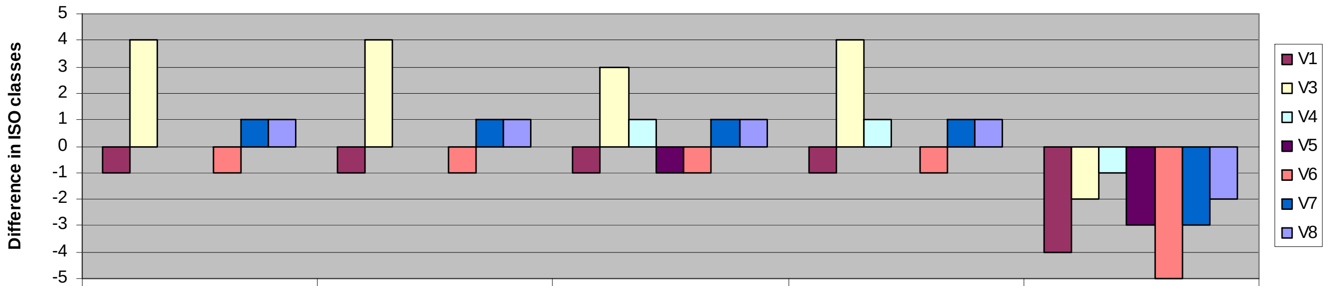
Solvent D: N-Heptane 1:3 Solvent E: Petroleum benzene 1:3

X:Y = Oil : Solvent ratio

Table 7. Number of particulates in 1 mL oil for the 3 size classes (> 4μm, > 6μm and > 14μm) included in ISO 4406;1999.

	PAMAS (optical, light deflection measurement)						**Olympus**
Sample No	**Undiluted**	**Diluted the sample with solvent**					(filtration & microscopy)
		Solvent A	Solvent B	Solvent C	Solvent D	Solvent E	
V1	>4 μm: 711 >6 μm: 176 >14 μm: 16	>4 μm: 492 >6 μm: 119 >14 μm: 12		>4 μm: 445 >6 μm: 110 >14 μm: 9	>4 μm: 340 >6 μm: 93 >14 μm: 16	>4 μm: 477 >6 μm: 142 >14 μm: 17	>4 μm: 64 >6 μm: 31 >14 μm: 8
V2	>4 μm: 935 >6 μm: 399 >14 μm: 11		>4 μm: 778 >6 μm: 496 >14 μm: 318				>4 μm: 170 >6 μm: 87 >14 μm: 18
V3	>4 μm: 181 >6 μm: 40 >14 μm: 3	>4 μm: 3498 >6 μm: 273 >14 μm: 20		>4 μm: 4499 >6 μm: 270 >14 μm: 16	>4 μm: 1704 >6 μm: 329 >14 μm: 16	>4 μm: 2989 >6 μm: 478 >14 μm: 33	>4 μm: 54 >6 μm: 26 >14 μm: 5
V4	>4 μm: 1092 >6 μm: 141 >14 μm: 5	>4 μm: 1298 >6 μm: 208 >14 μm: 12		>4 μm: 1222 >6 μm: 178 >14 μm: 3	>4 μm: 1332 >6 μm: 205 >14 μm: 8	>4 μm: 1493 >6 μm: 258 >14 μm: 13	>4 μm: 394 >6 μm: 150 >14 μm: 16
V5	>4 μm: 5084 >6 μm: 726 >14 μm: 27	>4 μm: 9856 >6 μm: 919 >14 μm: 34		>4 μm: 5607 >6 μm: 850 >14 μm: 29	>4 μm: 4704 >6 μm: 793 >14 μm: 52	>4 μm: 5024 >6 μm: 768 >14 μm: 32	>4 μm: 913 >6 μm: 321 >14 μm: 36
V6	>4 μm: 2671 >6 μm: 174 >14 μm: 12	>4 μm: 1634 >6 μm: 317 >14 μm: 26	>4 μm: 2194 >6 μm: 446 >14 μm: 36	>4 μm: 1707 >6 μm: 314 >14 μm: 28	>4 μm: 1656 >6 μm: 337 >14 μm: 32	>4 μm: 2321 >6 μm: 458 >14 μm: 33	>4 μm: 155 >6 μm: 61 >14 μm: 9
V7	>4 μm: 2760 >6 μm: 165 >14 μm: 8	>4 μm: 9530 >6 μm: 813 >14 μm: 48		>4 μm: 8585 >6 μm: 616 >14 μm: 23	>4 μm: 8608 >6 μm: 777 >14 μm: 144	>4 μm: 8753 >6 μm: 734 >14 μm: 93	>4 μm: 511 >6 μm: 98 >14 μm: 9
V8	>4 μm: 2252 >6 μm: 245 >14 μm: 13	>4 μm: 4152 >6 μm: 607 >14 μm: 28		>4 μm: 3767 >6 μm: 522 >14 μm: 23	>4 μm: 4052 >6 μm: 557 >14 μm: 32	>4 μm: 4121 >6 μm: 534 >14 μm: 33	>4 μm: 516 >6 μm: 123 >14 μm: 11





	Sol A - direct	Sol C - direct	Sol D - direct	Sol E - direct	Olympus - direct
V1	-1	-1	-1	-1	-4
V3	4	4	3	4	-2
V4	0	0	1	1	-1
V5	0	0	-1	0	-3
V6	-1	-1	-1	-1	-5
V7	1	1	1	1	-3
V8	1	1	1	1	-2

Figure 28. ISO code results for >4 µm.

