Technical Note TN-280 November 1998

THE SUITABILITY OF ENVIRONMENTALLY COMPATIBLE HYDRAULIC FLUIDS IN CANADIAN FOREST OPERATIONS

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Abstract

In response to requests from its members and partners, FERIC has investigated the problems and potential of using environmentally compatible hydraulic fluids in forest operations. This report summarizes the types of bio-oils currently available, their operational characteristics, their compatibility with forestry machinery, and important considerations for their use.

Introduction

Environmentally compatible hydraulic fluids ("bio-oils") are non-toxic and rapidly biodegradable, and thus minimize damage to the environment after a spill. In addition, some bio-oils are fully or partially manufactured from renewable resources, and could potentially reduce net emissions of greenhouse gases. The clients of many forestry companies are beginning to require audits of the sustainability and environmental compatibility of the company's forestry practices and operations before placing purchase orders, and more clients will require such audits in the future. As well, many governments consider the use of bio-oils to represent good environmental policy. Thus, the use of bio-oils may become a requirement in the future, particularly on sensitive sites.

It is important to note that although these fluids have low toxicity, they can still cause environmental damage at high concentrations; for example, they can deprive other organisms of oxygen and if they cover an organism completely, can even cause death. Thus, irrespective of what fluids are used, the best way to protect the environment remains spill prevention, and this requires operators to repair minor leaks immediately and replace damaged hoses using quality materials. Making machines less prone to leaks is good environmental policy for their users, dealers, and manufacturers.

Bio-oils have only been used in a few forestry operations in Canada, such as at permanent processing sites near water and in operational tests to gain experience with the oils. Although Europeans have used bio-oils for more than 10 years, premature equipment failures and other unexplained occurrences remain a fact of life; even where tests have been successful, it's important to note that European operating conditions differ from those in Canada, and the European experience may not be applicable here. Consequently, forestry companies must become aware

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KEYWORDS: Forest operations, Forest machines, Hydraulic oils, Environmentally compatible fluids, Bio-oils, Sensitive sites.

of how and at what cost their fleets can be converted to use bio-oils, which are more expensive than mineral oils. This will be particularly important if the use of hydraulic bio-oils becomes a regulatory requirement.

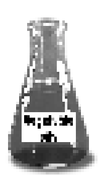
To meet the industry’s information needs, FERIC has previously reported on test machines that used hydraulic fluids based on vegetable bio-oils (Makkonen 1997a,b) and on a feller-buncher that used a fire-resistant, group I hydraulic fluid that has since obtained the Canadian EcoLogo certification (Makkonen 1996). However, to more fully assess the suitability of bio-oils under machine and environmental conditions typical of Canadian forestry operations, FERIC monitored hydraulic system performance in a sample of machines using mineral oils in various parts of eastern Canada, and compared the results with the oil manufacturer's stated requirements for each bio-oil.

The 14 machines in FERIC's study (Appendix 1) included harvesters, feller-bunchers, forwarders, delimbers, a plantation cleaning machine (with two separate hydraulic systems), and graders. To assess the suitability of hydraulic bio-oils for these machines, it was considered necessary to know the fluid's operating temperatures, cleanliness, and water content. To obtain this information, FERIC recorded the ambient and oil operating temperatures for a minimum of three shifts for each machine and analyzed one or more oil samples for cleanliness and water content. FERIC also obtained filter information from manufacturers to compare the filter's actual performance with its potential performance. To provide a context for the data, FERIC obtained ambient temperature records from Environment Canada for various parts of Canada.

Available Bio-oils

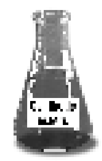
There are many types of bio-oils, and FERIC has tested only a few. To provide an overview of the offerings on the market, the available types of bio-oils are presented in this section; Appendix 2 lists some of the bio-oil brands that are currently available in Canada. At present, the availability of various bio-oils can be problematic because of limited demand.

Vegetable Oils



Rapeseed (canola) oil is the most common source for vegetable-based hydraulic fluid. Vegetable oil is pressed from seeds and refined, then an additive package is incorporated to produce the final product. Vegetable oils can also be formulated to pass Group II fire resistance requirements (see the discussion later in this section). Tall oil (pine oil) has been evaluated as a potential base stock for hydraulic fluids in Finland, but the results have been mixed. Hydraulic fluids based on vegetable oils are good lubricants and can reduce component wear compared with mineral oils. However, they have relatively poor oxidation stability and thus require low operating temperatures. In addition, their cold-temperature behavior limits their use in Canada. Costs average about \$3.50/L versus around \$1.20/L for mineral oils.

