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CONVERTING A FORESTRY MACHINE TO USE ENVIRONMENTALLY COMPATIBLE HYDRAULIC OILS

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Abstract

Environmentally compatible oils are now available in Canada and the first trials have been completed. This Technical Note summarizes the differences between hydraulic fluids based on mineral oils and new environmentally compatible oils, how to verify a machine's compatibility with these new oils, how to choose a hydraulic bio-oil, the required oil change procedures and how to monitor the machine's operational performance.

Introduction

FERIC's research on environmentally compatible oils ("bio-oils") began with a technical mission to Europe in 1993 that was partially funded by the Canadian Forest Service. The findings from this trip were published in a contract report (Makkonen 1994). FERIC's Western Division recently completed a study on the use of vegetable-based hydraulic oils in a truck-mounted loader (Jokai 1995). The present report focuses on hydraulic bio-oils based on vegetable oil or synthetic esters that are less toxic than mineral oils and biodegrade more rapidly. Therefore, such bio-oils have a much lighter impact on the environment because the effect of a toxic material relates to both its inherent toxicity and the exposure time. Bio-oils also cause less eczema and fewer oil-related sicknesses in mechanics and operators than do mineral oils. The pressure to use bio-oils in forestry comes from the needs to protect ground water; to conserve non- renewable resources (i.e., mineral oils); to comply with existing or impending environmental standards, regulations or legislation; and to meet customer preferences.

In the mid-1980s, hydraulic fluids based on vegetable oils were developed as a commercial product, and Germany was the first country to use them on a large scale. Testing of environmentally compatible synthetic esters began in the early 1990s, and usage of hydraulic bio-oils should increase slowly but steadily in Europe. In Canada, "Demo-92" in Kelowna, B.C., was the first national forestry equipment exhibition that dis- played hydraulic bio-oils. Only a few mobile forestry machines currently use these oils in Canada. About 2% of hydraulic fluids and lubricants in use worldwide are non-toxic and biodegradable (Busch and Backe 1993).

Hydraulic bio-oils are two and a half to six times as expensive as conventional mineral oils and their use

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can increase maintenance time. Moreover, because bio-oils perform differently than mineral oils and have different limitations, a good understanding of the subject is necessary before testing or using them operationally. The purpose of this report is to familiarize readers with the process of converting a machine's hydraulic system to use a bio-oil and to avoid implementation problems. This process comprises four steps: determining the hydraulic system's compatibility with bio-oils, choosing an appropriate oil, developing an oil-change procedure, and monitoring the system to confirm safe and adequate performance. An overview of this process is provided on page 12, and details are discussed in the following sections.

As research on bio-oils is ongoing, some information in this report may soon become outdated. *All change-over and maintenance procedures must be approved by the oil's supplier and the machine's manufacturer to avoid warranty problems.*

Differences Between Bio-oils and Mineral Oils

Common hydraulic bio-oils are based on vegetable oils or synthetic esters; however, synthetic esters are a large group of chemical compounds, and not all are bio-oils. Some vegetable oils are mixed with up to 30% synthetic esters. Bear in mind that there are more differences among bio-oils than among mineral oils due to a lack of standards and the newness of these products.

Although bio-oils are similar to mineral oils (hydrocarbon base, lubricity, density, specific heat, viscosity, viscosity index, and bulk modulus), there are important differences (Table 1). These differences may require changes in maintenance procedures and ma- chine design. The most important differences include:

1. **Oxidation Stability** - Synthetic esters have relatively good oxidation stability and some can even withstand higher temperatures than mineral oils. In contrast, vegetable oils oxidize at lower temperatures than mineral oils, and oil temperature in the reservoir should not exceed 70 to 80°C for extended periods. However, it is difficult to keep summer reservoir temperatures below 80°C in many machines. The products of oil oxidation are acidic and will accelerate oxidation further; they will also oxidize the surfaces of components (Busch and Backe 1993), and as components rub against each other, the oxidized layer will release into the oil. This will show up in the oil analysis as wear particles. Antioxidant additives help to neutralize the acids caused by oxidation or inhibit the oxidation process.