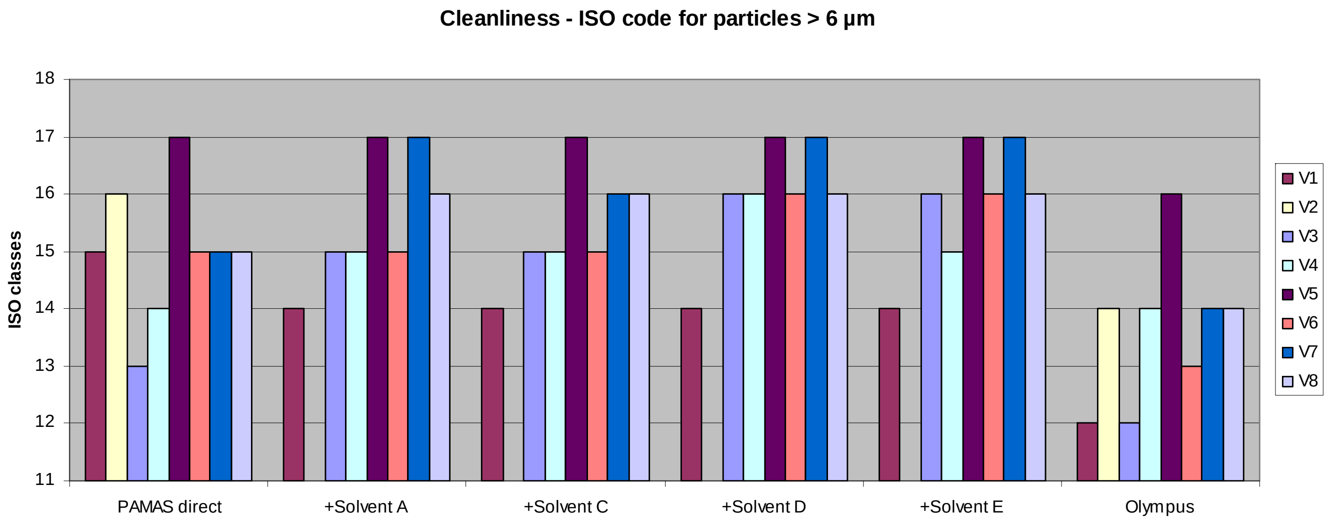
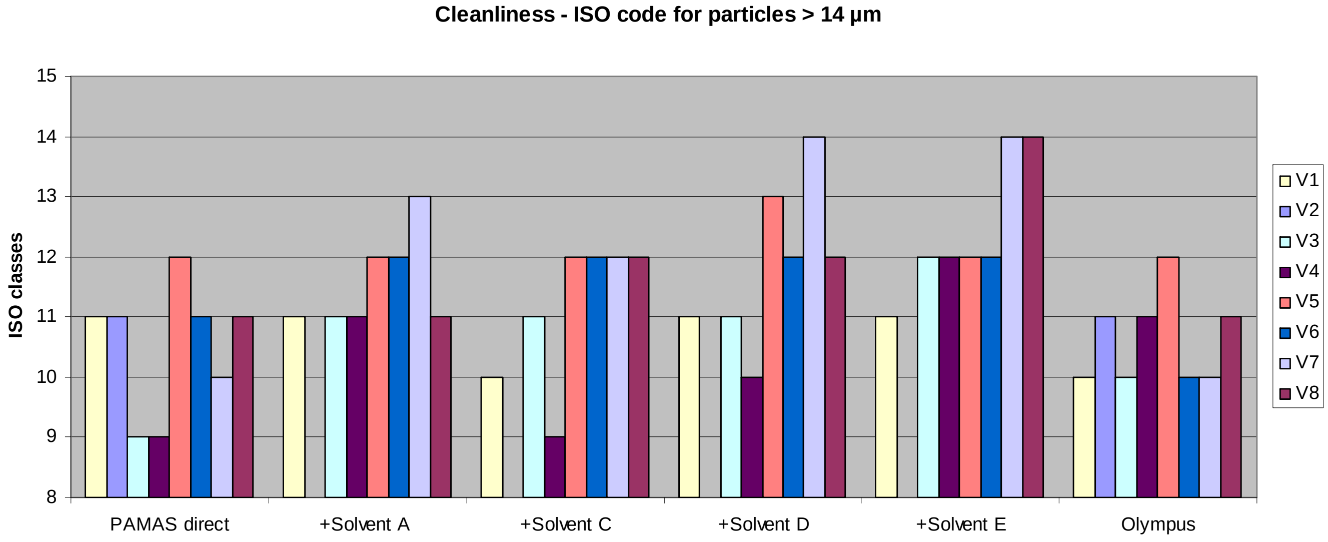
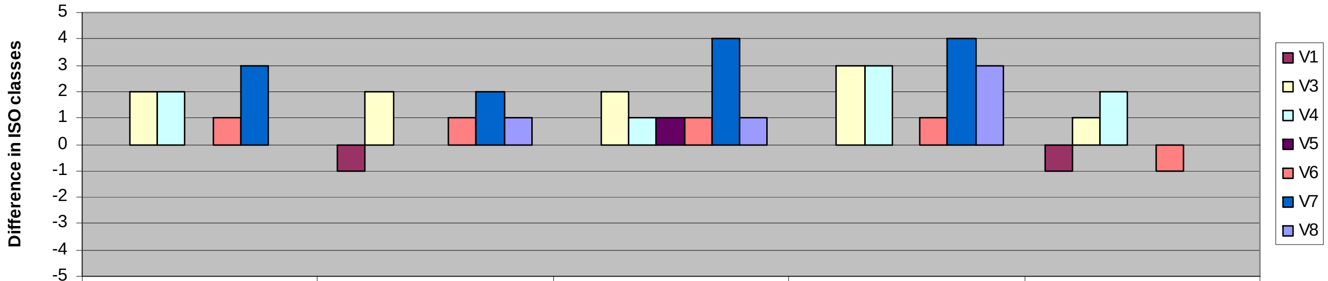


Figure 29. ISO code results for >6 μm.





	Sol A - direct	Sol C - direct	Sol D - direct	Sol E - direct	Olympus - direct
V1	0	-1	0	0	-1
V3	2	2	2	3	1
V4	2	0	1	3	2
V5	0	0	1	0	0
V6	1	1	1	1	-1
V7	3	2	4	4	0
V8	0	1	1	3	0

Figure 30. ISO code results for >14 µm.

Appendix C: Laboratory test of offline-filters for wind power gearbox applications

Jens Carlevi, Jan Ukonsaari, Vattenfall Research and Development, 2012-08-29.

Goal

The goal is to compare two different filter systems regarding performance and achieved cleanliness in the oil.

Tested system

The tested systems are a Europafilter system and a CJC HDU 15/25 PV with filter insert GV 1525, see Figure 31.

Figure 31. Filter system from CJC (left) and Europafilter (right).

