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INTRODUCTION TO HYDRAULIC OIL CONTAMINATION

DLT-30 OIL FILTRATION SYSTEM

Comprehensive presentation of
DLT-30 function test for the
verification of the achieving
cleanliness level

Preface

This document is aimed at assisting the designer, operator or manager of a hydraulic installation to set and maintain the requirement for a specific minimum cleanliness of the hydraulic fluid. Supportive to this decision-making tool is the presentation of the DLT-30 function test.

Introduction

Hydraulic fluids are of utmost importance to many applications across a wide range of industrial sectors including but not limited to marine, mining, manufacturing, offshore, power production, transport, aerospace and agriculture. Hydraulic oil is one of the most important elements of any hydraulic system.

Its fundamental role in a hydraulic system is to act as a medium of energy transmission between its components. At the same time hydraulic oil has a few supplementary roles which significantly affect the overall performance of the hydraulic system. Heat transfer is one of them. Circulating through the hydraulic network, the hydraulic oil reservoir and any existing cooling installation, hydraulic oil transfers heat caused by friction, pressure differential and any heat-emitting engines in the system, efficiently acting as a coolant. Additionally, hydraulic fluids transfer harmful contaminants such as solid particles and water existing in the network through filters and other conditioning devices thus, suspending them and enabling recirculation of clean hydraulic fluid. While sealings and O-rings are applied for relatively larger clearances between parts, hydraulic oil works as a sealant to very fine clearances enhancing the overall sealing capacity of the respective component. Moreover, the required lubrication protection of the hydraulic components is provided by the hydraulic fluid which creates a lubricating film between moving parts.

Understandably, it is imperative that hydraulic oil maintains its intended properties throughout its lifecycle. Within the scope of this report, the degradation mechanisms of hydraulic oil will be thoroughly discussed. Furthermore, the best practices with regard to hydraulic oil monitoring and management will be elaborately presented and finally the case study of DLT-30 filtration system will take place.

Contamination of hydraulic oil

Solid contamination

Solid particle contamination is the most common form of contamination of hydraulic oil. Hydraulic system failure caused by solid particle contaminants accounts for 55-70% of the total failures due to oil contamination [1-4]. These failures have been widely studied and found to mainly involve component wear or particulate lock [5-9].

Four failure modes of hydraulic systems caused by solid particle contaminants are: (i) damage of the oil film and scratch formation on the surfaces of moving components; the hard, solid particles can readily scratch hydraulic components when there is high flow and high power. A typical example is the inner ring of bearing in hydraulic pump, an image of which is shown in Fig. 1a. The hard, solid particles in oil scratch the inner ring and induce serious damage to the bearing. (ii) Reduction of lubrication, which increases heat generation and reduces efficiency. (iii) Scratch and detachment of rubber seals that produce new contaminants. A typical example is the rubber seal of the hydraulic cylinder, whose image is shown in Fig. 1b. The rubber seals are damaged by the scratch of hard solid particles. (iv) Increase in friction that block valves and other control components, resulting in equipment failures.

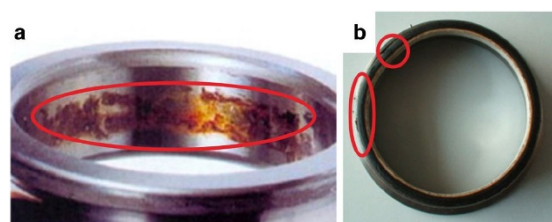


Figure 1. Images of component damage caused by solid particle contaminants. a) Scratch of solid particles on bearing inner ring. b) Damage on rubber seals ([1])

The sources of solid contamination have typically been reported as the following:

- Inadequate cleanliness of the fresh fluid

- The use of dirty containers during manufacture
- Faulty container sealing and poor transportation or storage of the fluid when contamination from dirt, rust, water and so on can occur through rough handling, temperature cycling and the use of fluid taken from part-containers
- The manufacture, installation and repair of the hydraulic system, for example paint chips and welding spatter
- Airborne dirt that enters the system from the external environment via reservoir covers and breathers
- The rust and corrosion of internal system surfaces arising from cooler leaks, high ambient humidity, condensation and so on
- Component wear in service. While this is usually metallic in nature, wear of elastomers can also occur
- The release of filter materials into the fluid (e.g. fibers or particles of the purification media used to condition certain fire-resistant fluids)
- Contamination generated as a result of fluid degradation (e.g. thermal/oxidative degradation)

The aforementioned sources can be categorized as shown in Table I. Typical component dynamic clearances are to be found in Table II and cover the range 0.50–250 μm . In order, therefore, to avoid component wear, the filters selected should ideally be able to remove particles of a size similar to the smallest clearances found in the system.

With regard to the importance of particle size, it is fairly typical that the most damaging particles are those equal to or slightly larger than the component’s dynamic film thickness. Smaller particles will simply pass through causing less damage. Larger particles are less likely to cause abrasive wear until they have been recirculated and broken into smaller, more numerous clearance-sized particles.

Table I. Typical particles size ranges for solid contaminants in hydraulic fluid (based on [2]).

Category	Sources	Typical size range (μm)	Most common contaminants
System-build contaminant	System manufacture, installation and repair	1–500	Casting sand, welding spatter, machining chips, paint, rags
Externally sourced contaminant	New fluid as initial charge and top-up	3–10	Filter medium, paint/lacquer/dirt from drum surfaces (internal and external)
	Contamination in use	1–30	Airborne dust and dirt entering through reservoir covers, breathers and actuator seals
Internally generated contaminant	Component		
	-Abrasive wear	5–250	Metal particles
	-Adhesive wear	5–750	Metal particles and chips
	-Surface fatigue	5–50*	Metal particles
	-Cavitation and erosion	40–250	Metal particles
	Rust and corrosion	5–150	Rust particles
	Fluid degradation		
-Varnish	>0.08	Polymeric fluid breakdown products	
-Dieseling and static discharge	>0.1	Carbon particles	
-Carbonising on heater Filters	>100	Carbon particles	
Filters			
-Unloading/failing		0.2–750	Fibers, solid conditioning media

* Up to several hundred microns in rolling element bearings.

Table II. Typical dynamic clearances found in hydraulic system components (based on [2]).

Component	Typical dynamic clearances (μm)
Gear pump	0.5–5.0
Vane pump	0.5–10
Piston pump	0.5–40.0
Servo valve	1.0–4.0
Proportional valve	1.0–6.0
Directional valve	2.0–8.0
Actuator	50–250

Although very fine filters are available, most fine filtration systems today may only be effective in catching particles down to about 3 μm in size [2].

There is also an assumption that metallic particles are of greatest concern, and little attention has been given to the effects of ‘softer’ particles apart from the recent focus on varnish formation in lubricant systems. However, investigations into fluid and lubricant breakdown as a result of micro-dieseling [10] and static discharge [11] have shown that these processes also produce non-metallic fine particles in hydraulic systems and prolonged exposure to these processes can result in the formation of substantial amounts of dispersed/suspended solids.

Varnish formation

Varnish is the result of the precipitation of polar, polymeric compounds (also known as varnish precursors) arising from the thermal/oxidative breakdown of hydrocarbons and phosphorus-containing additives at relatively ‘low’ temperatures [2]. Following precipitation, these higher molecular weight products readily deposit onto colder system surfaces such as those of the cooler, tank and actuators, and this is accelerated in areas of low flow — although still a slow process if allowed to occur naturally. However, varnish is also found on hotter surfaces such as valves and bearings. It is assumed that under these higher temperature conditions, the varnish precursors have a higher molecular weight than those precipitating under cooler conditions.

Varnish precursors are regarded as ‘soft’ contaminants, but when deposited in thin

layers on hot surfaces, they thicken and harden over the course of time into ‘lacquer’. The precipitation of varnish precursors in the bulk of the fluid is often referred to as ‘sludge’.

The size of varnish precursor particles can vary significantly. Their average size has been suggested to be about 0.08 μm [2]; however, in common with other small non-metallic particles, they will agglomerate in time and may become large enough to affect the ISO cleanliness code for particles up to 6 μm in size. The colour of the deposit is initially pale yellow but this darkens with time and with increasing amounts of deposit.

Although most of the problems associated with varnish in terms of valve sticking, reduced efficiency of heat exchangers, bearing wear and so on were initially encountered with turbine — particularly gas turbine — oils, the problem is now accepted as also applying to hydraulic fluids [2].

Miro-dieseling and cavitation

The mechanism of the high-temperature degradation of hydraulic oils and fluids through the dieseling process [10] involves the rapid compression of air bubbles in the system pump. It has been shown that bubble wall temperatures can reach very high levels dependent on bubble diameter and rate of compression. The worst possible condition is adiabatic compression when no heat is conducted away from the bubble as it is compressed. Under such conditions, the air temperature within the bubble has been calculated to reach at least 1000°C with the formation of carbon particles as a result of incomplete combustion, as well as a wide variety of organic species including low

molecular weight hydrocarbons. However, this is an extreme case, occurring with large bubbles and assuming no heat loss to the surrounding liquid. It is more likely that degradation occurs at lower temperatures from 300–900°C, still high enough to cause molecular breakdown and a wide range of degradation products.