2. Vegetable oils and synthetic esters are more sensitive to **hydrolytic splitting** than mineral oils. Hydrolytic splitting is a form of oxidation that occurs in the presence of water at high temperatures. In practice, it is difficult to differentiate between hydrolytic splitting and oxidation. A concentration of 500 ppm water (0.5 L in 1000 L) may be acceptable, but oil deterioration will accelerate in hot systems at higher water contents. Mannesmann Rexroth GmbH, a leading manufacturer of hydraulic components, recommends

Table 1. Comparison of unused hydraulic oils based on different base oils[a]

	Influence on humans	Influence on environment	Lubricity	Pour point	Oxidation	Price
Traditional mineral oil	-	-	-	0	0	+
White mineral oil[b]	+	0	0	0	+	0
Vegetable oil	+	++	+	-	-	0
Synthetic ester	+	+	+	+	0	-
Synthetic PAO oil[c]	+	0	+	+	+	--

[a] The ratings shown vary from "--" (undesirable technical feature or environmentally harmful) to "++" (desirable technical characteristic or environmentally harmless).
[b] Highly refined oil used where a high degree of purity and chemical stability is required.
[c] Poly-alpha-olefin oil is an extremely stable oil synthesized from mineral oil.

(Anon. 1992) that synthetic esters should be changed when the water content reaches 1000 ppm. Synthetic esters are often used in high-temperature systems, but in addition to hydrolysis, corrosion of non-ferrous metals can occur. Even in systems that operate at lower temperatures, oil should be changed or purified when its water content exceeds 2000 ppm. Oxidation and hydrolytic splitting both increase the viscosity and acidity of the oil. Often, however, the viscosity of the oil will drop at first because thickeners, viscosity index improvers and pour-point depressants partially break down before oxidation and hydrolytic splitting begin.

3. The **pour point** of vegetable oils is around -20°C, but can be lowered to about -40°C with additives (Figure 1). However, not all manufacturers add the optimal amount of pour-point depressants, resulting in a higher pour-point temperature. When vegetable oils cool below their pour point, they begin to solidify (i.e., crystallize), and starting a hydraulic pump under these conditions can result in pump failure. To decrystallize the oil, the whole machine must be warmed up to -15°C. Note, however, that pour point alone does not fully describe a vegetable oil's cold behavior. In long-term cold-soak tests, these oils crystallize at temperatures above their pour point; the longer the cold-soak, the higher the crystallizing temperature. In cold-soak tests carried out at -26°C by Statens Maskinprovningar in Sweden (Johansson 1994), some vegetable oils showed signs of crystallization after 16 days, and all four vegetable oils tested showed at least some crystallization after 26 days (two had solidified almost completely). The three synthetic esters used in these tests did not crystallize, but the viscosity of one synthetic ester was too high for start-up at -30°C and the viscosity of another was at the start-up limit. Cold-soak test results with a different vegetable oil are shown in Figure 2 for temperatures more typical of Canadian conditions; the supplier can provide more specific information on oil crystallization during long-term exposure to low temperatures.

Figure 1. The pour point, start-up viscosity and crystallizing temperature of a bio-oil must be appropriate to the operating environment.

4. **Bio-oils have somewhat poorer filterability** than mineral oils. Filterability measures the extent to which clean new oil blocks a test filter. In practice, filters may have to be changed at irregular intervals or more often than with mineral oils when bio-oils are used.

5. **Bio-oils release air more slowly** than mineral oils. If air bubbles tend to form within mineral oils in a given system, bio-oils are not recommended since they will "aggravate the situation" by increasing the

	Temperature (°C)			
Test duration (h)	-40	-37	-35	-33
12	+	+	+	+
24	+	+	+	+
36	-	+	+	+
48	-	+	+	+
60	-	+	+	+
72	-	+	+	+
84	-	+	+	+
96	-	+	+	+
108	-	-	+	+
120	-	-	+	+
132	-	-	+	+
144	-	-	+	+
156	-	-	+	+
168	-	-	+	+

Figure 2. Cold-soak tests of Raisio vegetable-based hydraulic oil ("+" indicates acceptable fluidity and "-" unacceptable fluidity).

likelihood of bubbles forming. Small reservoirs with suboptimal design accentuate the problem.

6. In laboratory tests, **bio-oils release metals** such as lead, copper, tin and zinc from alloys used in bushings and seal plates, as shown in oil analysis reports (Johansson 1994). However, premature component failure is not believed to have occurred due to this leaching, which can be reduced with additives (Busch and Backe 1993).

