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How to check the compatibility of hydraulic fluids through laboratory testing

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Summary

A lubricant is selected for a target application and should perform these functions over the intended service life. However, when lubricants become mixed, performance may change, and depending on the degree of incompatibility, potentially lead to a catastrophic machine failure. Interactions between a fluid's ingredients may occur and lead to a lack of additives solubility, a change in composition or a deterioration of performance.

The evaluation proposed in this article is a step-by-step approach. Firstly, a review based on information we have on Hydraulic Fluid (HF) components chemistry. Next there is an evaluation of some mixtures to check signs of visual incompatibilities before carrying out filterability tests and surface properties deterioration.

The last step is to check the long-term compatibility through laboratory performance tests, considering the fluids composition, the operating conditions, the materials, the seals, and the environment.

1. Introduction

Hydraulic fluid is a non-compressible fluid which is primarily used to transfer power within machinery and equipment. The heart of any hydraulic system is the pump, which draws fluid through its inlet and forces the fluid through its outlet, usually against pressure created by valves, plumbing, and actuators downstream of the pump. Pumps, actuators, and other system components have surfaces that move relative to one another, often at high speeds, pressures, and temperatures. These components require cooling and lubrication for efficient performance and durability.

Hydraulic systems are most commonly found in construction and industrial vehicles, such as excavators or fork-lift trucks, but these fluids are used in many other applications like log splitters, lifts, snow plows, aircraft, air tools, tractors, ships and others.

Hydraulic systems are being optimised to become more compact and operate in more severe conditions than in the past. The smaller oil quantity, higher pressure and temperature as well as mechanical constraints require the additives and lubricants manufacturers to create better performance lubricants. The need for oxidation and corrosion resistance, thermal stability, good surface and anti-wear properties make the formulation more complex, using more advanced chemistries.

Most hydraulic fluids consist of a mineral or synthetic base fluid and a combination of additives; they are classified according to ISO 6743-4 in 15 categories based on their base fluid type, applications and composition & properties.

Due to the variability of components, precautions have to be taken while mixing fluids together. It is important to check the compatibility between hydraulic fluids.

For some companies, inadvertent or unintentional mixing of fluids is a frequently encountered problem. Mixing different fluids may be the result of improper markings on containers, similar product descriptions, lack of knowledge or information given to operators, and even carelessness.

The degree of incompatibility can vary from complete to slight depending on the miscibility, the base oils and additives chemistries and the loss of fluid performances.

2. Miscibility and compatibility

Differences must be made between miscibility and compatibility. Lubricants use a combination of several base oils and additives in a precise ratio to obtain the desired performances; when mixing, reactions can occur to form insoluble materials, flocculation or stratification.

2.1 Miscibility

The miscibility is the ability of two substances to completely mix in any concentration to form a homogeneous solution.

Separation phase, flocculation, stratification, insoluble materials (precipitation) characterise immiscible fluids.

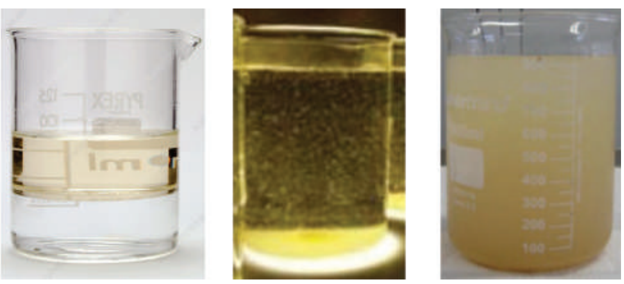

Figure 1. *Examples of immiscible fluids*

It is obvious that immiscible fluids are incompatible.

2.2 Compatibility

The term compatibility is a general term which can be used for metals, seals, paints, materials, ...

Hydraulic fluid compatibility is the ability of hydraulic fluids to mix without degradation of properties or performances.