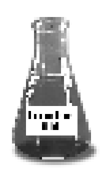
Synthetic Esters



Synthetic esters are synthesized from alcohols and saturated or unsaturated fatty acids. The alcohol component is derived from petroleum products, and the fatty acids can be derived from vegetable oils or petroleum products. Synthetic esters are generally good lubricants. Most synthetic esters are made with unsaturated fatty acids derived from vegetable oil, and are at least as resistant to oxidation as mineral oils. However, they are sensitive to hydrolysis, oxidation that occurs in the presence of water at high temperatures. Their costs average about \$6.00/L.

FERIC found only two manufacturers (Panolin AG, Madetswil, Switzerland; Fuchs GmbH, Mannheim, Germany) that produce synthetic esters from saturated fatty acids. Although these oils are much more resistant to oxidation and hydrolysis than unsaturated esters, the base material, an ester of dicarboxylic acid, is a petroleum product (van Slingerlandt 1996) and thus represents a non-renewable resource. Some manufacturers only approve these two brands of synthetic ester for the hydraulic systems of their machines. Costs average about \$8.00/L.

Fire-resistant Fluids



Group I fire-resistant fluids are water–glycol mixtures that have generally been approved only for low-pressure applications, but Union Carbide has recently developed an additive that makes the fluids suitable for use in high-pressure applications (Makkonen 1996). Water–glycol mixtures can be manufactured to be non-toxic and rapidly biodegradable. Water–glycol mixes offer better protection against fire than Group II fluids, but all spilled fluid must be washed away immediately, since the glycol is flammable once the water evaporates. Because of the fluid's high specific gravity, suction conditions are critical and must usually be improved during conversion of the machine to use the fluid (e.g., by pressurizing the reservoir), and other extensive modifications may also be necessary. Group II fluids offer somewhat better protection against fire than mineral oils, but less protection than Group I fluids. Many polyol esters and vegetable oils are formulated with approved additives to meet Group II fire resistance requirements. Improper additives can lower fire resistance. The polyol esters used as the base stock are readily biodegradable, but the additive package may be toxic. Costs average about $3.50/L for both water–glycols and polyol esters.

Test Results

Ambient and Oil Temperatures in Forestry Operations

FERIC obtained ambient temperature records for typical regions across eastern Canada. In general, maximum summer temperatures reach about 30°C in most forestry operations in eastern Canada. The lowest winter temperatures in forestry operations vary from –25°C in Atlantic Canada to –40°C in the northern forests of other eastern provinces.

The machines in this study were monitored at different ambient temperatures, so FERIC calculated the difference between the oil and ambient temperature readings (Table 1) because this temperature difference should be roughly constant for any given level of hydraulic system output. For example, the machines in FERIC’s study spent an average of 19% of their operating time at oil temperatures more than 60°C above ambient. Although some machines never reached this temperature, one machine actually spent 65% of its operating time at oil temperatures more than 60°C above ambient. Since most of the machines monitored work at a fairly steady (high) hydraulic output, the information in Table 1 permits an estimate of oil temperature at various ambient temperatures. For example, if the ambient temperature is 30°C and the temperature difference is known to be 60°C, then the maximum oil temperature would be 90°C.

Caution: The averages in Table 1 represent a wide range of machines and operating conditions, and thus may not accurately represent the actual oil performance of a given machine under specific operating conditions.

Table 2 shows the estimated maximum hydraulic oil temperatures at 30°C ambient temperature based on the data from FERIC's field tests. These temperature values describe the conditions hydraulic oils must endure in the summer. The table suggests that 52% of the test machines exceeded the commonly recommended 90°C maximum temperature for most hydraulic components. One reason to avoid high oil temperatures is that even mineral oils begin to oxidize at temperatures above 60°C, and oil life decreases by up to 50% for every 10°C temperature increase beyond this point (Anon. 1962).

Table 1. Proportion of total operating time during which machines operated at various oil temperatures (expressed in terms of the difference between ambient and oil temperatures)

	% of total operating time		
	Average for all machines	Best machine	Worst machine
Temperature difference (oil minus ambient) (°C)			
>60	19	0	65
>55	34	0	85
>50	51	0	95
>45	65	0	96
>40	77	0	97

Table 2. Estimated maximum hydraulic oil temperatures at a 30°C ambient temperature

	% of machines
Maximum oil temperature (°C)	
>90	52
86-90	20
81-85	7
76-80	7
70-75	7
<70	7

The ambient temperature close to a machine can be higher than the overall ambient temperature of the site; this is especially true for harvesters and feller-bunchers, which are often surrounded by trees and brush and thus tend to retain heated air around the machine. When Environment Canada records are used to estimate oil temperatures, higher ambient temperature around the machine should be anticipated.