The tested oil is a Mobil SHC 320XMP (synthetic gearbox oil) which has been in use for 12,458 hours in a 2MW turbine located in south of Sweden. The oil sample is taken 2012-03-15 and the accumulated production since previous oil change is 8,598 MWh. The oil has been transported to the lab in Älvkarleby from the turbine in plastic barrels. The gearbox was under investigation for damages.

Test design

The test setup consists of a barrel (~50liter) and the tested filter system (Figure 32). The barrel is located in a heat cabinet to keep an oil temperature of 60 degrees C. The temperature in the oil as well as in the cabinet is measured. Both actual and accumulated flow through filter as well as pressure drop over the filter is measured.

Figure 32. General test design (left), oil flow sensor (middle), data panel (right)

Test procedure

Prior to the test, approximately 150 litres of test oil has been put in a big barrel and mixed well to eliminate any difference between the individual plastic transportation barrels. The test barrel has then been filled with 50 litres of oil and placed in the heat cabinet.

The 0-sample has been taken after the temperature has stabilized and the filter been running until all air has been removed and stable conditions prevail. The oil sample point is located just before the filter.

The oil samples have been analyzed by the Vattenfall Petroleum Chemistry laboratory in Älvkarleby. The methods used are particle counting and gravimetric measurement. The filter paper used during the analyze has also been saved for visual comparison.

The oil samples have been taken in 0.5 l plastic bottles according to the following procedure:

1. Valve opened
2. About 0.4 l disposed
3. Tapping of oil into bottle, thoroughly shaking of bottle and disposal
4. Repetition of 2) and 3)
5. Tapping of test oil sample

The flow valve was not changed during the procedure and the bottles were filled from the free out coming oil jet.

Appendix D: Off-line filter test optical microscopy photos

Results

Optical microscopy images with 1000 times magnification using polarized light are shown in page 2-7 below. Scale for the figures is shown in Figure 33.