7. Synthetic esters are generally more aggressive than vegetable oils on seals. **Bio-oils attack natural rubber, and butyl and styrene-butadiene rubbers**. Binol Filium AB claims (Davner 1994) that nitrile, Viton® and acrylate seals work well with vegetable oils. There are many different nitrile rubbers on the market with various compatibilities, and the German seal manufacturers' association's compatibility recommendations are provided in Table 2 (Peschk 1993). In strongly oxidized oils, seals swell and lose elasticity much faster than in new oils.

8. **Conventional hydraulic hoses can deteriorate** over time in bio-oils (Davner 1994; Törmänen 1995). The hose's inner liner loosens, then stretches and breaks, preventing oil flow or causing a leak. The rate of oxidation of leaked oil increases in the presence of sunshine, dirt and microorganisms, and the corrosive, acidic oxidation products may dissolve a hose's outer shell. Several hose manufacturers have therefore introduced hoses designed specifically for use with bio-oils. However, one such product tested by Statens Maskinprovningar, the BTR Greenline® hose with a nitrile rubber inner liner and neoprene rubber outer shell (Davner 1995), resisted degradation little better than regular hoses (Johansson 1994).

9. Leaking bio-oils, and especially vegetable oil, tend to adhere to and later harden on the surfaces of the machine. Hardened oil is difficult to remove. Alkaline cleaners are recommended.

Verifying Machine Compatibility

Most hydraulic systems in forestry equipment are designed to use mineral oils, and many are incompatible with bio-oils. New machines with piston pumps are usually more suitable than older machines or machines with gear or vane pumps. The following guidelines will help to determine if a machine is compatible before beginning a conversion to bio-oils. *However, the conversion process should be discussed with the manufacturer to confirm that the warranty will still be honored.* The manufacturer may also provide important advice on compatibility, and may not recommend using bio-oil in particular machines.

- **Avoid converting old machines with dirty systems**. Their hydraulic systems can be hard to clean, and sediments in various components of the system can contain chemicals that react with a new type of oil. Contractors in Finland claim that seals and hoses in old machines often start to leak after a machine is converted to use bio-oils (Törmänen 1995).

- **Test the miscibility** of an oil sample from the machine and the proposed bio-oil to avoid

Table 2. Seal material compatibility with bio-oils (+ = compatible, - = incompatible)

	Seal material[a]				
	NBR, X-NBR	H-NBR, P or S	AU	FPM1, FPM2	EPDM, SBR
Vegetable oil	+	+	+	+	-
Synthetic ester	+[b]	S only	+	+	-

[a] NBR = nitrile-butadiene rubber, X-NBR = carboxylated nitrile-butadiene rubber, H-NBR = hydrogenated nitrile-butadiene rubber (P = biphenolicly linked, S = sulfuricly linked), AU = polyurethane, FPM = fluorine rubber, EPDM = ethylene-propylene diene rubber, SBR = styrene-butadiene rubber.

[b] With pre-testing only.

surprises. This is recommended for older machines or those in which oils (e.g., engine oil or automatic transmission fluid) other than regular mineral oil-based hydraulic fluid were used.

- **Determine oil cleanliness and water and wear metal contents** by analyzing an oil sample or by reviewing previous records, and *verify the filter's performance and compatibility*. Contaminated oil results from inadequate filter size, infrequent filter changes or an overly coarse filter element. The return-flow filter's nominal flow should be at least three times the following figure: the pump's flow (L/min.) multiplied by the cylinder's bottom-end piston area (mm²) and divided by the cylinder's rod-end piston area. For this calculation, choose a cylinder that is often used with full flow and that has (relatively) the thickest piston rod. For example, for a 230 L/min (60 U.S. gal/min) pump and a cylinder with a 127-mm (5-in.) diameter and a 51-mm (2-in.) diameter rod, the filter's flow capacity should be:

  $$\text{Flow} = 3*230 \text{ L/min} * (\pi/4)(127)^2/(\pi/4)(127^2-51^2)$$
  $$= 822 \text{ L/min.}$$

  The use of clean, unoxidized oil increases component life and clean oil oxidizes more slowly. Bio-oils are more expensive than mineral oils, thus extending their life span is important for reducing operating costs. Therefore, the Swedish recommended bio-oil cleanliness code is 15/11 as per ISO 4406[(1)] (Myhrman 1995). The highest code (i.e., dirtiest oil) recommended for a mobile machine with piston pumps and proportional valves is 17/14. The filter should have an absolute rating of 5 μm ($\beta_5 > 75$) for code 15/11 and 10 μm ($\beta_{10} > 75$) for code 17/14. Table 3 provides more examples of recommended cleanliness levels. Note, however, that these levels are currently being reviewed and will likely become stricter. If the sys- tem operates at low temperatures and a low maxi- mum working pressure (<16 MPa), slightly more contamination may be acceptable. A filter-bypass warning light or filter pressure gauge and oil tem- perature gauge are recommended. Verify that the filter elements are compatible with bio-oils, since some elements disintegrate in bio-oils.