When hydraulic fluids are mixed, interactions between fluid's ingredients may occur and lead to a lack of additives solubility, a change in composition or a deterioration of performances. Although new hydraulic fluids may be compatible, in-service fluid of the same type may be degraded or contaminated to such an extent that the new fluid added may not be compatible with the system fluid. In-service fluid compatibility with new fluid additions should also be evaluated on a case-by-case basis to check if the mixtures still have the required properties.

3. Hydraulic Fluids categories

The categories of hydraulic fluids within this classification ISO 6743-4 include:

- mineral oil which refers to specification ISO 11158 for categories HH, HL, HM, HR, HV, and HG; the difference between categories is based upon additive content. From HH non-inhibited, HL contains rust and oxidation inhibitors, while HR additionally include VI improver. HM fluids contain antiwear in addition to rust and oxidation inhibitors. HG fluids contain similar anti-wear additives to HM fluids plus additives for improved stick/slip performance and friction modifiers. The basic chemistry of HV fluids is similar to HM fluids but includes a VI improver.
- environmentally acceptable fluids which refer to specification ISO 15380 for categories HETG, HEES, HEPG, and HEPR; (base oil chemistry in table below)
- fire-resistant fluids which refer to specification ISO 12922 for categories HFAE, HFAS, HFB, HFC, HFDR, and HFDU;

3.1 Chemistries of hydraulic fluids

Base oil composition exhibits some of the greatest contributions to finished fluid properties such as viscosity – temperature behaviour, pour point, thermal resistance and oxidative stability, compatibility with seals. Nevertheless, some of these properties can be enhanced with the use of additives in combination with base oils; the formulators search for the best synergic effects between additives themselves and base oils.

Hydraulic fluids have many chemical functions, summarised in the table below:

Type HF	Category	Base oil chemistry	Typical additives chemistry
Mineral Oil	HH	n-alkane	Phenols, amines, dithiophosphates, dithiocarbamates(AO) Triazole derivatives, amines, sulphides, phosphites (Metal passivator) Sulfonates, dithiophosphates, phenates, salicylates, amines, amines salts, esters, imidazolines,...(Rust inhibitor) Fatty acids, fatty amines, fatty esters, P and S compounds (Friction modifier) Zn dialkyldithiophosphate - ZDTP - (antiwear containing Zn) Organic phosphate and phosphite, sulfur and phosphorus compounds (AW & EP) Polymerized olefins or iso-olefins, butylene polymers, polymethacrilate (VI improver) Alkylated naphtylene and methacrilate polymers and copolymers (Pour point depressant) Silicone polymers, acrylate esters (Antifoam additive)
	HL	iso-alkane	
	HM	cyclo-alkane	
	HR	aromatic	
	HV	Olefin	
	HS		
	HG		
EAL	HETG	Triglycerides, vegetable oils and natural esters	
	HEPG	Polyglycol	
	HEES	Synthetic esters (polyol esters, neopentylglycols,	
	HEPR	Polyalphaolefins (PAO) or synthetic	
Fire resistant Fluid	HFAE	Water - soluble oils	
	HFAS	High water-based fluid	
	HFB	Invert emulsions - water	
	HFC	Polyglycols -water	
	HFDR	Phosphate esters	
	HFDU	Polyol esters	

Table 1.

3.2 Main incompatibilities depending on base oils and additives chemistries

The maintenance of the fluid composition is critically important if optimal performance has to be guaranteed.

The general classification of lubricant incompatibility are:

- Mixtures of some base oils can reject additive solubility
- Base oils can chemically react or reject other base oils
- Base oils can react with foreign additives, forming transformation products
- Additives can clash, forming insoluble reaction products
- Additives can neutralise, dominate or alter the performance of other additives.

Without going too much into details, we can already list some examples of incompatibilities based on base oils and additive chemistry.