The steady darkening of fluid colour, the development of a burnt odour and the formation of black particles in any deposit would be highly suggestive of dieseling in the system [10]. Particle sizes of 0.1–0.45µm have been shown to be present as a result, and while the focus has been on the presence of carbon, varnish precursors are also likely to be found, particularly under less extreme conditions. Significant amounts of carbon (as soot) have been found in systems that have been dieseling for long periods. Soot is commonly thought of as a ‘soft’ contaminant, but while this may be the case for agglomerates, which form layers that readily slide over one another, some aggregates of soot particles formed during combustion can be extremely hard, support a high load and cause abrasive wear [12].

In trying to reduce the incidence of dieseling, the focus has been on system design. Although good air-release properties of the fluid may initially help to reduce the number of air bubbles, the conditions can be severe enough to produce combustion of the fluid vapour inside the bubble and substantial amounts of carbon can be formed.

The following design recommendations are very important if this phenomenon is to be avoided:

- That variable volume pumps are used to minimise the often turbulent flow of fluid back to tank over the pressure relief valve;
- Good tank design is essential to allow air to escape from the fluid (adequate residence time; use of baffles etc.) while ensuring that all fluid returning to the tank is always discharged under

the liquid surface thereby reducing the amount of air entrained;

- Minimising turbulence in the return line to the tank; and
- Always maintaining the fluid in the reservoir at the correct level.

The effects of dieseling, in addition to the generation of carbon and varnish precursors, include the formation of flammable gases, low molecular weight hydrocarbons and a wide range of other species, many of which are detrimental to the performance of the fluid, and therefore to the overall performance of the system.

Cavitation is another bubble-generating process arising from the rapid volatilization/gasification of volatile contaminants under local conditions of reduced pressure. These bubbles may generate small amounts of debris if the gas/vapour bubbles formed then implode on the metal surface. If these bubbles are produced, for example as a result of pressure loss in the pump suction line, and are then compressed in the pump, they may also contribute to the generation of fine particles. However, cavitation is not frequently reported with mineral oil and other non-aqueous fluids because these fluids have much lower vapour pressures than water-containing products. Cavitation is therefore less likely to be a significant factor in the formation of very small particles.

Flow Electrification and Static Discharge

The generation of electrostatic charge in flowing liquid (Fig. 2) has long been recognised as a hazard with fuels.

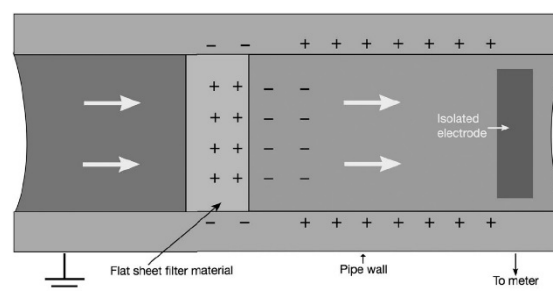


Figure 2. Streaming current or flow electrification. ([2])

However, the phenomenon was only associated with industrial oils, principally turbine oils, in the last 30 years and even more recently with hydraulic oils — possibly as a result of a trend towards ashless hydraulic oils, which are less conductive [2]. Indeed, the availability of electrostatic filtration equipment to remove particulate matter from these fluids [13] was probably in widespread use before the applicability of charge generation to industrial fluids was appreciated and investigated [11,14].

It is now understood that charge generation occurs in any moving liquid whether this is flow in pipes, into a reservoir or in a component such as a filter. It is highest when the fluid flow becomes two-phase (fluid/air) such as a spray or jet discharging into a reservoir. The rate of charge generation is dependent on a number of factors, e.g. flow rate, the electrical properties of the fluid (particularly conductivity), fluid temperature and viscosity, whether the equipment is grounded, its materials of construction and the dimensions of pipework or component through which the fluid is flowing [15,16]. If the charge on the component is not dissipated, it will accumulate until it is high enough to discharge to a part that is at a low potential, producing a spark. If the components are grounded, this will prevent a discharge but will not stop charge accumulation (at a rate dependent on the conductivity of the fluid) nor will it increase the speed at which the charge dissipates [15]. As hydrocarbon fluids normally have low conductivities, the charge accumulates rapidly but dissipates only slowly and sparking is possible with most filter elements using conventional synthetic media.

The problem was initially recognised from the metallic clicking sound in the filter housing as a result of the discharge, the presence of burn marks on filter element end caps and support layers, together with pitting on the central core [15]. However, the integrity of the media was rarely compromised. With later developments in system configuration, changes to filter design and also fluid

composition, the problem became worse and damage to filter media was occasionally found. While the cause was originally ascribed to friction between the fluid and the wall of its container, it was subsequently more accurately described as ‘flow electrification’ or the development of a ‘streaming current’ due to movement of the Helmholtz double layer [15].

Further investigations revealed that filters were most prone to charging the fluid because of higher flow rates through the reduced pore size, their large surface area and, for some designs, their nonconductive fibers [16]. The fluid was also able to discharge within the filter from the edges and corners of the filter pleats due to their proximity to the metal central core [11] (if manufactured of uncoated metal), but the exiting fluid was still charged.

Discharges have also been found to take place in the system reservoir [11, 16]. These arise due to the formation of two-phase flow as air bubbles are released from the charged fluid, the incorporation of yet more air into the fluid due to turbulent flow in the return line and the possibility that the fluid will be released as a spray or jet into the tank if the fluid level is below the point of discharge and if there is a sharp edge to the pipe wall where it discharges into the tank. The risk may be further increased if the fluid contains flammable gases formed when the fluid is subjected to high temperatures in dieseling or following electrostatic discharge in the filter.

Although the charge should be able to ‘relax’ and dissipate in the tank, the low conductivity of some hydraulic fluids means that a high residual charge can remain unless the residence time is long. Other factors that can influence the rate of charge dissipation and the residual charge on the fluid as it reenters the system include the following:

- The formation of varnish deposits on tank walls, which may insulate the tank and hinder ‘earthing’;
- The quantity of charge removed by air bubbles as they move to the surface;

- The efficiency of the bubble removal process; and
- Whether constant volume pumps continuously circulate substantial quantities of fluid over the pressure relief valve and back to the tank.

Tank design — and size — may, in fact, be found to be as important for maintaining a flow of charged liquid around the system as it is for the continuation of the dieseling process. Indeed, the two processes may be inter-related.

As the fluid ages, conductivity increases with the generation of polar degradation products and ionised particles. This will assist the loss of charge from the fluid. However, most fluid maintenance regimes endeavour to reduce/remove degradation products and dirt in an attempt to prolong fluid life and minimise system wear.

As yet, no systematic study has been made of dissolved gases in hydraulic systems where static discharge is taking place, and therefore, using this property to identify static discharge or dieseling is not currently possible [2]. In view of the potential risk of explosions occurring in systems where static discharge is occurring, [16] this should be investigated.

Breakdown voltage, that is the voltage required to achieve a discharge, is lowered with increasing amounts of particles, particularly fine particles [17]. Therefore, as the fluid cleanliness decreases, the likelihood of discharge increases.

While bubbles should not normally appear on the pressure lines of a hydraulic system, they are plentiful in the return line due to the release of pressure and the turbulent flow. They may increase further in the tank if the fluid is returned above the bulk liquid level. The possibility of this mechanism being an additional source of fluid degradation cannot therefore be excluded.

The response of additives in the fluid to electrification may also be significant. For example:

- When used as anti-foams, silicones are present as very dilute dispersions

(perhaps together with silica) in the oil or fluid. The droplets will also be charged as the fluid circulates, and if they receive the same charge as the air bubbles, the anti-foam particles could also be drawn towards particles or surfaces with the opposite charge. This would seem likely to have an adverse effect on their anti-foam behaviour.

- The use of polar additives in non-polar fluids would be expected to reduce the tendency for charge accumulation, and the widespread use of zinc dialkyldithiophosphate (ZDDP) antioxidant/extreme pressure additives in hydraulic fluids has been suggested as the reason why static discharging has only recently been associated with hydraulic oils, as they increase the fluid conductivity. Ashless hydraulic fluids (based on oils with a lower aromatic content and with no ZDDP or other metal-containing additives) are more susceptible to charge accumulation [18]. However, even ZDDP-containing fluids are now thought to be displaying signs of discharging as operating conditions (for example, higher flow rates) are introduced.

The failure of filters as a result of sparking caused investigations into ways of reducing static accumulation. These included the following [15]:

- Adding a conductive mesh upstream and downstream of the media to reduce residual charge;
- Reducing the flow density in the filter by increasing its size;
- Allowing more time for charge relaxation to occur by increasing tank size and residence time; and
- Making the fibers in the filter media more conductive.

While all these changes are feasible, they are more expensive either to install or to maintain.