- **Monitor the hydraulic system's operating temperature** during the warmest season. The difference between the ambient and oil temperatures is almost constant when the oil cooler's thermostat is fully open (the temperature difference becomes somewhat smaller as the temperature increases).

Table 3. Minimum recommended hydraulic system cleanliness limits[a]

Component or type of system	Recommended cleanliness limits according to ISO and NAS								
ISO	13/10	14/11	15/12	16/13	17/14	18/15	19/16	20/17	21/18
NAS	4	5	6	7	8	9	10	11	12
Servo valves									
Regulator valves									
Proportional valves									
Pumps (p >16.0 MPa)									
Pumps (p <16.0 MPa)									
Low-pressure hydraulics									
Required filterability[b] $\beta x = 75$ $\beta x = 100$	--- 3	--- 3	3 ---	5 ---	10 ---	20 ---	25 ---	25-40 ---	

[a] These standards are undergoing revision, and will likely be tightened.
[b] "x" is the required particle size (mm) above which a 75 or 100 times reduction in particle count is required.

(1) In the ISO 4406 standard, the quantities of contaminant particles >5 and >15 μm are counted per unit volume. Quantity ranges are coded using two numbers that range from 4 to 23: the first refers to particles >5 μm and the second to particles >15 μm.

The cleanliness of the machine and of its oil cooler, as well as the intensity of the duty cycle, will determine the temperature difference. To measure this difference, record oil and ambient temperatures with a data collector for about a week during the warmest season. (When a data collector is unavailable, recording can be done manually with thermometers, but the results may be less reliable.) The oil cooler should be clean at the beginning of the test. Carry out cleaning as usual and record the time of each cleaning. This information will help in subsequent evaluations of variations in the temperature difference. Adding the temperature difference to the hottest expected seasonal temperature yields the maximum expected oil temperature, which will help determine the choice between a vegetable oil and a synthetic ester. Even with synthetic esters, relatively low operating temperatures are recommended to prevent hydrolytic splitting and seal deterioration, and the oil cooling capacity may have to be increased in some machines.

Table 4. Examples of measured ambient and oil temperatures for seven forest machines

Machine		Temperature (°C)		
		Ambient	Oil	Difference
Forwarder	1	2	53	51
	2	-2	35	37
	3	40	110	70
Grader	4[a]	30	65	35
	5[a]	20	110	90
Delimber	6[a]	25	100	75
Harvester	7	-5	47	52

[a] Data from unpublished 1995 FERIC field study; other data from Table 21 in Makkonen (1994). Due to the variability of the data, every machine should be monitored to determine its unique temperature charac- ter- istics.

Table 4 provides examples of measured ambient and oil temperatures. Adding the difference between the two to the actual ambient temperature will give the expected oil temperature, assuming that operating conditions and operator input remain constant. Table 4 shows that the variability among machines of the same type can be high. For this reason, FERIC suggests that the operating oil temperature of each individual machine should be tested to determine its compatibility with different oils. For example, machines 2 and 4 could use vegetable oils if the maximum ambient temperature remains less than 35°C; conversely, machines 1 and 7 are at the limit of safe conditions for the use of vegetable oil, and machines 3, 5 and 6 could only be evaluated for synthetic esters or traditional mineral oils.

- To minimize contamination caused by air exchange, **the reservoir's breather (Figure 3) should incorporate a filter;** moreover, if water is a problem, the breather should also remove water from incoming air (e.g., by including a desiccant unit). The presence of water in oil samples can indicate condensation caused by alternating low and high oil operating temperatures, a long parking time or poor positioning of the air breather (in which case, relocation may reduce the water content). If the system is pressurized, verify that the pressurizing valve functions properly. A pressurized reservoir reduces cavitation, but also inhibits separation of air from the oil.