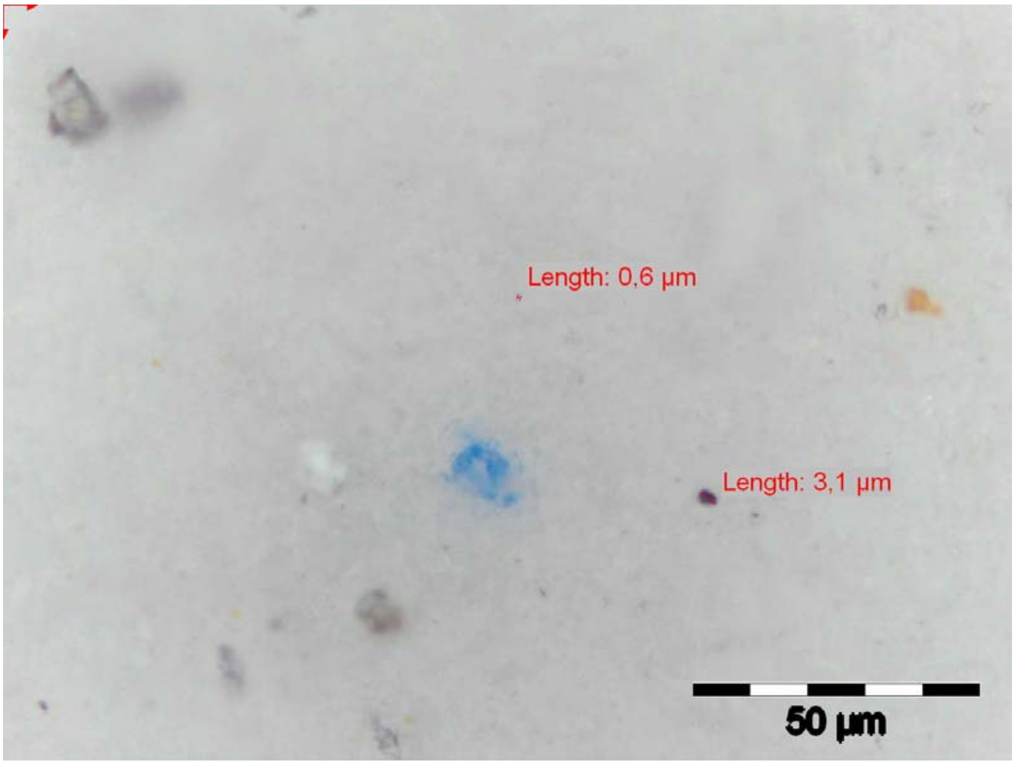
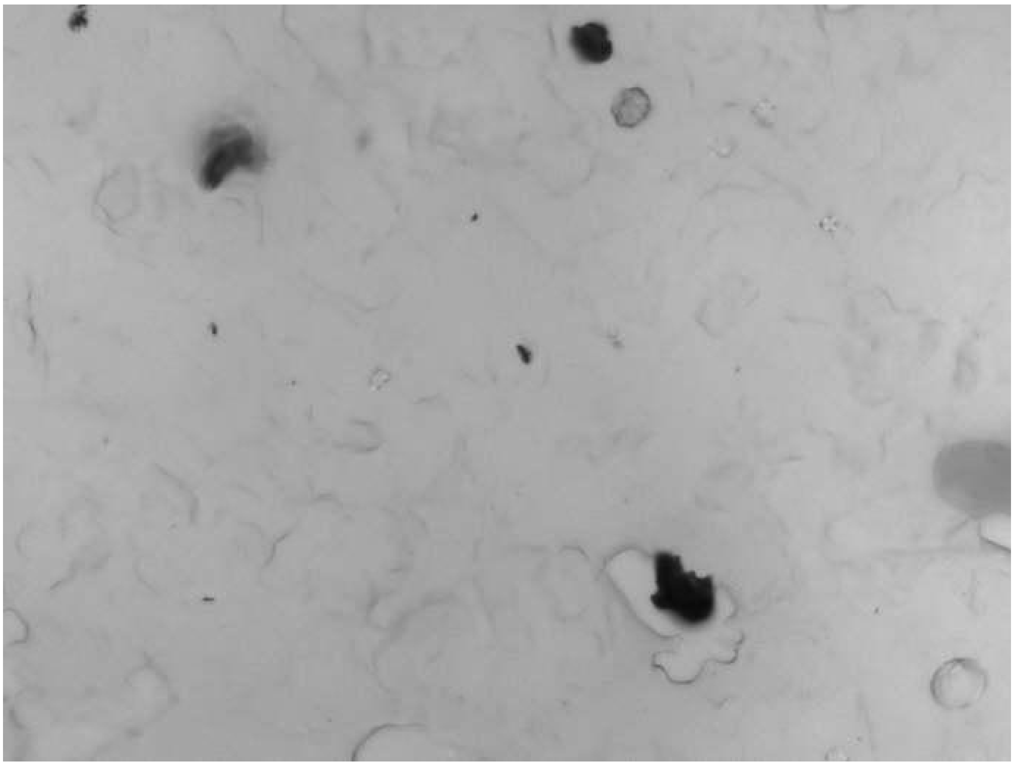
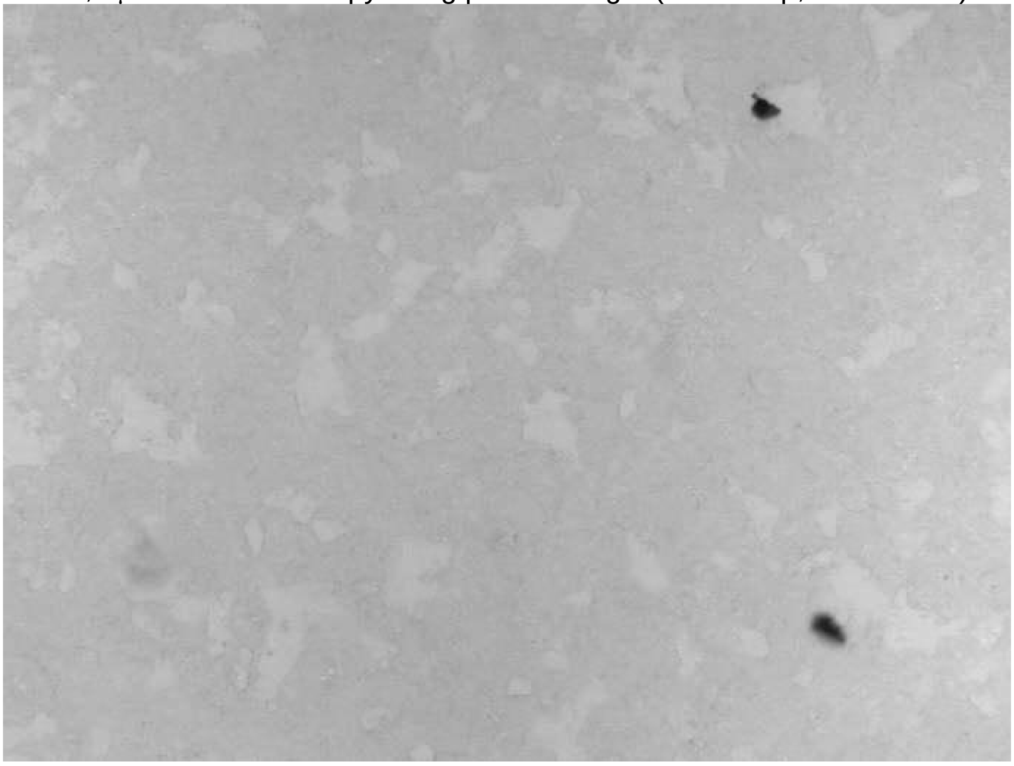
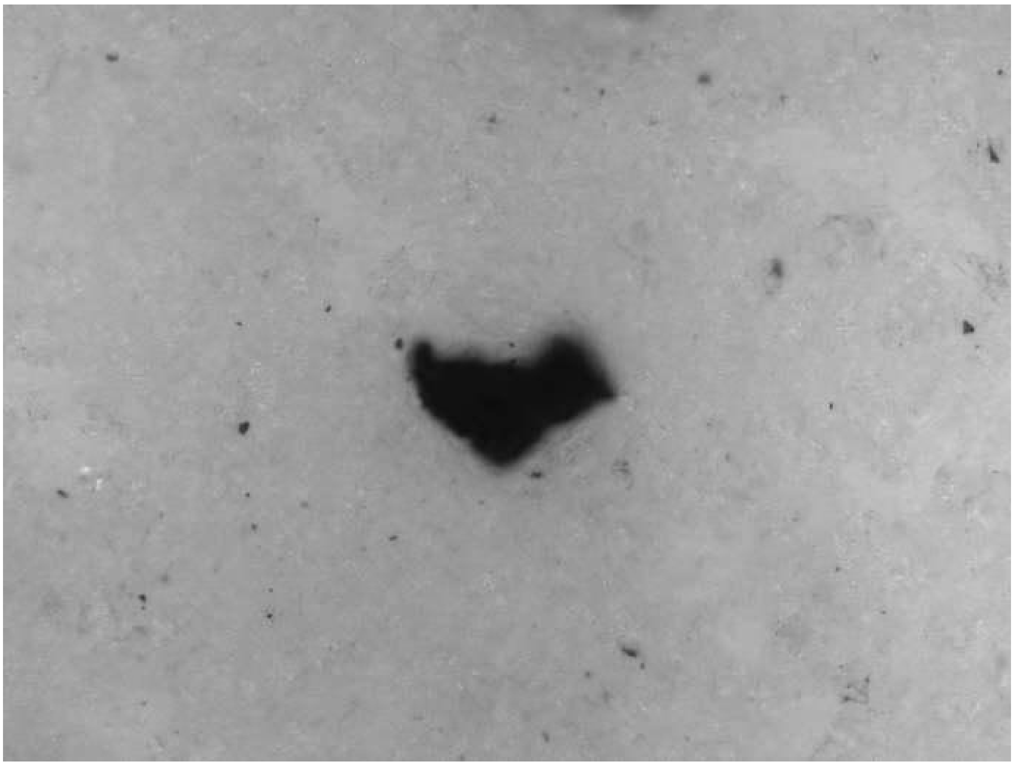
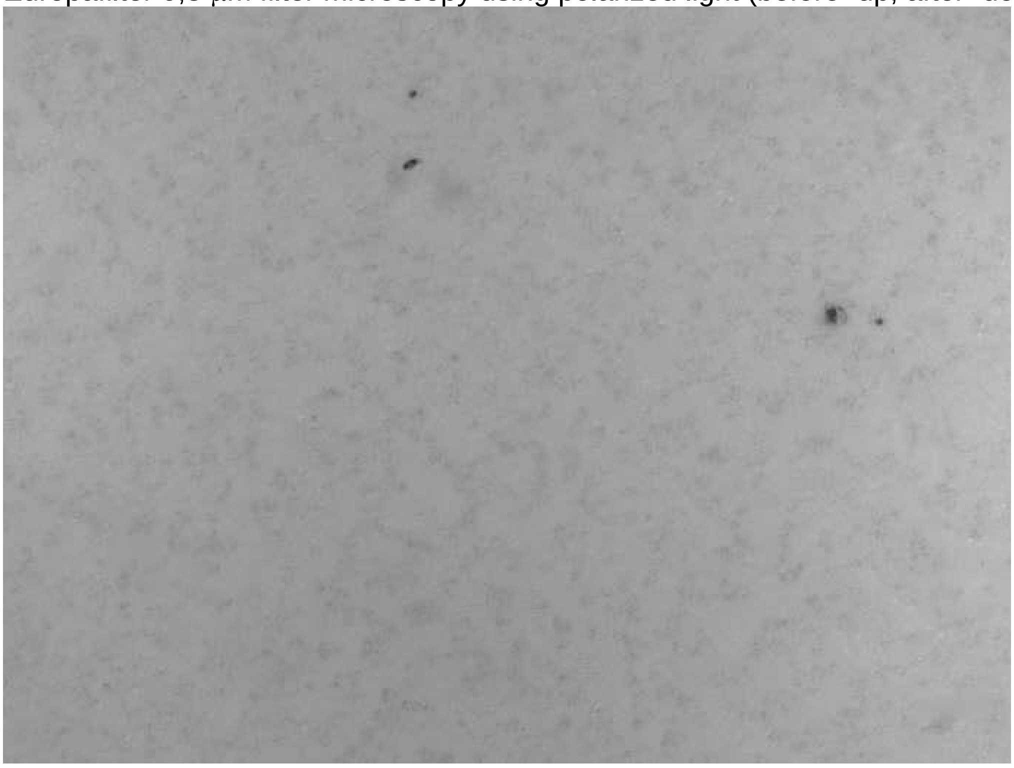