Use of an anti-static additive, as is popular in fuels, has had some limited application in ashless turbine oils but not, as far as is known, in hydraulic fluids. The reasons given include concerns over compatibility and storage stability; because until recently, static discharges were not considered a major problem in hydraulic fluids, and the hope that filter redesign would solve the problem and avoid the necessity for reformulating the hydraulic fluid additive package.

Water contamination

Fuel and lubricant condition monitoring in industrial equipment is one of the main means for preventing the premature wear of engines, mechanisms, and hydraulic systems. In particular, revealing of water in machine oil is one of the primary signals of the potential catastrophic wear of tribosystems [19].

Water may enter the system by different ways from the environment. Since water and mineral oil are incompatible fluids free water is accumulated at the bottom of the reservoir or in some lower places of the oil tube because of its higher mass density. During mechanism operation oil flows circulating in the system can entrap free dropped water. In the friction zone water replaces oil and disturbs the lubrication regime. In sliding bearings the damage of the hydrodynamic oil film can result in severe wear. Only 1 wt% water in oil can shorten the rated service life of a sliding bearing by almost 90% (Fig. 3.) [20]. Water also reacts with some additives performing antiwear, antioxidative, antifoam, and washing functions in oil. Water hampers totally or partially the action of dispersants and emulsifiers that prevent the agglomeration and merging of admixtures.

The polar nature of water molecules promotes the surface corrosion of common metals, especially in the presence of air, and favors electrochemical reactions between different metals. A typical example is the inner surface of the hydraulic pump, whose image is shown in Fig. 4. [1]. The inner surface of the hydraulic pump is seriously corroded when

chronically using hydraulic oil with high water content.

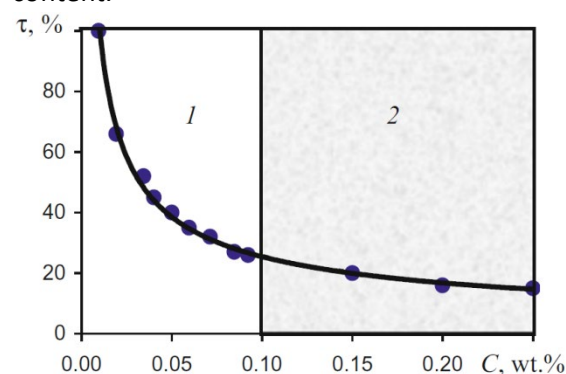


Figure 3. Service life of bearing as a function of water content in oil: 1—transparent oil; 2—turbid oil [20]

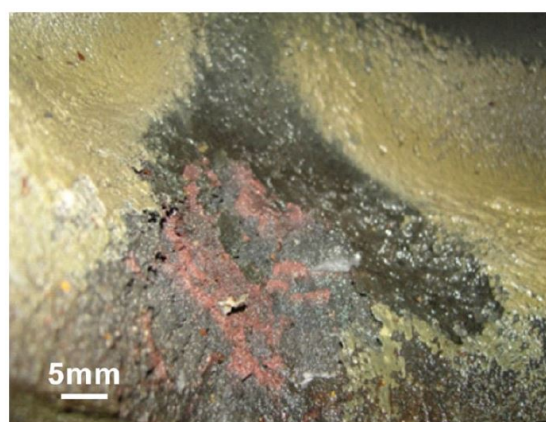


Figure 4. Image of corrosion on the inner surface of the hydraulic pump casing as a result of water ([1])

Water affects harmfully the machine part wear but also can enhance oil oxidation that may cause its premature aging, especially in the presence of catalytic metals including copper, lead, and tin. Moreover, it is known that some synthetic oils, e.g. esters of phosphoric acid and diacids react with water resulting in the decomposition of the oil fluid base and acid formation.

Water as well accelerates the aging process for transformer oils. Water can enter the tank from outside, either being carried in as a vapor in the air or via a leaky seal.

Water can exist in oil in three forms:

- dissolved water molecules are tied by hydrogen bonds to the hydrocarbon molecules of the oil;
- emulsified water is supersaturated in solution but has not yet totally

separated from the oil (it usually gives oil a milky appearance);

- free water is also supersaturated in solution but in a high enough concentration to form water droplets and separate from the oil.

Water whose molecules are bound by hydrogen bonds to polar oil molecules and additives is considered dissolved water. Moreover, water dispersed in oil and formed thermodynamically stable microheterogeneous system is also referred to as dissolved. Most industrial oils, for example hydraulic, turbine etc., can contain up to 0.02–0.06 wt% of dissolved water depending on temperature of the oil service. Aged oil is capable of retaining 3-4 times more dissolved water than the fresh one [20].

The maximal quantity of dissolved water in the oil is called the saturation level. At oversaturation water presents in oil as microscopic droplets forming an emulsion. In this case oil becomes turbid. There are two kinds of emulsions, i.e. macro- and microemulsions. Macroemulsions contain water droplets 0.2–50 µm in size visible in the microscope. Microemulsions contain water droplets 0.01–0.20 µm in size not visible in the microscope. At the particle diameter of 1 µm the emulsion is of milky-white color, 1.0–0.1 µm is white-blue, 0.1–0.5 µm is gray and semi-transparent, <0.05 µm the emulsion is transparent.

Further increase of water concentration in oil leads to separation of the two phases

producing a layer of free water formed by coalescent droplets of emulsified water.

The quantity of dissolved, emulsion or free water in oil depends on the solubility defined by the water quantity that can dissolve in oil at a certain temperature.

The effect of oil aging and additives on the solubility of water in oil is shown in Fig. 5. With increasing concentration of polar additives in oil its water solubility rises. Therefore, the introduction of additives (curve b) and oil aging (curve c) lead to increasing of the moisture adsorption compare to that of the new oil (curve a) at a given temperature.

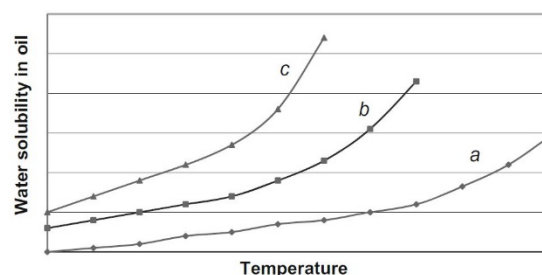


Figure 5. Effect of oil aging and additives on the solubility of water in oil: a—base oil, b—base oil with additives, c—used oil ([20])

Different oils are capable of dissolving water depending on their base and additive composition and, therefore, have different water saturation levels (Table III.).

The water solubility in oil increases exponentially with temperature. Fig. 6 shows the temperature dependence of the water saturation level for commercial hydraulic mineral oil with the operation temperature of 40 °C [20]. The saturation level is 0.06 wt% at the operation temperature and 0.02 wt% at the room temperature (20 °C).

Table III. Dependence of dissolved amounts of water on lubricant type

Lubricant type	Normal water content (%)	Saturation level (%)
Automotive lubricants		1–5
Diesel engine oil	0.5 (max)	
Industrial oil	0.02–0.06	0.06–0.5
Hydraulic oil	0.05–0.15	0.01–0.1
Gear box oil	0.05–0.15	
Turbine oil	0.05–0.15	0.01
Transformer oil		0.0001–0.0003
Pure mineral oil		0.0001

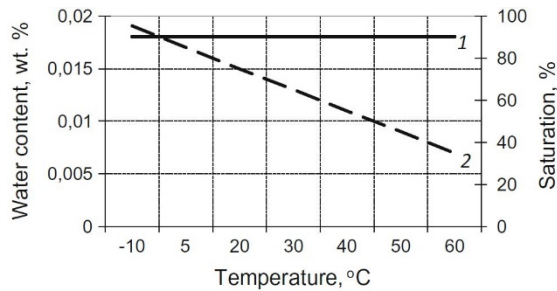


Figure 6. Temperature dependence of mass water content (curve 1) and oil saturation (curve 2) with water ([20])

Since free and emulsified water affect more harmfully compared to dissolved water it is important to prevent the appearance of free water when shut-downing the equipment (i.e. when it is cooled down to the room temperature). Therefore, in order to exclude the entering of free water when actuating the system, it is needed to monitor the moment when such water concentration is achieved in the oil at the working temperature which does not exceed the saturation level at the room temperature.

Selected cases of hydraulic oil contamination

In order to provide a more practical understanding of the effects of hydraulic oil contamination, a few indicative cases of various applications within different industries are presented next.

Mining, Forestry, Construction

Hydraulic oil analysis has been performed for single-bucket excavators used in mining operations [21]. According to the specific task assigned, the excavators can be interchangeably equipped with either a bucket or a hydraulic hammer as depicted in Fig. 7. All working functions of these excavators are carried out by hydraulic systems. They are powered by variable capacity multi-piston pump sets and a gear pump. The pump sets are directly driven by diesel engines. Proper oil parameters used in hydraulic systems of the excavators determine their reliable operation and increase the durability of their components.