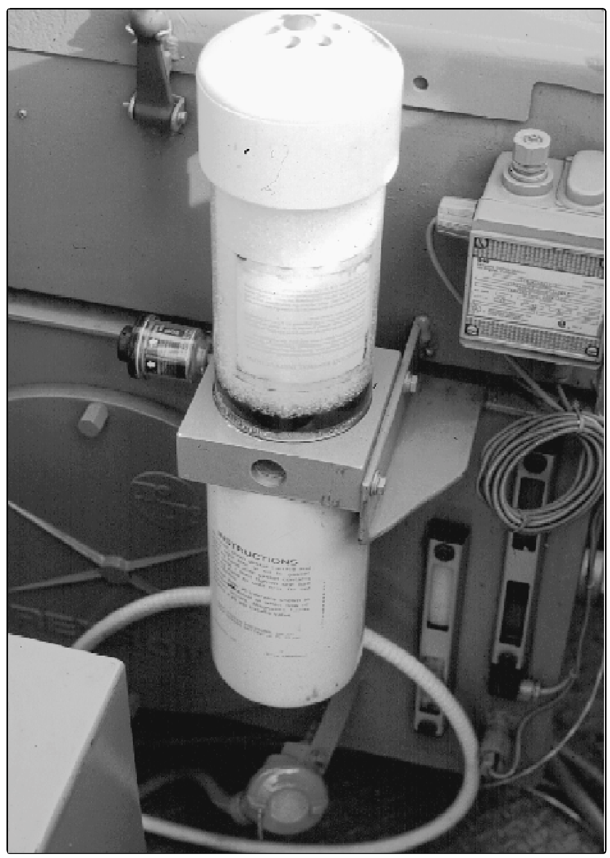

Figure 3. A reservoir's breather with a desiccant unit.

- **Verify that seal materials and hydraulic hoses are resistant to bio-oils**. Synthetic esters are usually more aggressive than vegetable oils on seals and hose inner liners. However, hydraulic hose outer shells, electrical wire harness covers, window-mounting rubbers and paint may dissolve when exposed to leaking vegetable oil or synthetic esters.

- Machines with long and undersized suction lines or elevated pump placement may experience **pump cavitation** caused by the slightly higher density of bio-oils, especially during cold starts.

- Vegetable oils and synthetic esters are unsuitable for systems with wet disc brakes or clutches or with transmission synchronizing rings because the oils form a hard, slippery surface that reduces friction on contact areas.

- **Confirm that the oil heater is approved for use with bio-oils**. Mineral oil heaters (7750 W/m^2) are generally too hot for vegetable oils, which will break down and form carbon deposits on the heater element. As the deposit grows, the heating element's temperature increases during heating and an explosion may eventually occur.

Choosing an Oil

Although vegetable-based oil is more expensive than mineral oil, it is significantly less expensive than synthetic esters and should be chosen when possible. The most common reason for not using vegetable oil is its low resistance to oxidation. The oil temperature must not exceed 70 to 80°C for long periods of operation. Vegetable oils also tend to crystallize over time in cold weather above their pour point temperatures. Because decrystallatization of the oil is time-consuming and requires a heated enclosure around the machine, vegetable oil should not be used when the risk of oil crystallization is high. Vegetable oil also requires frequent cleaning of the machine to prevent hardening of the oil on surfaces. This shortcoming may sometimes be a factor in choosing a synthetic ester for leaky machines.

Contact several oil suppliers and request that they provide all possible information and test reports on their products to find the best possible oil for your machine's specific operating conditions. When you speak with other users, inquire about operating conditions and temperatures.

Once a machine has been approved (and modified, if necessary) to use a synthetic ester or a vegetable oil, a product can be chosen based on the known operating temperature range and the hydraulic system's viscosity requirements. Many hydraulic systems are most efficient when the oil viscosity (which depends on temperature and the oil's properties) is between 15 and 50 cSt. The maximum permissible start-up viscosity varies among machines depending on system design, and can range from 5000 to 8000 cSt. Find the temperature at which the oil reaches the minimum permissible viscosity, usually between 10 and 13 cSt. The machine should not be used when the oil is hotter than this temperature. Determine the oil temperatures for the abovementioned viscosities and compare them with the machine's operating temperatures.

Changing the Oil in the Whole System

- **Manage waste bio-oils and mineral oils separately**. Waste oil containing bio-oils is usually destined for burning, whereas most mineral oil is destined for re-refining. Contact your waste oil collector for further advice.