- Water-based hydraulic fluids with non-water based fluids
- Mineral oil based fluids with environmentally-acceptable lubricants will impact the environmental properties (biodegradability and eco-toxicity) as well as viscosity – temperature behaviour
- HM fluids may not be compatible with each other if the type of antiwear differs
- HFDR with mineral or ester-based hydraulic fluids
- HEPG fluids contain polyglycols which may be incompatible with mineral-based hydraulic fluids.
- Hydraulic fluid heavy metal-free and hydraulic fluid heavy metal-containing (generally zinc). Both additive systems are most often incompatible with each other.

The chemical functions change with tribo-chemical reactions due to heat, friction, wear, oxidation, pressure and mechanical stress so it becomes even much more complex with lubricants in use.

4. Evaluation of HF compatibility step-by-step

There are many risk factors related to lubricant cross-contamination and this occurs for a variety of reasons such as:

- The reduction of the number of lubricants in use
- Change in lubricant supplier (agreement not renewed)
- New machine application or reliability requirements triggers the need to switch to a lubricant with enhanced performance or modified properties
- Accidental mixing of lubricants caused by untrained personnel or packaging / labelling error

- Impossibility to drain out the previous lubricant when switching lubricant types

It begins with a vigilant inspection, looking for symptoms of incompatibility, side effects and/or impaired performance. This is where oil analysis can play a vital role to evaluate the degree of incompatibility.

4.1 Signs of incompatibility

The signs of incompatibility are:

- Stratification of the oil, flocculation, insoluble formation, deposit, gelling, silting
- Reduced filterability or filter blockage, stable foam, air release deterioration
- Loss of properties & performances, additives inefficiency. The equilibrium of the well-balanced selection of additives risks being disturbed

Integration of a higher quality lubricant can lead to a loss of properties and may have an unfavourable impact, meaning the mixture can be worse than the performances of the initial lubricants.

The laboratory approach is an evaluation of hydraulic fluids compatibility step-by-step. If one step fails, It's not required to go further. Otherwise, it is recommended to check the next steps.

4.2 Heating and cooling cycle of mixtures

The compatibility of mixtures of hydraulic fluids are examined using new lubricants and/or the effect of combining new (replacement) lubricant with in-service (original) lubricant in the system.

The proportion (% weight per weight (w/w)) when using two new hydraulic fluids is often :10/90 – 50/50 – 90/10. When the in-service fluid is used to check the compatibility, the mixtures often used are 2% (w/w) of original fluid with 98% (w/w) of replacement fluid and 10 % (w/w) of original fluid with 90% (w/w) of replacement fluid.

Other proportions may also be used.

As part of the procedure, the pure oils and mixtures are heated in an oven for a fixed period of time and then remove and cooled down before the selected tests are carried out.

In ASTM D 7752, the recommended temperature is 70°C +/- 2°C following by a cool down for 24 hours in the dark.

Some other conditions may be applied (from 24 hours to 336 hours and from room temperature to 204°C).

4.3 Step 1: visual inspection and filterability

The first step after the heating and cooling cycle is a visual examination and filterability tests (the compatibility index).

The visual examination checks for separation, flocculation, stratification and precipitation, which are all signs of immiscible fluids.

A mixture of incompatible fluids may produce a substance that is markedly inferior to its constituents. Even in identical base stocks, the formation of a precipitate may occur as a result of additive interactions.

The ability of a hydraulic fluid to pass through fine filters, without plugging them, is known as its filterability.

In this practice, compatibility will be determined using ISO 13357-1 (ASTM D 7752) or ISO 13357-2 filterability test methods. Since hydraulic systems utilise fine filtration to protect components from wear, incompatibility often exhibits itself as premature filter plugging.

The membrane used must be compatible with the type of fluid.