Figure 7. Single-bucket excavators in the mines of rock raw materials carrying out: a) loading, b) shredding oversized lumps ([21])

The aim of this research is to: a) determine the influence of working time of hydraulic hammers on the rate of the ageing process of oil, b) assess the correctness of the time intervals between oil changes which are recommended by the manufacturers and c) propose a scheme for oil changes based on the results obtained.

Six excavator models were selected. Namely, Hyundai R 330LC-9A, Hyundai R 480 LC-9A (2 units), Hitachi ZX 470 LHC-5B, Caterpillar CAT 340F and Volvo ce 460 CL. The selection of the above-mentioned excavators was based on the fact that they had similar working periods at the mines, varying working times using the hydraulic hammers and the fact that all of them used the same type of hydraulic oil.

Indicative examples of the test results are presented. Fig. 8 and Fig. 9 show the contamination increase as a function of the hydraulic oil operation time in the R 330LC-9A excavator (working time with a hydraulic hammer was 295 hours) and in the ZX 470 LHC-5B excavator (working time with a hydraulic hammer was 385 hours).

As indicated by Fig. 8 and Fig. 9, the increase in working time with a hydraulic hammer contributes to an increase of the level of contamination. In the case of the R 330 LC-9A excavator, the hydraulic oil did not meet the requirements of the adopted cleanliness class after 600 hours of operation. In the case of the ZX 470 LHC-5B excavator, the acceptable threshold of oil cleanliness was exceeded after 400 hours of use.

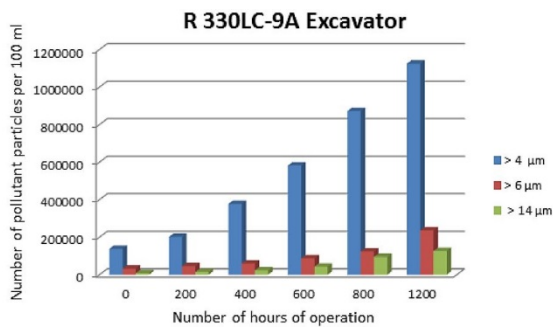


Figure 8. Content of solid particles in hydraulic oil as a function of its operating time for the R 330LC-9A excavator ([21])

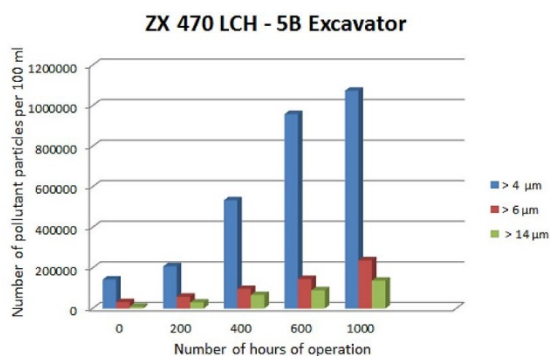


Figure 9. Content of solid particles in hydraulic oil as a function of its operating time for the ZX 470 LCH – 5B excavator ([21])

This is the result of the longer working time of the excavator with a hydraulic hammer in the first phase of operation. Fig. 10 shows the working time of the hydraulic oil in the excavators, taking into account the working time of a given excavator with a hydraulic hammer.

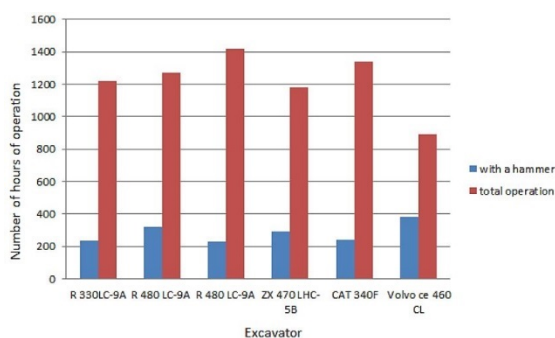


Figure 10. Service life of hydraulic oil including time of work with hydraulic hammers ([21])

It is clearly visible that the increase in the number of working hours of an excavator equipped with a hydraulic hammer results in a significant decrease in the total service life of

the hydraulic oil. This phenomenon appeared in all excavator models that have been tested.

One of the most significant findings of this research [21] is that the actual service life of fresh hydraulic oil, taking into account the working time of excavators with a hydraulic hammer, differ from the values recommended by the excavator manufacturers. The obtained test results indicate that the service life of hydraulic oil in these cases is shorter by 10-18% compared to the recommended values. It is worth noting that the degree of oil contamination increased since the beginning of the use of hydraulic hammers, and after about 180 hours of operation of the excavator with the hammer the increase in the degree of pollution was very intense. Consequently, it seems necessary to monitor the cleanliness level starting after 200 hours of operation with a hydraulic hammer.

It is worth mentioning that similar tests have been performed targeting similar pieces of hydraulic machinery such as the Baljer & Zembrod handling line shown in Fig. 11 [22], ESSEL 180Z and Epsilon 250 Z hydraulic cranes shown in Fig. 12 [23], Caterpillar hydraulic excavator shown in Fig. 13 [24] and a 22 t excavator operating in construction works [25].



Figure 11. Handling line Baljer & Zembrod ([22])



Figure 12. Hydraulic cranes a) ESSEL 180Z and b) Epsilon 250 Z ([23])



Figure 13. Caterpillar hydraulic excavator

Among other findings, these analytical experiments [22-25] have drawn a common conclusion regarding hydraulic oil contamination. They have concluded that it is inadequate to base the maintenance scheme of hydraulic machinery solely on the guidelines and recommendations of OEMs and hydraulic oil providers. It is because of uncertainties about the specific conditions of products operating in the field make it extremely difficult for OEMs to plan maintenance schedules efficiently and cost effectively. This results in a greater risk that products are under-maintained, which can lead to failure. It is proposed that systematic oil contamination monitoring provides vital information that can help service technicians to follow and conduct suitable service procedures to prolong a product's service life, and prevent downtime.

Furthermore, it is suggested [25] that the main focus in contamination detection should be metallic particulates such as Cu and Fe, as they are considered as wear metal and represent the majority of the main materials used in current hydraulic components such as pumps and valve blocks. However little research can be found in both academia and industry to allow metallic particulates to be detected at the required resolution level [25].

The particulates shown in Figs. 14 and 15, are built-in contaminants. The grain on the sliding wear particle shown in Fig. 14 indicates the direction of the sliding motion.

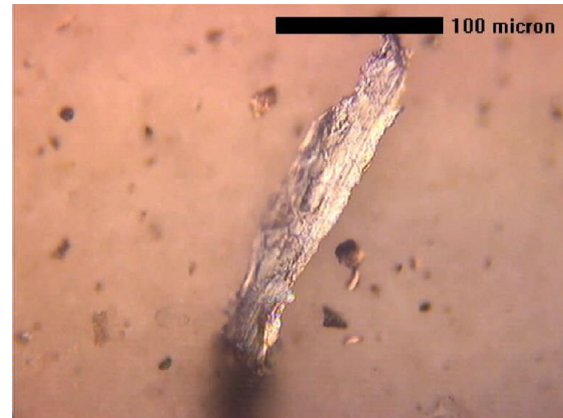


Figure 14. 1st Filter microscopic image A ([25])



Figure 15. 1st Filter microscopic image B ([25])

The particulates shown in Figs. 16 and 17, tended to be flat with irregular shapes, which is an indication of fatigue wear, and most commonly occurs by normal and tangential force through contacting asperities [25].

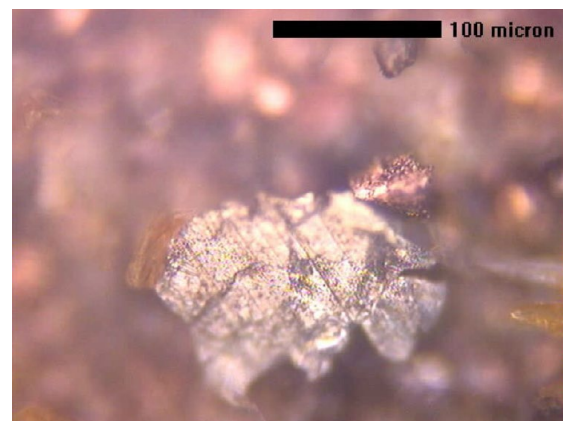


Figure 16. 4th Filter microscopic image A ([25])

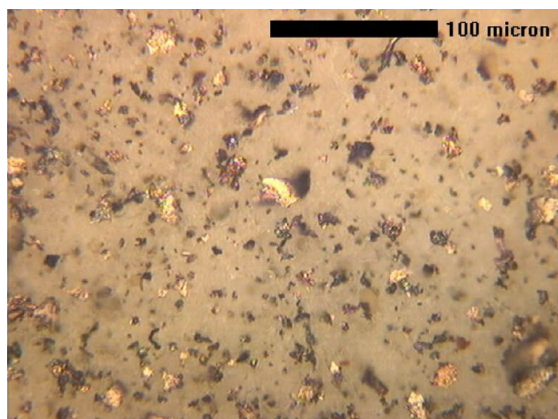


Figure 17. 4th Filter microscopic image B ([25])

Marine

An accident that highlights the significance of clean hydraulic oil in a hydraulic system is presented next, based on the accident report by the National Transportation Safety Board (US) [26].