- **Don't mix different types of oils**. Pure mineral oils and bio-oils are miscible, but problems have arisen from the presence of additives and system contaminants. For example, motor oil dispersants contain calcium, which can greatly reduce the filterability of bio-oils, and automatic transmission fluid and diesel fuel also undergo reactions that reduce filterability, reduce boundary lubricity and cause sedimentation or foaming. Additionally, a mixture of bio-oil and mineral oil is less biodegradable and possibly more toxic.

- **Flush systems thoroughly before converting a machine to use bio-oils**. The oil reservoir's capacity is often about half that of the entire hydraulic system. Some operators only change the oil in the reservoir and allow the remaining oil to stay in the system until it is changed gradually by top-ups that replace leakage. In such cases, top-ups amounting to three to four times the reservoir volume are necessary for the new oil to reach >90% purity (assuming that the new oil mixes fully with the rest of the oil before the next top-up). This process takes so long that chemical reactions can occur with contaminants in the old oil, causing the problems described in the previous paragraph. In one example (Johansson 1994), a front-end loader filled with bio-oil at the factory was found to contain 6% mineral oil from purchased components (pumps, motors, cylinders and valves) that had been filled or tested with mineral oil during manufacturing. In another front-end loader, the mineral oil content was 12% after the reservoir had been refilled three times. To minimize the risk of complications, there should be less than 10% mineral oil mixed with a bio-oil, and some manufacturers may require a lower content.

- **Flushing the system is fastest when all hydraulic functions are operated and the returning oil is collected in a waste-oil container**. Prevent old oil from returning to the reservoir during flushing to prevent contamination of the new oil supply. The pumps will consume all the oil in the reservoir quickly, especially in open-center systems (most often equipped with fixed-displacement pumps). Therefore, watch the oil level during flushing and stop the engine when the minimum level is reached. Operate all cylinders through two complete cycles, or three cycles if their hoses are long. Disconnect and flush cylinder hoses with volumes greater than the actual cylinder volume; the cylinder can then be actuated by connecting one hose at a time, with the cylinder exhaust flow from the other port directed to a waste oil container. Use this method for cylinders at the end of stroke delimber booms, grapple cylinders and non-continuous grapple rotators on knuckle-boom loaders. Single-grip harvester heads may have to be drained at the directional control valve in the head itself during flushing. Motor circuits must be operated in one direction until all the old oil is exhausted from the circuit. Conduct the flushing operation where all machine movements can be operated to their fullest extent (i.e., outdoors in most cases).

- **Carefully plan the flushing order** in multi-pump machines to minimize wasting new oil and to prevent old oil from returning to the reservoir. Each machine is different and needs its own flushing plan, which your dealer can provide. Some general principles include.

  a) Closed-center circuits will circulate only minimal amounts of oil when the actuators are not operated. Flushing can be carried out simply by operating all work circuits one after another.

  b) In open-center circuits, oil is always pumped when the engine is running. To avoid wasting new oil in multi-pump machines, first flush all open circuits (from pump through control valve to waste oil container) simultaneously (Figure 4). Next, redirect flow from all but one pump directly back to the reservoir. Flush the work circuits of the one connected circuit to a waste oil container, then repeat this procedure for the other circuits. Bypass any flow-control valves (e.g., proportional and priority-type flow dividers) that drive more than one circuit so that only one circuit will be flushed at a time. When all circuits have been flushed, reconnect all pumps to their circuits.

  c) Flush closed-loop hydrostatic transmissions with flush valves by connecting the drain line to a waste-oil container while operating the main pump at a lower output flow than that of the charge pump. Because the charge pump delivers oil continuously, the hydrostatic transmission circuit should be flushed first when other circuits have closed centers (e.g., many Nordic harvesters and forwarders). Open-loop hydrostatic drives with directional control valves (as in most excavators) are flushed in the same way as other work circuits.

  d) Charge pump, oil cooler and pilot circuits are often complicated and draining them must be planned carefully to avoid mixing old and new oil.