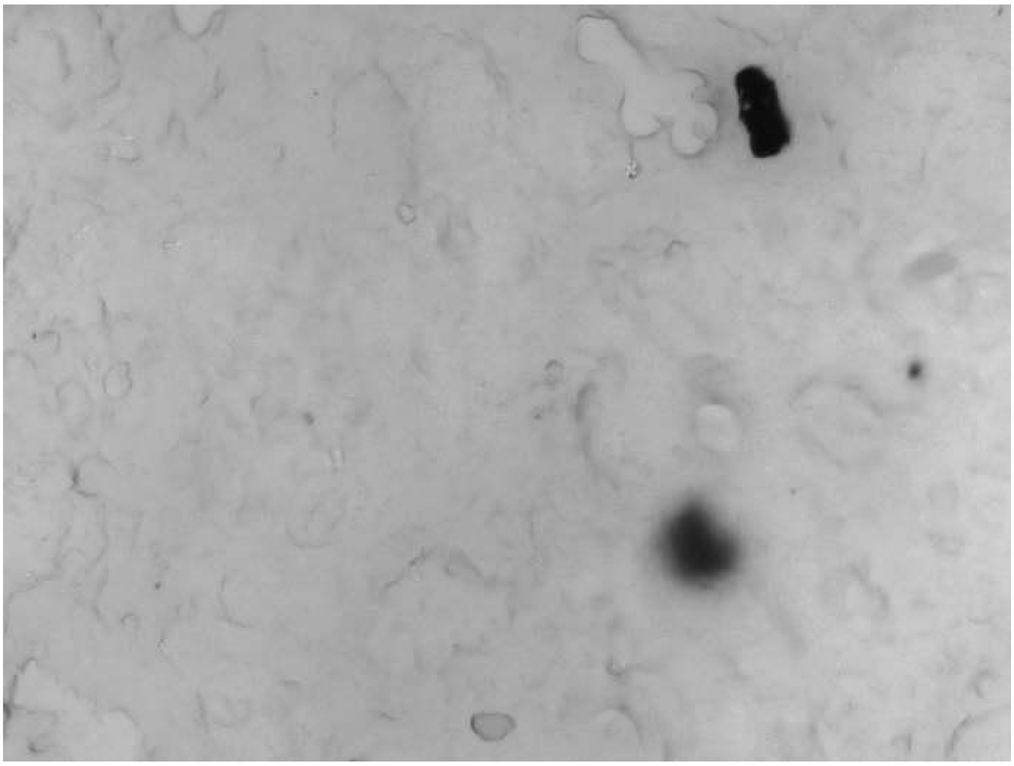
Figure 33. Scale for 1000 times magnification. Europafilter 0,45 µm filter microscopy using normal light before filter start, compare to page 5 upper photo.