On August 12, 2014, the outbound bulk carrier Flag Gangos collided with the berthed oil tanker Pamisos on the Mississippi River at Gretna, Louisiana. The Flag Gangos subsequently allided with a pier at the facility where the Pamisos was berthed and the pier struck and damaged a fuel barge, WEB235 berthed behind the Pamisos. No one was injured, but about 1,200 gallons of oil that was being transferred at the time spilled from the transfer lines and some of the oil entered the river. Damage amounts were reported as \$16 million for the terminal, more than \$500,000 each for the Flag Gangos, shown in Fig. 18 and the Pamisos, shown in Fig. 19, and about \$418,000 for the fuel barge.



Figure 18. The Flag Gangos after the accident ([26])



Figure 19. The Pamisos after the accident ([26])

During post-accident examination, after extensive testing and inspections, investigators discovered that a hydraulic solenoid valve and coil had failed in the port side of the hydraulic control block of the Flag Gangos' steering system (SV850-3 FCP400 rotary vane steering gear system). The hydraulic valve was jammed with debris and unable to move properly. The coil failed electrically and was unable to actuate the hydraulic solenoid valve as designed.

In addition, soon after the newly-built Flag Gangos left the Guangdong shipyard, onboard alarms indicating clogged steering system filters began to activate repeatedly. From October 2013 through April 2014, the alarms activated as frequently as 48 times per month. In response to the filter alarms, the engineering crew would open, inspect, and clean the filter inserts—although the filters reportedly looked clean—and put them back in service. After the chief engineer sent a guarantee claim to the Guangdong shipyard, new and larger filters and housings were sent out but took nearly 8 months to reach the Flag Gangos due to the bulk carrier's operating schedule. Once the new filters were installed in June 2014, the filter alarms no longer activated. However, the crew did not send samples of the hydraulic oil ashore for analysis to determine the cause of the filter alarms at any time after the alarms activated. The steering system's operating instructions stated that the oil should be analyzed every 6 months.

After the accident, in March 2015, investigators obtained oil samples from the steering system and filters and sent them for

laboratory analysis, and the results were “critical” (in a possible range of “good,” “caution,” and “critical”) for the port side. This oil, which should be clear and light yellow in color, was dark yellow and turbid with visible debris. Microscopic examination showed ferrous particles, oxides, sand, and silt. The results from the portside filter were also “critical,” with very high levels of ferrous particles, sand, plastic particles, and dust.

The oil analysis from the starboard side revealed clear oil without visual foreign matter; nevertheless, the oil was dark yellow in color and the overall diagnosis was “caution.” The oil from the starboard side filter was also diagnosed “caution”; it contained ferrous particles, sand, dust, silt, and lube degradation products.

Guidelines for hydraulic oil cleanliness

Hydraulic fluid features

Hydraulic fluids have the primary purpose of transferring potential or kinetic energy (pressure and movements), create volume flow between pump and hydrostatic motor, and reduce the wear of parts that rub against each other. In addition, they protect the system from corrosion and help carry away the heat produced during energy transformation.

Tables IV, V give an outline of the requirements for hydraulic fluids. For most of the identifying characteristics listed in the tables, already exist standards or at least preferred testing procedures which allow a numerical classification of these identifying features.

Viscosity

A hydraulic fluid has a low viscosity when it is thin and a high viscosity when it is thick. The viscosity changes with the temperature. If the temperature increases, viscosity is reduced. If the temperature decreases, viscosity is increased. Hydraulic units work under extreme temperature changes, especially in heavy duty vehicles.

The viscosity range of the hydraulic fluid is extremely important. The hydraulic fluid must be thin enough to flow through the filter, inlet and return pipes without too much resistance. On the other hand, the hydraulic fluid must not be too thin, in order to avoid wear due to lack of lubrication and to keep internal leakage within limits.

Typically, the kinematic viscosity 'v' (1 cSt = 1 mm²·s⁻¹ = 10⁻⁶ m²·s⁻¹) is used for calculations, mainly for calculating the pressure drop in the connecting hoses and pipes.

Table IV. Necessary characteristics of hydraulic fluid

Required	Prerequisites
Volume stability	adequate capacity to separate air
Wear protection capacity	for a hydrodynamic or hydrostatic fluid layer between sliding surfaces adequate viscosity at operating temperature for all others wear reducing additives
Corrosion protection capacity	non-aggressive toward customary materials and rust protection additives

Table V. Desirable characteristics of hydraulic fluid

Desirable	Prerequisites
Only slight change in usage	adequate oxidation resistance for some cases of application adequate de-emulsification capacity adequate shear stability, if polymer viscosity index improvers are used
Viscosity–temperature behavior	so that oil changes due to summer and winter operation become redundant adequate Viscosity–Temperature behaviour
Interaction with seals / gaskets	standard sealing materials can be used minimal characteristics changes of standard elastomers

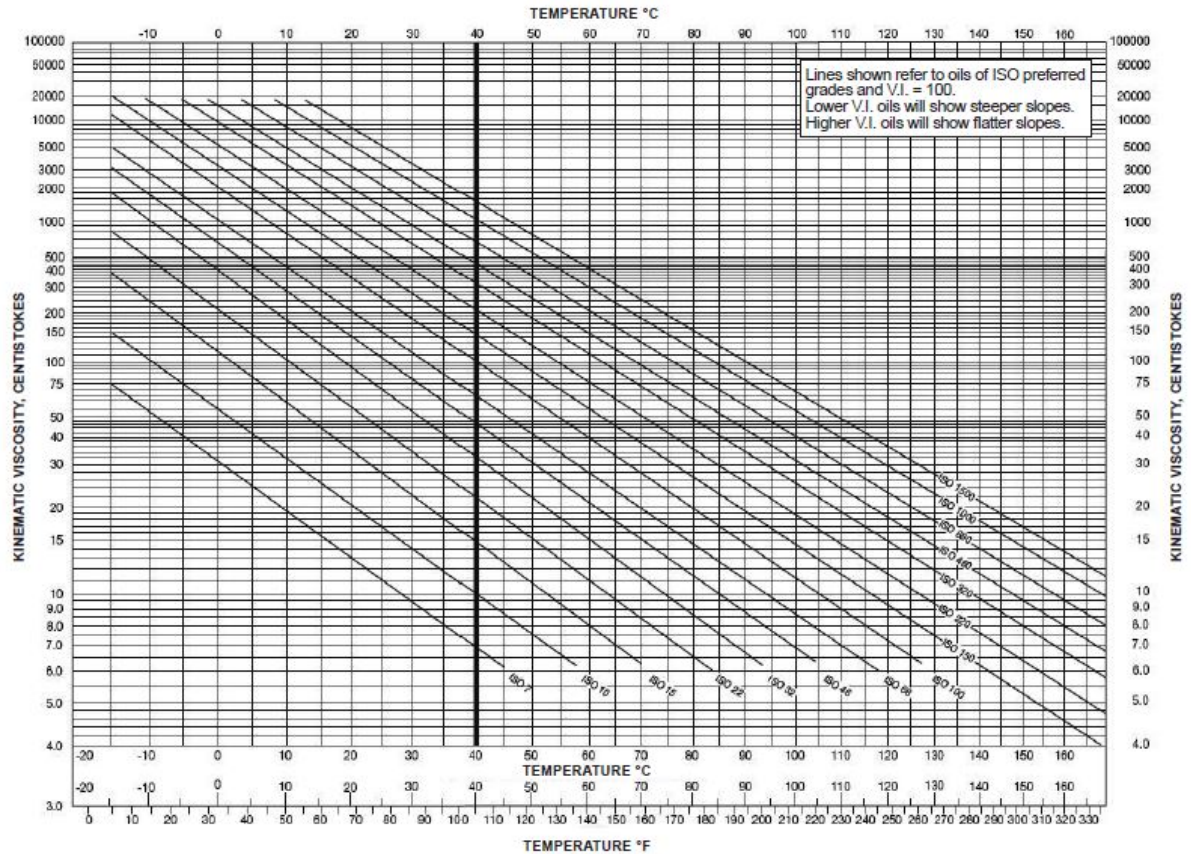


Figure 20. Viscosity – Temperature diagram

The other measure is the dynamic viscosity ' η ' (mPa·s). Dynamic viscosity is used for calculating the lubricating film thickness in a journal bearing and similar sliding films between adjacent parts. The relation between kinematic and dynamic viscosity is:

$$\text{Dynamic viscosity} = \text{kinematic viscosity} \times \text{density}$$

$$\eta = \nu \cdot \rho \text{ (mPa} \cdot \text{s)}$$

Viscosity index (VI)

The viscosity index is a calculated number according to DIN ISO 2909, which describes the viscosity change of a mineral oil based or a synthetic fluid in dependence of temperature. High viscosity index means a small viscosity change when the temperature changes while a low index means a large viscosity change when the temperature changes. Viscosity – temperature diagram is shown in Fig. 20 representing the temperature operating range of hydraulic fluids with different viscosity index (VI).