- Oil change procedure:

  a) Drain the oil from the reservoir, the oil cooler and the hoses that lead to the cooler using dry compressed air at less than 50 kPa (7 psi). **Remove dirt and sludge from the reservoir.**

  b) Connect each pump, motor and pilot-system drain hose to a **separate** waste-oil container to help verify (by volume) when all the old oil has been displaced by new oil in each unit or circuit. Connect return-flow hoses to another large waste-oil container. Plug the fittings for any disconnected hoses in the reservoir or filter.

  c) Change all filters and fill the reservoir with bio-oil. **Ensure that air can easily enter the reservoir** during flushing, since the oil level will decrease rapidly.

  d) Start the engine. Carry out flushing according to a preset plan **while the engine idles**. Stop the

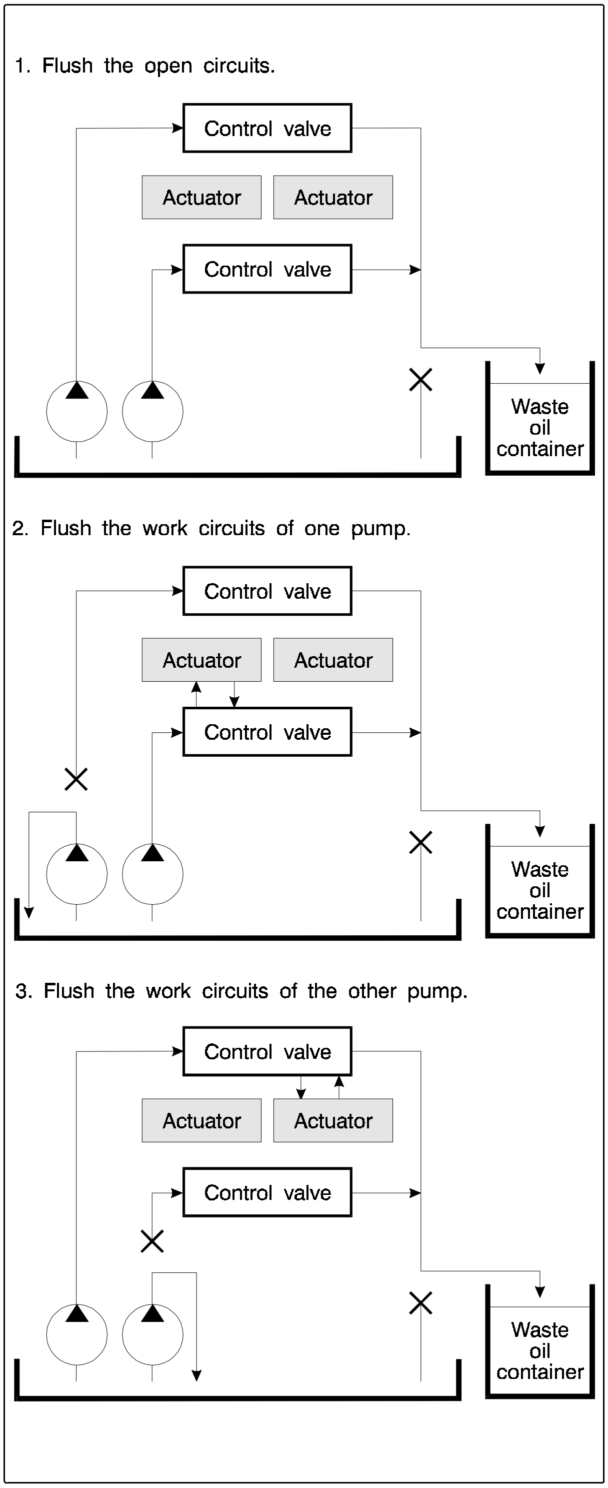

Figure 4. Flushing a system with more than one control valve.

engine when the oil level in the reservoir is low (to prevent cavitation) and top it up before continuing.

e) Once the work circuits have been flushed, reconnect the return hoses and refill the reservoir. Operate hydraulic motors until all old oil from the pumps, motors and pilot systems has drained into waste-oil containers, then reconnect the drain lines. **Check the oil level again**.

Monitoring Performance

- Conduct normal periodic maintenance. Machine manufacturers and oil dealers may request modifications to the service schedule, such as more frequent oil changes.
- Monitor hydraulic oil temperature and clean the oil cooler when the temperature starts to rise above its normal level.
- **Analyze a sample of new oil to obtain a reference for comparison.**
- Take a sample from the machine's reservoir after about 20 h of operation to verify oil cleanliness and to check that no chemical reactions are occurring.
- **More frequent periodic oil sampling is usually recommended**. Monitor oil oxidation, viscosity and water content. An increase in the total acid number (TAN) indicates that the oil is undergoing oxidation. When the TAN reaches 2, change the oil. Some oil suppliers suggest an oil change when the TAN is 3, but the higher the TAN, the more vigorously the oil will attack non-ferrous metals, seals and other rubber components. The TAN number of new bio-oils varies by make and manufacturing batch from 0.1 to 1.3. Oil oxidation is also accompanied by an increase in viscosity, but a 20% increase in viscosity is usually considered acceptable. Permissible water content varies from 1000 to 2000 ppm depending on the type of oil and the operating temperature.