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The filterability test conditions are summarised hereafter:

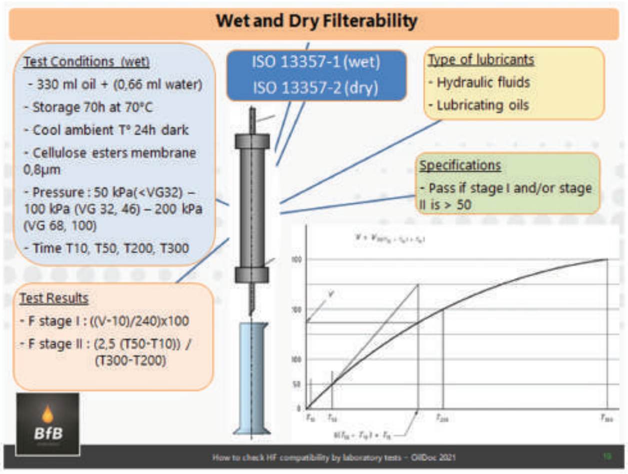

Figure 2. Description of wet and dry filterability test ISO 13357-1&2

The Stage I determination is based on a comparison of the mean flow rate of a fluid through a test membrane with its initial flow rate The Stage II determination is based upon the ratio between the initial flow rate of fluid and the flow rate at the end of the test. It is considered that the Stage II result is a more severe test and is more sensitive to the presence of gels and fine silts in the oil. When a mixture passes the Stage II of filterability ISO 13357-1, it is considered compatible.

4.4 Step 2: surface properties

The surface properties, including the air release value, the foaming characteristics and water separability are often sensitive to composition changes and oil degradation; the by-products are not only specific to the composition of the base oil and its source but will also vary depending on the degradation conditions; they are alcohols, aldehydes, ketones, esters, acids. One of the most important properties is the air release, which must remain acceptable during the fluid life. The degradation associated with the presence of air in the fluid are oxidation, fluid compressibility, Microdieseling, cavitation and wear.

A survey based on dry filterability and surface properties carried out on more than 50 miscible oils showed than more than 25% of the tested oils were not compatible.

4.5 Step 3: loss of performance

The last step is often not realised when the HF compatibility is examined. It is however important because, if the hydraulic fluids mixtures are slightly incompatible, the effect, like seals deterioration, deposit formation, oxidation, corrosion or hydrolysis won't be seen rapidly.

In any case, vigilant monitoring and inspection must be done to detect signs of incompatibility at an early stage; unfortunately, once detected, damage control and remediation as well as fluid replacement may be the only practical alternatives.

This is where product performances evaluation through oil analyses can play an important role.

The last part of this article focuses on some examples of possible incompatibility, taking into account the types of HF mixed together, the components and the material.

The most relevant test that may put into evidence the incompatibility is described.

4.5.1.1. HM or HV mixed with HL or HR in a hydraulic system which contains copper-based alloys

These fluids are all mineral oil-based. The HL and HR contain rust and oxidation inhibitors (and VI improver for HR) and are known as R&O oils. Some hydraulic fluids which contain antiwear (HM or HV) can be aggressive to yellow metal (brass and bronze) as well as silver alloyed components in piston pumps.

4.5.1.2. Top up with HE fluids (HEES)

In high pressure hydraulic system, the use of biodegradable fluids has come under scrutiny due to corrosive effects with copper-based alloys. The consequence of this type of corrosion usually occurs only after several thousand hours and can lead to substantial damages.

The most relevant test to evaluate the anti-corrosion property on yellow metal is the dynamic Linde test according to VDMA 24570. This laboratory test is a screening method capable of establishing a correlation between field experience and the results of accelerated tests.

It consists of a thermostatically controlled heater plate with the test container. The container is filled with the test fluids (89% of fluid (ester), 10% of mineral oil and 1% of water) and glass beads (550g). Four specimens of different materials (brass, cast bronze, sintered bronze and steel) are fixed on a specimen holder which is attached to the stirrer. The stirrer is inserted vertically and rotated at 200 rpm. The vertical shaft is routed through a condenser in order to keep the water content of the fluid constant. The test duration is 100 hours at 120°C. Upon completion of the test run, the weight loss is measured on each specimen and reported in g/m^2.