Hydraulic fluids with a VI larger than 110, e.g. between 130 – 200, are not as sensitive to temperature change. These hydraulic fluids distinguish themselves by starting up well and having minimal loss in performance at low temperatures. At high temperatures a sufficient sealing effect and protection against wear is achieved by using hydraulic fluids with high viscosity index. The high durability of a hydraulic fluid with a high viscosity index avoids damage and machine breakdown, lowers the operating cost and increases the life of hydrostatic transmissions and units.

Shear stability

Fluids using polymer viscosity index improver may noticeably shear down (> 20 %) in service. This will lower the viscosity at higher temperatures below the originally specified value. The lowest expected viscosity must be used when selecting fluids.

Pour point

The pour point according to ISO 3016 defines the temperature when the fluids stops to flow. Start up temperature is recommended to be approximately 15 °C above hydraulic fluid pour point.

Density

The density has to be specified by the manufacturer of the hydraulic fluid. Using hydraulic fluid with a high density requires the sufficient diameter of the suction line and/or elevated tank to provide positive inlet pressure.

Sealing compatibility

The procedure for testing the compatibility of the seal material is described in ISO 6072. In general, NBR (Nitrile) or FPM (Fluorocarbon, Viton) is used as seal material for static and dynamic seals. For most hydraulic fluids both seal materials are suitable, but for some hydraulic fluids only one kind is preferred. When ordering hydrostatic products the desired hydraulic fluid should be specified.

Air in hydraulic fluid

Air in a system is regarded as a contaminant. Air increases the compressibility of the fluid, resulting in a “spongy” system that is less responsive. Air creates a loss of transmitted power, higher operating temperatures, increased noise levels, and loss of lubricity. Air typically enters the circuit through the suction line if the seals and fittings are not tight. This free air then may be dissolved in the hydraulic fluid. Mineral based hydraulic fluid may contain up to 9 % volume percent dissolved air at atmospheric pressure.

Air release

Air release is a measure for the time needed to release air bubbles (free air) contained in the fluid to the surfaces. Air typically enters the circuit through the suction line if the seals are not tight as explained

above. Air release time is tested according to ISO 9120.

Foaming characteristic

Foaming characteristic defines the amount of foam collected on the surface in the reservoir and the air bubble decomposition time. Foaming may become a problem when air has entered the circuit as explained above, through an insufficient tight suction line. The foaming characteristic of a hydraulic fluid is tested according to ISO 6247.

Bulk modulus

While fluids are usually considered incompressible, the pressures that can occur in hydrostatic systems are of a magnitude that fluid compressibility can be significant. In applications that experience system pressure fluctuations resulting in random high pressure rise rates, consideration must be given to fluid compressibility when sizing a charge pump to ensure adequate charge pressure.

The amount that a specific fluid compresses for a given pressure increase is related to a fluid property known as the bulk modulus. The bulk modulus is a measure of a fluids resistance to being compressed. It depends on pressure and temperature. The air content is important as well especially below 50-100 bar [725-1450 psi]. The higher the air content the spongier the system (lower bulk modulus). For a given pressure increase and fluid volume, a fluid with a large bulk modulus will experience a smaller reduction in volume than a fluid with a low bulk modulus.

Mathematically, bulk modulus is defined as follows:

$$E = \frac{\Delta p \cdot V_0}{\Delta V} = \text{bar}[\text{psi}]$$

Where:

E = bulk modulus of the fluid bar [psi]

Δp = change in pressure bar [psi]

ΔV = change in volume l

V₀ = volume of oil experiencing the change in pressure l

Bulk modulus increases with increasing pressure (stiffer) and decreases with increasing temperature (spongy). The relation between bulk modulus and Δ pressure for different temperatures can be seen in Fig. 21. Bulk modulus increases with increasing pressure (stiffer) and decreases with increasing temperature (spongy).

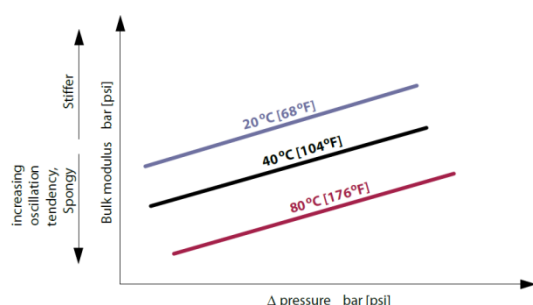


Figure 21. Bulk modulus - Δ pressure diagram

Compressibility

Compressibility is the reciprocal of the bulk modulus. It defines how much a fluid can be compressed. It is defined as:

$$\text{Compressibility} = \frac{1}{E} = \frac{\Delta V}{\Delta p \cdot V_0} = \text{bar}^{-1} [\text{psi}^{-1}]$$

Fluid compressibility becomes a concern for a hydrostatic system which has large volumes of oil under pressure, such as long or large system lines, and experiences high system pressure spikes during operation.

Water solubility

Base oils of different types have limited water solubility. Blending the base oils with additives leads to a significant increase of the water solubility. Also, the amount and the kind of used additive packages are crucial for this property. There is a general thumb rule: the higher the amount of additives, the higher the water solubility of a fluid. Consequently, different fluid types have different water absorptive capacity, which depends on the molecular structure and the additive packages of the fluid. Some fluid types are able to dissolve more water by integrating it in the molecular structure, others less. When the

absorbance of water reaches the saturation point, residual water separates from the fluid forming free water. Dissolved water in fluid is less harmful than free water, since it is bound and has no reactivity. In case of pressure or temperature fluctuations dissolved water can get undissolved leading to an enormous change of fluid properties. The consequences of that are listed above. Strongly increased content of free water in a fluid can be detected optically, since it is leading to a clouding of the fluid.

β -ratio, efficiency, filter fineness

The β -ratio is defined in ISO 16 889 Multi-pass test as:

$$\beta_x = \frac{\text{Number of particles} > x \mu\text{m upstream of the filter}}{\text{Number of particles} > x \mu\text{m downstream of the filter}}$$

As a characteristic number the β_{10} -ratio is to be specified.

Example:

$$\beta_{10} = \frac{500 \text{ particles} > 10 \mu\text{m upstream of the filter}}{10 \text{ particles} > 10 \mu\text{m downstream of the filter}} = 50$$

This number defines the ratio of the number of particles before and after the filter. This means from 500 particles larger than 10 μm before the filter, 490 particles are retained in the element and only 10 pass through or from 50 particles before the filter, 49 are retained and only 1 passes through. This can be expressed as a filter efficiency:

$$\text{Filter efficiency} = \frac{500 - 10}{500} = \frac{50 - 1}{50} = 98\%$$

$$\text{Filter efficiency} = 1 - \frac{1}{\beta_{10}} = 1 - \frac{1}{50} = 98\%$$

Efficiency makes the filter performance more understandable. The table below shows clearly the relationship between β -ratio and efficiency. In practice the following term is often used: $\beta_x = 75$ (= 98,67% efficiency). Increasing the β -ratio by 50% (from 50 to 75) the efficiency only increases by 0.67%,

Efficiency increase is shown indicatively in the Table VI., the $\beta_{10} = 75$ -ratio has been established as a standard. This specifies the particle size (indicated as “X”) were the β -ratio is equal to 75. This particle size is used to classify the filter fineness. The term absolute filter fineness may not be used. Together with the β -ratio the related differential pressure at the filter element has to be specified.

Table VI. β -ratio - efficiency

β -ratio	efficiency
1.0	0
1.1	9.1
1.5	33.3
2.0	50.0
2.5	60.0
3.0	66.6
3.1	67.7
4.0	75.0
5.0	80.0
7.0	85.7
9.0	88.9
10	90.0
50	98.0
60	98.3
70	98.6
75	98.67
80	98.7
90	98.9
100	99.0
200	99.5
500	99.8
1000	99.9
2000	99.95
-	

ISO 4406 cleanliness levels

The cleanliness level of a hydraulic fluid is determined by counting the number and size of particles in the fluid. The number of particles is defined as a cleanliness level according to ISO 4406. The ISO code is expressed in 3 numbers. Each number quantifies particulate contamination levels per milliliter of fluid at 3 sizes $4\mu\text{m}$, $6\mu\text{m}$ and $14\mu\text{m}$ (example: 19/17/14, 19 specifies the number of particles larger than $4\mu\text{m}$, 17 specifies the number of particles larger than $6\mu\text{m}$ and 14 specifies the number of particles larger than $14\mu\text{m}$ related to 1 ml respectively 100 ml of the inspected fluid). It is important to note that each time a code

increases, the quantity range of particles is doubling and inversely, as a code decreases by one the contaminant is cut in half.