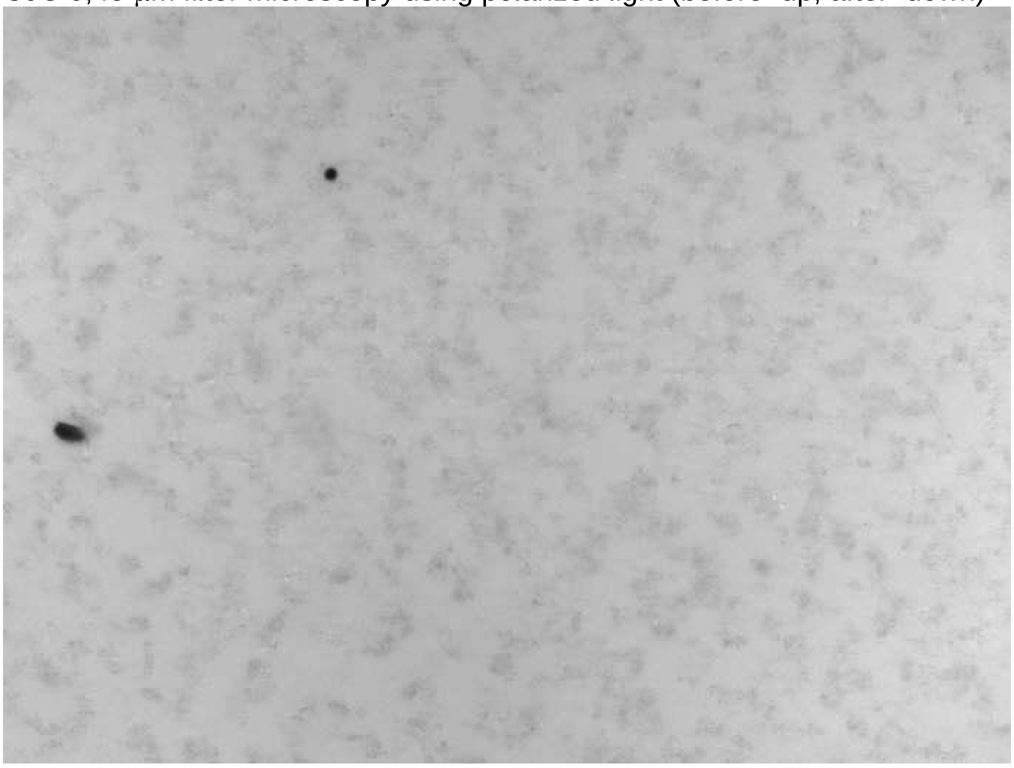
CJC 0,8 μm filter microscopy using polarized light (before=up, after=down)

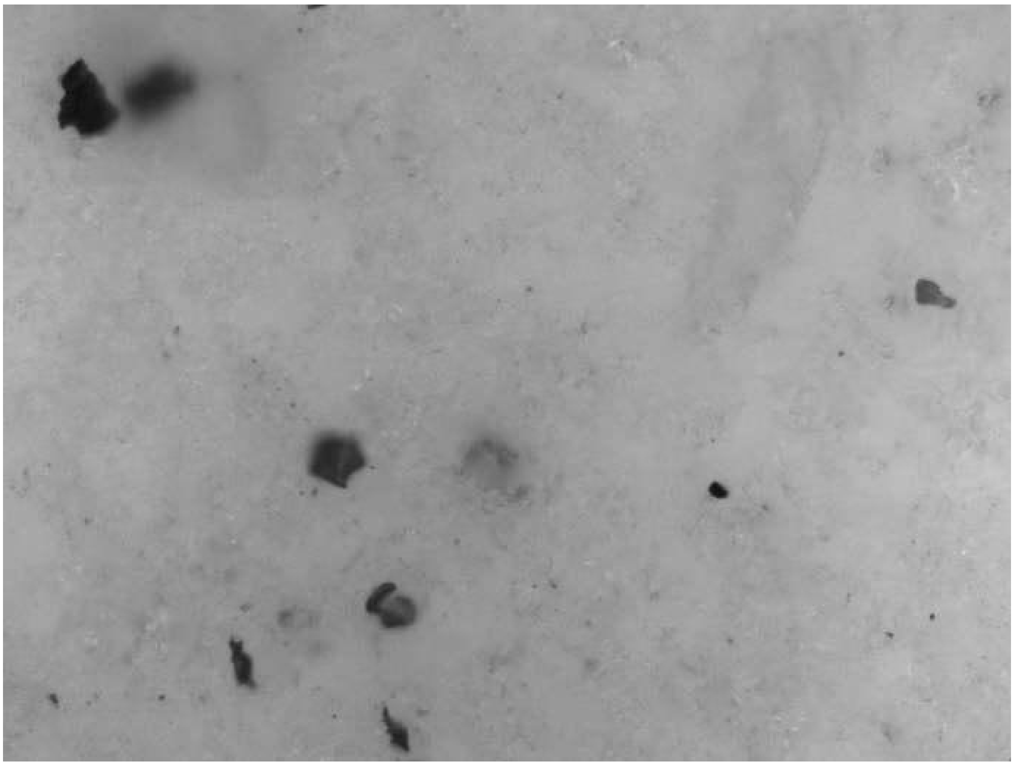



Europafilter 0,8 μm filter microscopy using polarized light (before=up, after=down)