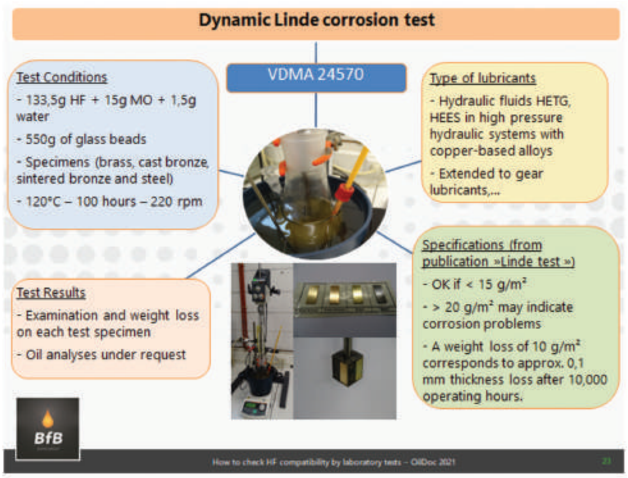

Figure 3. *Description of dynamic Linde corrosion test VDMA 24570*

4.5.2. Effect on seals when mineral oil based HF is mixed with a synthetic HF

Some incompatibilities are already known and may occur with HE fluid and NBR seals or HL fluid and EPDM seals.

The compatibility of an elastomer with hydraulic fluid is a critical factor in system performance and reliability. As there is a broad range of chemical and mechanical interactions and environmental conditions, it is difficult to predict the compatibility without being exposed to the system's fluid and environment.
An attempt may however be made with the elastomer compatibility test. The evaluation is carried out by comparison of some seals parameters (hardness, volume, tensile strength and elongation at break) before and after a soaking period.

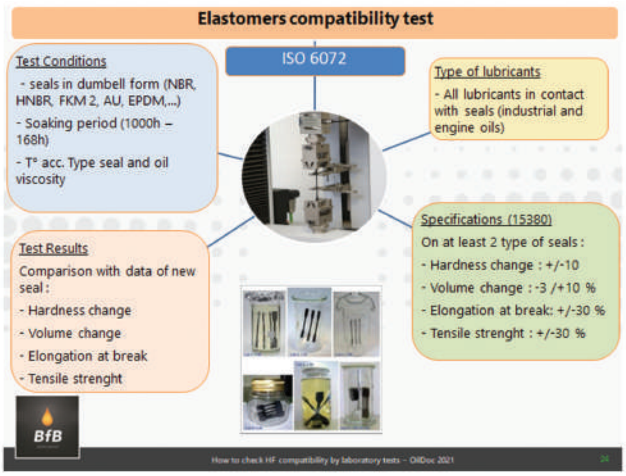

Figure 4. *Description of static seals compatibility test ISO 6072*

Figure 5. *Traction machine used for seal tensile strength and elongation at break*

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4.5.3 Top up with an ester based HF: does the mixture remain hydrolytic stable?

In unfavourable operating conditions (high water content, high temperature), ester based hydraulic fluids tend to hydrolysis (more critical with partially unsaturated ester). The acidic organic decomposition products from the ester can chemically attack materials and components.

The test ASTM D2619: Hydrolytic Stability of Hydraulic Fluids (Beverage Bottle Method) covers the determination of the hydrolytic stability of petroleum or synthetic-based hydraulic fluids.

This test method differentiates the relative stability of hydraulic fluids in the presence of water under the conditions of the test. Hydrolytically unstable hydraulic fluids form acidic and insoluble contaminants which can cause hydraulic system malfunctions due to corrosion, valve sticking, or changes in the viscosity of the fluid. The degree of correlation between this test method and service performance has not been fully determined.