Table VII. ISO 4406 code chart

Range Code	Particles per milliliter	
	More Than	Up to/Including
24	80000	160000
23	40000	80000
22	20000	40000
21	10000	20000
20	5000	10000
19	2500	5000
18	1300	2500
17	640	1300
16	320	640
15	160	320
14	80	160
13	40	80
12	20	40
11	10	20
10	5	10
9	2.5	5
8	1.3	2.5
7	0.64	1.3
6	0.32	0.64
5	0.16	0.32
4	0.08	0.16
3	0.04	0.08
2	0.02	0.04
1	0.01	0.02

The cleanliness of a fluid is one of the most important features to guarantee a satisfying performance of the hydraulic system. Contamination of a fluid with solid particles can lead to a failure of the complete hydraulic system by locking of the pistons or blocking the valves. Different systems have different sensitivity to solid contamination of the fluid, so different levels of fluid cleanliness are determined by ISO 4406. The determination of the cleanliness level is made by counting the particles, distinguishing the particle size.

Fluid cleanliness requirements

To achieve the specified unit life a cleanliness level as shown below must be met (Table VIII and Fig. 22). Fluid samples shall be taken either in the loop or at the entry to the pump, which is typically the suction line. Fluid cleanliness requirements depends on the

product and the products' acceptable continuous or rated pressure limits.

Table VIII. Fluid cleanliness requirements according to product

Product	Required cleanliness class ISO 4406	Curve in the diagram (Required fluid cleanliness)
Steering components with open center	22/20/17	A
Orbital motors	22/20/16	B
Steering components with LS and closed center	21/19/16	C
Proportional spool valves		
Axial & radial piston pumps and motors	22/18/13	D
Gear pumps and motors		
Cartridge and electrohydraulic valves	18/16/13	E

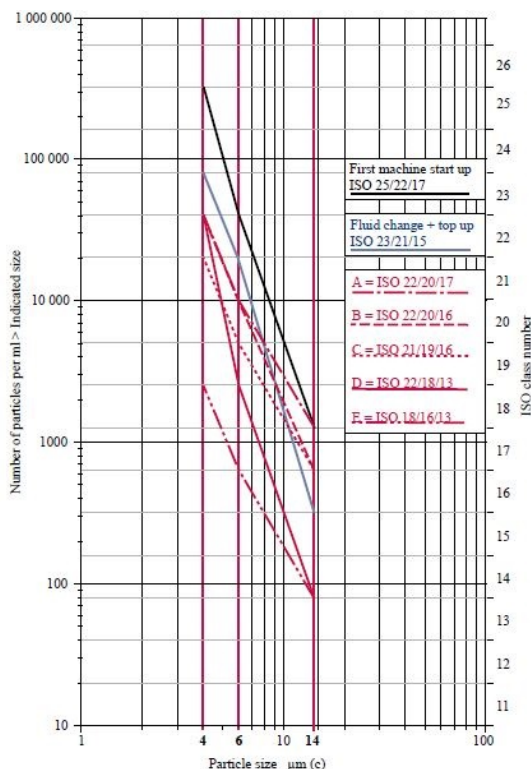


Figure 22. Required fluid cleanliness diagram

These cleanliness levels cannot be applied for hydraulic fluid residing in the component housing/case or any other cavity after transport.

In general, for fluid change and new fluid top up minimum cleanliness class 23/21/15 and for first machine start up at the factory minimum cleanliness 25/22/17 must be met if not otherwise specified. Exceeding these levels may result in start-up damage.

The before mentioned requirements reflect the experience gained from a broad range of applications. For very high lifetime requirements or contamination sensitive components (e. g. servo valves) better cleanliness levels are necessary.

Function test of DLT-30 oil filtration system

Description of DLT-30 oil filtration system

The DLT-30 oil filtration system shown in Fig. 23 performs two basic functions, oil-water separation through coalescence and multi-stage membrane filtration. The system is integrated on skid mount for increased adaptability. DLT-30 is suitable both for hydraulic and lubricant oil filtration.



Figure 23. DLT-30 oil filtration system

The equipment consists of 9 main sub-systems: chassis, oil filtration system, oil heating system, oil-water separation system, vacuum system, water condensation system,

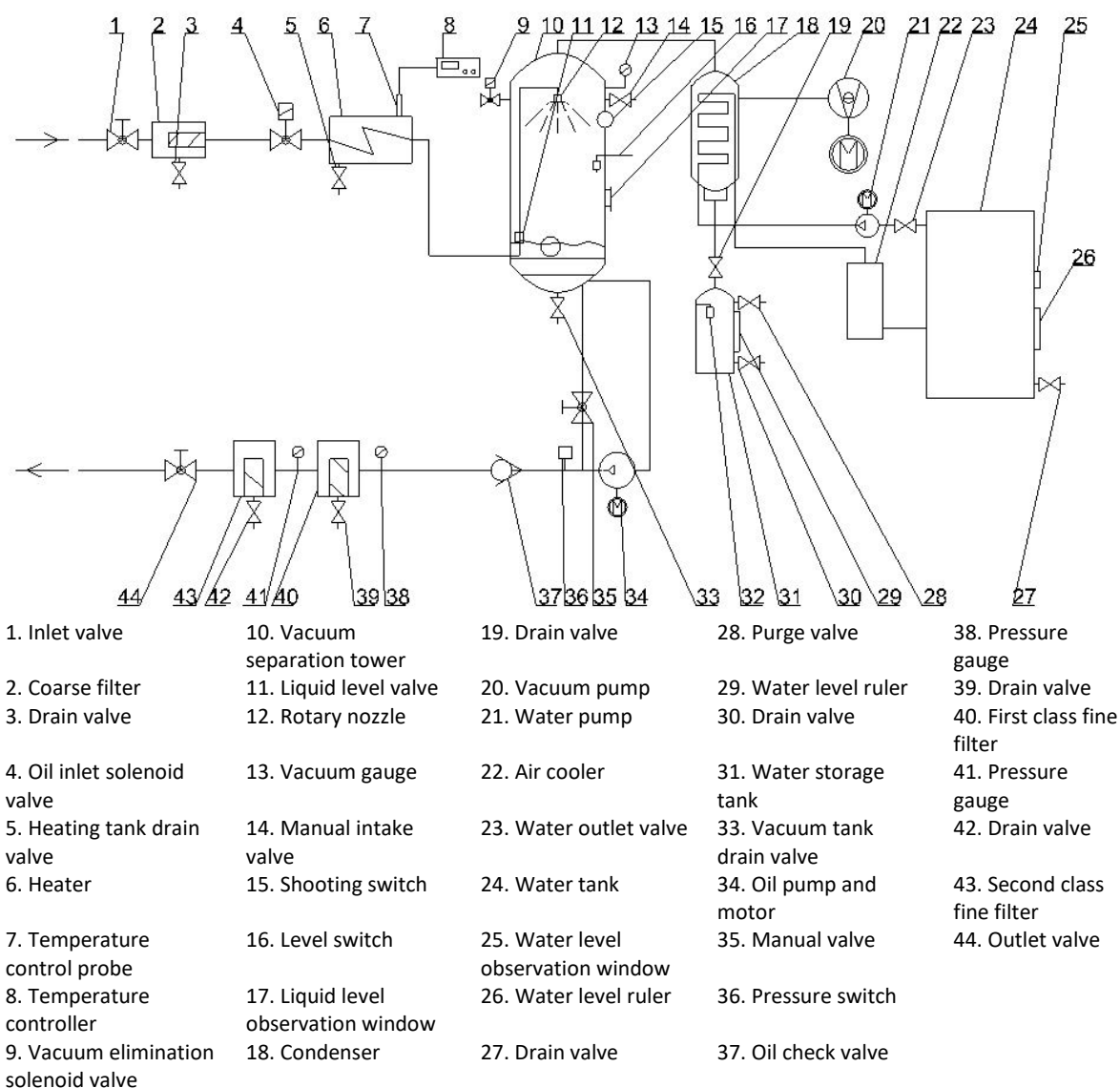


Figure 24. DLT-30 workflow diagram

oil circulation system, pipeline/valve system and electric control system. A qualitative depiction of the system's function is provided by the workflow diagram shown in Fig. 24.

The technical parameters as provided by the manufacturer are presented in Table IX.

Sampling procedure

The function test of DLT-30 has been conducted under the guidance and supervision of ISE Pumps Engineering, at the request of the equipment's distributor, Hydrotitan Ltd Cyprus. The sample analysis has been performed by Hexagon Solutions.

The aim of the test was to verify the performance of the system with regard to the

Table IX. DLT-30 technical parameters

Performance parameters		Model
		DLT-30
Operating parameters	Flow(L/min)	30
	Breakdown Voltage (KV)	≥50
Degree of vacuum (MPa)		-0.06 ~ -0.09
Working pressure (MPa)		≤0.4
Noise level at operation (dB)		≤75
Gas content (%)		≤0.1
Cleanliness level class (NAS)		6 - 8
Total heating power (kW)		20
Power supply		50Hz 380V
Oil in/out pipe diameter (mm)		25
Oil temperature (°C)		20-80

achieved cleanliness level. Thus, a detailed technical assessment of the system is out of

the scope of this report.