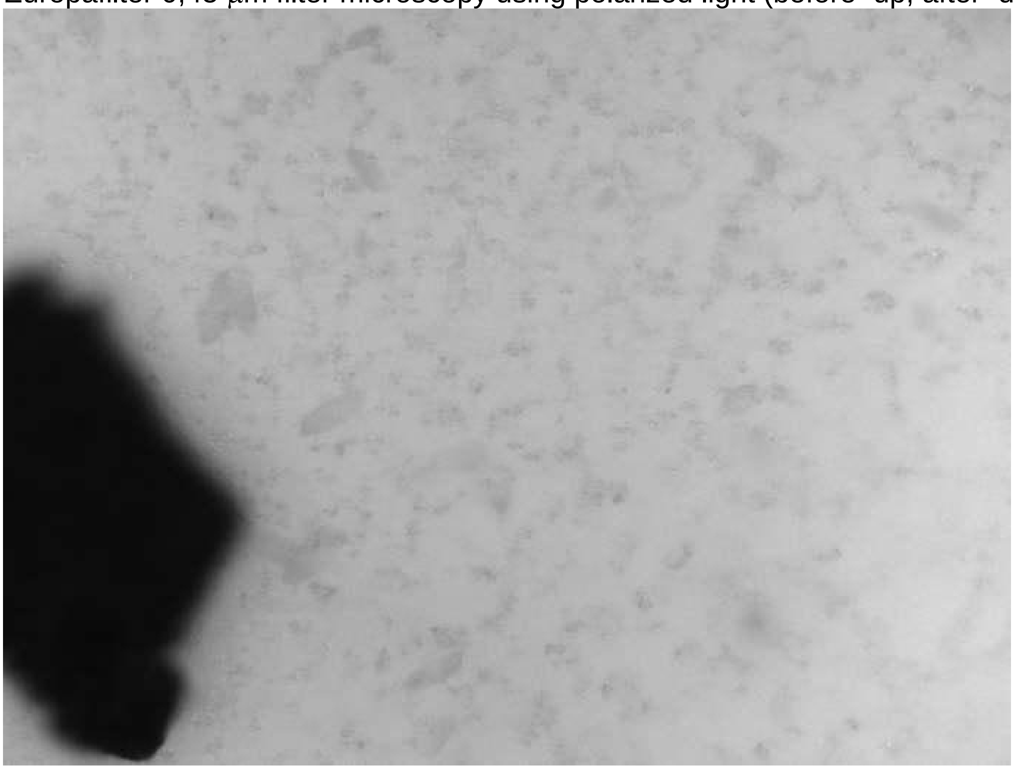


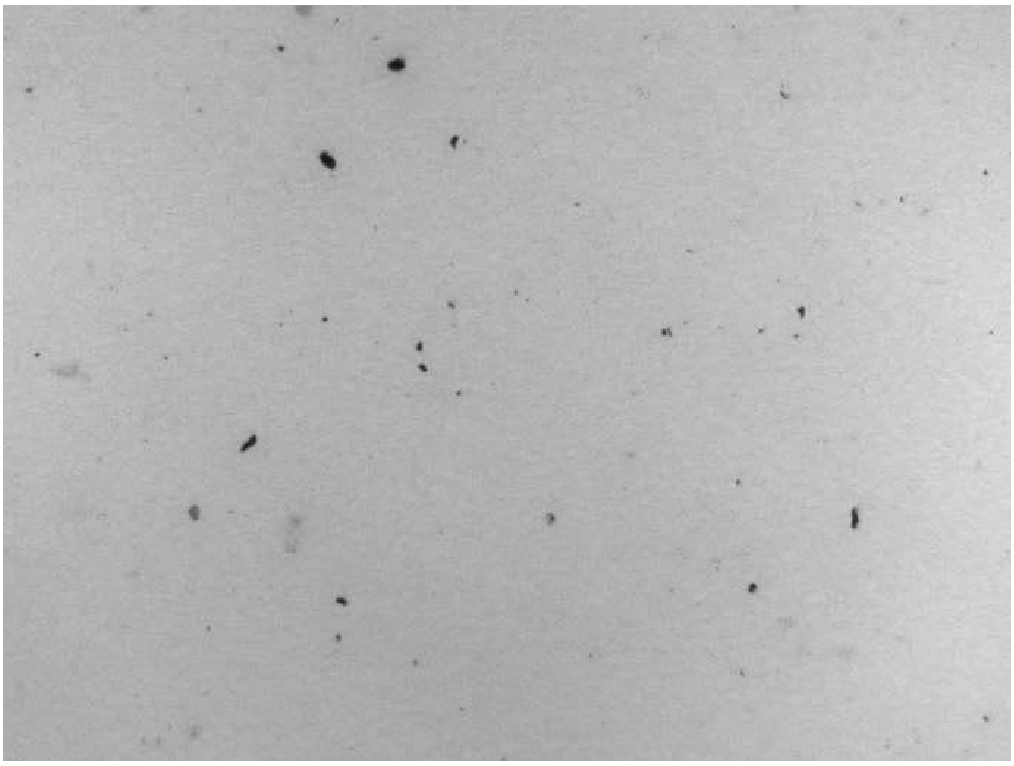
CJC 0,45 μm filter microscopy using polarized light (before=up, after=down)