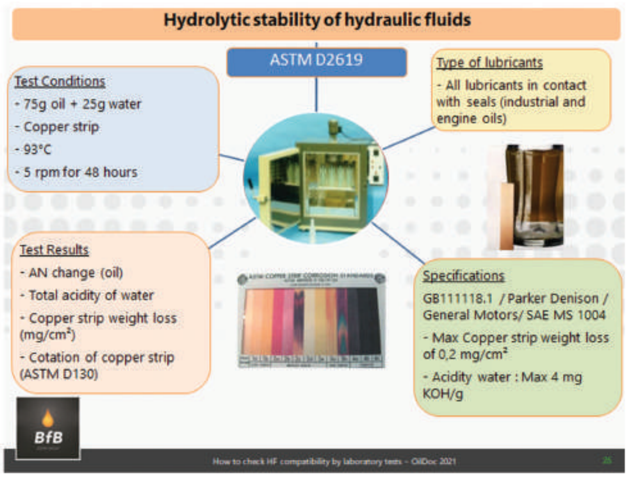

Figure 6. Description of hydrolytic stability test ASTM D2619

In this test, a copper test specimen and 75 g of test fluid plus 25 g of water are sealed in a pressure-type beverage bottle (Cola bottle which is resistant to a high pressure). The bottle is rotated for 48 h in an oven at 93 °C. Layers are separated and the weight change of the copper specimen is measured. The acid number change of the fluid and acidity of the water layer are determined.

In the literature we also found the following incompatibilities:

- HF with rust inhibitor that contains succinic acid mixed with rust inhibitor calcium-based used in antiwear HF: HL and HM fluids may result in the formation of precipitates that can cause valve sticking and filter plugging.
- HM type hydraulic fluid with ZDTP mixed with another HM containing Zn-free or ashless AW additives may not be compatible with each other.
- Water-glycol fluids are highly alkaline due to the presence of amine-based corrosion inhibitors. As a result, this fluid can attack zinc, cadmium, magnesium, and on-anodized aluminium, forming sticky or gummy residues. Fluorocarbon-based elastomers, such as Viton, are also incompatible with amines.

Add	In	Properties to be checked
HEES / HETG	HL/HM/HR/HV	Fluidity Cold properties Hydrolytic stability Oxidation resistance Sludge tendency Thermal stability Corrosion properties Seals compatibility
HL/HM/HR/HV	HEES / HETG	Antiwear properties Corrosion properties Hydrolytic stability Seals compatibility Biodegradability Toxicity
HEPR/HS	HL/HM/HR/HV	Seals compatibility Additives solvency
HL/HM/HR/HV	HEPR/HS	Oxidation resistance Thermal stability Cold properties Seals compatibility Deposit formation
HFDR /HFDU	HL/HM/HR/HV	Fire resistant properties

Table 2.

After the above examples, a selection of the most relevant tests that can reveal a long-term incompatibility between hydraulic fluids are listed in the table above.

The mentioned properties must consider the fluids composition, the operating conditions, the materials, the seals, and the environment, ...

5. Conclusion

Hydraulic fluid is one of the most vital components of a hydraulic system.

Interpretations must be done carefully when we speak about fluid compatibility. Even if a lubricant manufacturer or an operator declare the hydraulic fluids are miscible, are they compatible? In other words, does the HF mixture still provide the required properties at the same performance level as the original fluids.

The evaluation proposed in this article is a step-by-step approach. Firstly, a review based on information we have on HF components chemistry.

Next, there is an evaluation of some mixtures to check signs of visual incompatibilities before carrying out filterability tests and surface properties deterioration.

The last step is to check the long-term compatibility through laboratory performance tests, considering the fluid's composition, operating conditions, materials, seals, and the environment.

At each step, if an incompatibility is detected, it's not necessary to go further. The last step is important in order to detect a long-term risk which originally comes from a hydraulic fluids mixture.

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