The hydraulic oil that was used for this test had already been disposed of by the initial user. The subject oil batch was used in the hydraulic network of a bulk carrier's crane; however, it has not been possible to retrieve detailed information about the specific conditions of operation. The knowledge that the subject hydraulic oil was significantly degraded (had already been disposed of) combined with visual inspection which showed the specific batch was in very poor condition, ensured that the oil subject to filtration and analysis would be highly contaminated. In terms of viscosity it is an ISO VG 46 hydraulic oil.

The sampling took place on the 14th of June 2020. The total volume of the hydraulic oil that has been filter is about 60 L. Before the initiation of the filtration process, the total volume of the oil was recirculated several times in the storage tank with the use of the system's circulation pump. This allowed the sediment of solid and water contaminants to be distributed evenly in the volume of the oil, creating a homogeneous mixture and simulating the actual operating conditions of the hydraulic oil. The high water-content made that evident even by visual observation of the oil in the storage tank as shown in Fig. 25 and Fig. 26. In Fig. 26 the emulsification of the mixture is clearly visible.



Figure 25. Test batch of hydraulic oil before the recirculation in the storage tank



Figure 26. Test batch of hydraulic oil after the recirculation in the storage tank

After the recirculation of the oil in the storage tank the operating temperature of the system was set to 75°C at the control panel as shown on Fig. 27. The oil heaters were electronically controlled during operation keeping the temperature relatively stable, only exceeding the set temperature for a few seconds until the temperature dropped and the heaters operated again.



Figure 27. Operating temperature during the filtration process of the hydraulic oil

Before the sampling a quantity of about 2 L was drained from the draining valve in order the valve to be flushed and the sample to be as representative as possible (Fig. 28). This allowed any sediment in the valve to be carried away. The drainage and the continuous flow of the oil enhanced the sampling method. The special sampling kits were provided by Hexagon Solutions (Fig. 29).



Figure 28. Drainage of the hydraulic oil before sampling



Figure 29. Sampling of the hydraulic oil with continuous flow, after drainage



Figure 30. Samples before and after filtration

The distinctive colour difference is indicative of the poor condition of the tested oil. The difference is observable even though the special sampling bottles are not completely transparent as shown in Fig. 30.

In Fig. 31 the array of the paper membranes can be seen as well as the change in colour after the filtration. The component where the membrane filtration takes place can be used independently from the dehydration component. For the purpose of this function test an array of 18 paper membranes has been used.

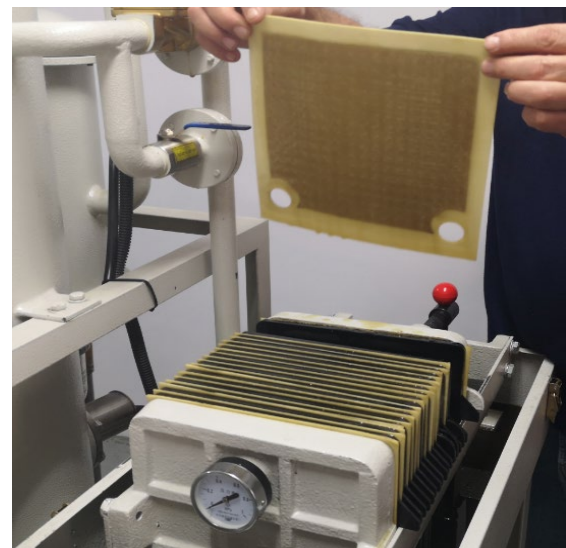


Figure 31. Membrane filtration component and membrane colouring after the filtration

Analysis results and discussion

As already mentioned, the analysis of the samples has been conducted by Hexagon Solutions. In Table X. the physicochemical properties of the two samples (before and after the filtration) are presented along with the additives' analysis. "Sample 1" refers to the sample before the filtration and "Sample 2" refers to the sample after the filtration. In Table XI. the element analysis is presented.

Hexagon Solutions use a three-colour scale to visually indicate the significance of each measurement. "White" - normal, "Grey" – attention and "Red" – serious.

Table X. Physicochemical characteristics and additives

Physicochemical characteristics		
Date: 17/6/2020	Sample 1	Sample 2
Viscosity at 40°C	46.46 cSt	46.46 cSt
Appearance	30	10
Water	1623 ppm	171 ppm
TAN	0.52	0.55
ISO cleanliness level	24/21/17	19/16/12
Non-distinguishable	0.1 ppm	0.06
Additives (ppm)		
Ba	<1	<1
Ca	100	71
Mg	9	7
P	235	233
Zn	64	67

Table XI. Element analysis – wear particles

Element analysis		
Date: 17/6/2020	Sample 1	Sample 2
B	<1	<1
Na	52	17
Si	2	1
Li	<1	<1
Al	1	1
Cr	<1	<1
Cu	5	4
Fe	25	24
Pb	1	1
Sn	<1	<1
Mo	<1	<1
Ni	<1	<1
Ti	<1	<1
Ag	<1	<1
Mn	<1	<1
V	<1	<1

The most important value of the above analysis within the scope of this report is the ISO cleanliness level. The DLT-30 filtration system demonstrated a satisfactory increase of the cleanliness class by five levels in the ISO scale. Namely, from ISO 24/21/17 (marked “Red” – serious by Hexagon Solutions) the filtered oil met a cleanliness ISO level of 19/16/12 (marked “White” – normal by Hexagon Solutions). The reader can refer to the “ISO 4406 cleanliness levels” paragraph of this report where the ISO scale is explained.

According to Table VII, the number of particles larger than 4µm went from the range of 80,000-160,000 (24 in the ISO 4406 code chart) down to the range of 2,500-5,000 (19 in the ISO 4406 code chart).

The number of particles larger than 6µm went from the range of 10,000-20,000 (21 in

the ISO 4406 code chart) down to the range of 320-640 (16 in the ISO 4406 code chart).

The number of particles larger than 14µm went from the range of 640-1300 (17 in the ISO 4406 code chart) down to the range of 20-40 (12 in the ISO 4406 code chart).

When the cleanliness target for a specific hydraulic application has to be set and maintained, it is safe to adopt a cleanliness level at the range of 19 per ISO 4406. The reader can refer to “Fluid cleanliness requirements” paragraph of this report and more specifically to Table VIII and Fig. 22. The relevant cleanliness requirements reflect the experience gained from a broad range of applications. Nevertheless, best practices have to be always in place with regard to hydraulic oil handling and the specific instructions of the hydraulic component’s manufacturer have to be taken into consideration.

Another interesting finding is the dehydration performance of the system. DLT-30 achieved a reduction in water content from 1623 ppm (marked “Red” – serious by Hexagon Solutions) to 171 ppm (marked “White” – normal by Hexagon Solutions). Considering that the tested oil operated in the marine environment (ship crane) it is assumed that water ingress must have been substantial. That has also been evident by the emulsification of the sample before the filtration.

Macroscopic visual examination is standardized according to the qualitative scale shown in Table XII. The tested oil showed a remarkable visual enhancement, scaling from 30 (Hazy) to 10 (Clear and bright). This is how the tested oil is expected to have appeared before it was used.

Table XII. Element analysis – wear particles

Appearance	
Clear and bright	10
Dark	20
Hazy	30
Cloudy	40
Emulsified	50
Two-phase	60
Solid debris	70

It is worth mentioning that when lubricant oil is to be examined, darker colouring is to be expected in the same scale.

The additives show a very small reduction, this is probably due to the progressive clogging of the filter membranes which led to a partial entrapment of additives. Typically, the size of additives is smaller than 4µm and close to 2µm in order to avoid being entrapped by filter elements.

The ferrous content is an important indicator of increased wear between the moving parts of the components in the hydraulic system. Hydraulic oil monitoring and analysis can lead to targeted maintenance of the specific components.

Once more it has to be noted that in relation to specific analytical measurements, detailed knowledge of the specific operating conditions of the hydraulic system is needed. That would allow to make more accurate assessment of the analysis. However, it is safe to expect a cleanliness level at the range of 19

per ISO 4406 if the DLT-30 system is properly used and maintained.

Conclusion

Hydraulic oil is one of the most important elements of any hydraulic system. Maintaining a specific cleanliness level is very important as it can ensure the extended service life of the system's components. At the same time, it will contribute to a reduced life-cycle cost of the system as the total downtime will be kept to a minimum. The required cleanliness level for a hydraulic system is largely based on the sensitivity of its components. DLT-30 oil filtration system demonstrated a satisfactory performance. According to the described function test it achieved an ISO cleanliness level of 19/16/12. Based on the experience gained from a broad range of applications, a cleanliness level of this range can be deemed adequate for a wide spectrum of hydraulic appliances. Understandably, for each specific hydraulic component the manufacturer's specifications have to be considered with focal point the clearances between moving parts. Achieving and maintaining the required cleanliness level for a hydraulic system is not an easy task as it is affected by a number of factors. Nevertheless, it is clear that filtration planning and implementation for a hydraulic system is pivotal for the efficient performance of the system.

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