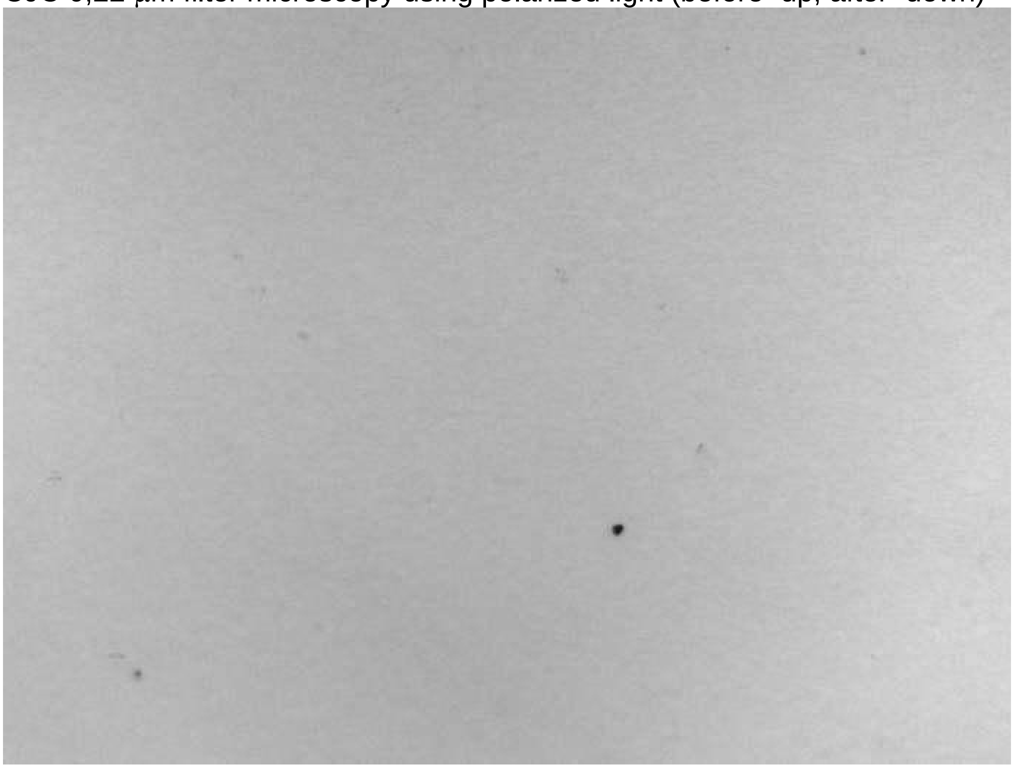


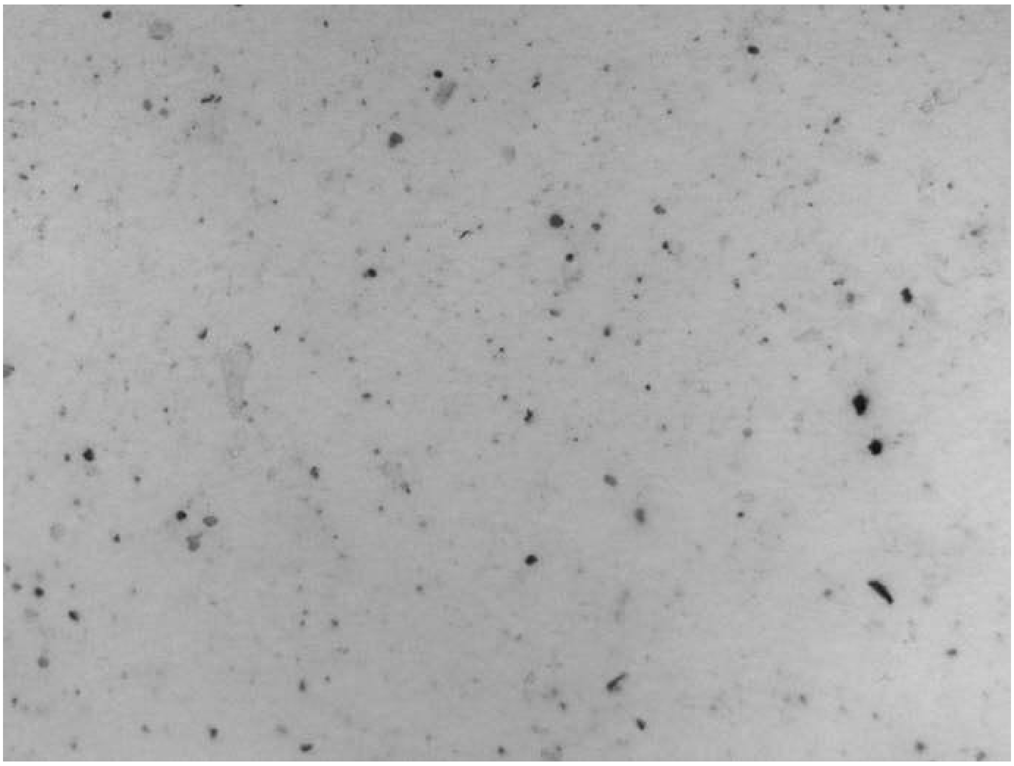
Europafilter 0,45 μm filter microscopy using polarized light (before=up, after=down)



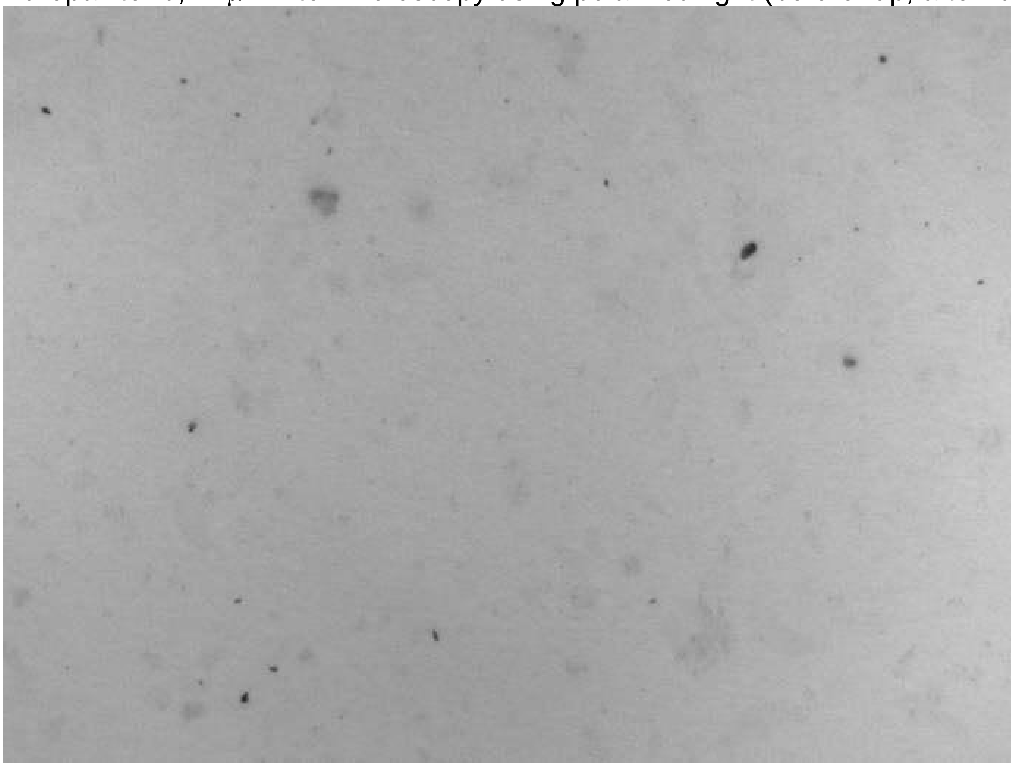


CJC 0,22 μm filter microscopy using polarized light (before=up, after=down)





Europafilter 0,22 μm filter microscopy using polarized light (before=up, after=down)



Appendix E: Oil sampling procedure

Sampling Procedures: Methods of taking samples from hydraulic applications using appropriate recepticles [Fluid condition Handbook]

Sampling procedures are defined in ISO4021. Extraction of fluid samples from lines of an operating system. Receptacles should be cleaned in accordance with DIN/1505884. The degree of cleanliness should be verified to ISO3722.

Method One – Preferred method (Using a suitable sampling valve with PTFE seating method)

1. Install sampling valve in pressure or return line (in closed condition) at an appropriate point under constant flow or turbulent conditions.
2. Operate system for at least 30 minutes before taking a sample
3. Clean outside of sampling valve
4. Open the sampling valve to give appropriate
5. Flow rate and flush at least one litre of fluid through the valve. **Do Not Touch Valve After Flushing. (**If not a proper sampling valve is used, more flushing is required).
6. Remove cap from sampling bottle. Ensure cap is retained in hand face downwards
7. Place bottle under sampling valve.
    a. Fill bottle to neck. Cap bottle & wipe.
    b. If not cleanliness of sample bottles are according to standard, fill the bottle to half, put on cap, shake thoroughly and dispose. Repeat 7 b. at least twice. Now, fill bottle to neck. Cap bottle & wipe.
8. Close the sampling valve.
9. Label the bottle with the necessary information for analysis e.g. Oil type, running hours, system description etc.

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