- Maintain oil cleanliness. Change oil filters when alerted by the filter-bypass warning light or the pressure gauge. **Expect an early first filter change** (10 to 50 h), as bio-oils will mobilize sediments from the tank and other components. For example, certain elements such as zinc and calcium that are not part of the bio-oil additive packages will appear in the oil samples until the sediments from mineral oils are depleted and the oil is changed. Continued filter blocking can be caused by excessive levels of prior sedimentation in the system, a high residual amount of previously used oil, rapid oxidation, hydrolytic splitting, or an undersized filter.

- Change or clean the reservoir's breather at regular intervals.

- **Be careful in cold starts**, especially after a long parking period and when the oil is already partially oxidized (Busch and Backe 1993). In northern Finland, contractors using vegetable oil have complained of frequent pump breakdowns believed to be caused by cavitation (Törmänen 1995). If a bio-oil is changed only once per year (in low-leakage systems), it should be changed late in the fall to offer the best possible cold start properties during the winter.

- Since bio-oils are expensive, **repair all leaks immediately**. Wash off any spilled oil with common household detergents to prevent the development of hardened deposits.

- Some bio-oils change color but remain usable. To confirm this, analyze an oil sample and consult the oil supplier.

- Clean the machine thoroughly three to four times per year. Vegetable-based oil hardens on the machine and becomes difficult to remove if left on for too long. Synthetic esters are less prone to hardening. When oil hardens on a machine, scrape away any layer of dirt, then apply an alkaline cleaner. Wait 10 to 15 min., then wash the surface with hot pressurized water.

Storing Machines that Use Bio-oils

Follow normal storage instructions. In addition:

- Change the oil in the hydraulic system, particularly if the oil is neither clean nor in good condition.

- Wash the machine to remove any hardened bio-oil.

- With vegetable-based oil in the system, operate all cylinders once per month. If this is impossible, clean all exposed cylinder rods until they are free of vegetable oil and coat them with mineral oil or grease. Otherwise, **vegetable oil will harden on rods and damage piston-rod seals** when the machine is restarted.

- During long outdoor storage (several months) with variable temperatures reaching down to -5°C, vegetable oil can thicken without crystallizing. Warming and agitating the oil will restore its normal viscosity (Andersson 1993). Machines are rarely parked for so long, but thick oil could cause pump cavitation on start-up.

Conclusions

The pressure to use hydraulic bio-oils is mounting. However, these oils are more expensive than mineral oils and their hydraulic system requirements are different. Whereas newer machines may have hydraulic systems that are more compatible with bio-oils, converting old machines to these oils may be expensive if the oil filtering and cooling systems must be upgraded or if incompatible seals and hoses must be replaced. Extensive cleaning of the system and sealing of leaks are also recommended, and careful monitoring is necessary after conversion, as bio-oils are sensitive to extreme operating conditions that cause physical and chemical changes. The use of deteriorated oil may result in component failures (e.g., leaking seals or pump damage).

The annual hydraulic oil costs increase by $400 to $9000 depending on the machine and the hydraulic oil type, and initial conversion costs per machine vary between $800 and $25 000. Economic considerations may thus prevent conversion of some machines.

Research and development on bio-oils continue and new recommendations and products may be introduced. For example, less-expensive synthetic esters with improved properties have recently appeared on the market.

When a machine is converted to use a hydraulic bio-oil, the conversion must be done in close cooperation with the machine manufacturer and the oil supplier to ensure success and to protect existing warranties.

Disclaimer

This report is published solely to disseminate information to FERIC's members. It is not intended as an endorsement or approval of any product or service to the exclusion of others that may be suitable. Modifications to any machine without the manufacturer's approval may void the warranty and result in damage to the machine or injury to the operator. Although all attempts have been made to provide the best knowledge available, the Forest Engineering Research Institute of Canada (FERIC) makes no warranty or representation with respect to the accuracy or completeness of the information contained in this report. Moreover, since FERIC has no control over the oil conversion process itself and subsequent machine maintenance, FERIC accepts no liability as to equipment malfunction and failure, or as to personal injury, or for any losses thereby incurred.

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