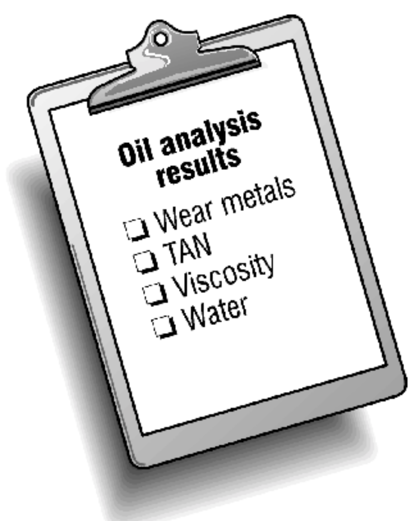
The temperature differences among the various machine types in FERIC’s study were quite small. Table 3 shows the expected maximum oil temperatures at 30°C ambient temperature.

Table 3. Estimated maximum oil temperatures by machine group at 30°C ambient temperature

	Oil temperature (°C)	
	Group average	Range
Silvicultural machine	99.5	99 – 100
Graders	99.5	67 – 132
Delimbers	99.0	93 – 105
Feller-bunchers	90.7	87 – 96
Harvesters	86.5	72 – 101
Forwarders	86.0	85 – 87

Oil Analysis Results

Oil analysis results suggest that the hydraulic mineral oils were mostly within the acceptable ranges for viscosity, oxidation, and other factors. However, the viscosities of the oil samples from about one-third of the machines differed considerably from the viscosity of the oil that the operator claimed was in the system. The most probable cause was that the oil had been partially replaced with oil of different viscosity (e.g., a seasonal oil change). Shearing of the viscosity-index improvers, oil oxidation, or the presence of water in the oil could also change the viscosity slightly. Water contents should not exceed 300 ppm for mineral oils (zinc-based anti-wear additives are destroyed by water) and 500 to 700 ppm for natural and synthetic esters, depending on the product; at temperatures above 80°C, these limits do not apply and a water-removing filter should be used to remove as much water as possible to reduce hydrolysis. Water contents in the tested samples were all less than 300 ppm. An increase in the oil's TAN (total acid number) can indicate oxidation of the oil, and increased TAN values were recorded in both tests of vegetable oils that FERIC carried out previously.



Filter Capacity and Measured Cleanliness

The ß-rating (beta ratio) describes a filter's contaminant separation efficiency, and Appendix 3 presents the potential level of oil cleanliness attainable under good operating conditions in relation to a filter's ß-rating. Many factors prevent a filter from providing these theoretical levels of oil cleanliness; these include a pulsating flow through the filter, an undersized filter element, too much oil bypassing the filter, insufficiently frequent changes of the filter elements, excessive ingress of contaminants from outside the system, and an accumulation of oil deterioration byproducts that blocks the filter. Operators sampled and analyzed hydraulic oil regularly in only five of the tested machines, and these machines had cleaner oil than the others. In general, the oils in FERIC's study were generally more contaminated than one would expect given the ß-rating of the mounted filters, but the reasons for this were not studied. Levels of oil contamination were so high that comparably contaminated bio-oils could not have been used in all of the machines. All machines would require changes in design, maintenance practices, or both to achieve adequate bio-oil cleanliness.

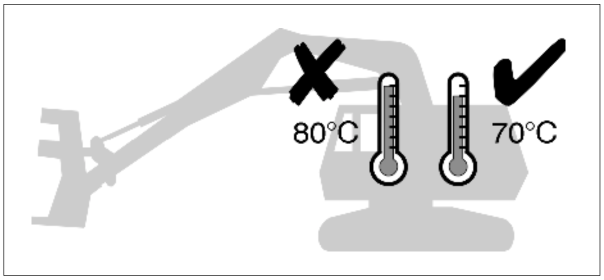
Discussion

Machine Compatibility with Vegetable Oils

The often-stated maximum operating temperature for vegetable oils is 70°C, though product literature recommends maximums varying from 60 to 80°C. The viscosity of rapeseed oil is about 33 cSt at 40°C and its viscosity index is about 230, so it can be used year-round. Some manufacturers add other base stocks (synthetic esters or mineral oil) or additives to enhance certain properties or to change the oil's viscosity grade. A literature review identified vegetable oils available in viscosity grades of 15, 22, 32, 46, and 68, with 32 and 46 being the most commonly available grades.

Only 7% of the tested machines had a maximum oil temperature under 70°C, which suggests that the life of vegetable-based oil would be reduced because of an increased oxidation rate. Moreover, the minimum start-up temperature for vegetable oils varies between –20°C and –30°C, and this would likely limit their year-round use in eastern Canada to the Atlantic provinces.

In an earlier FERIC test, one vegetable oil's temperature often exceeded 80°C, but the system did not create the large amount of local overheating that greatly exacerbates oxidation. Local overheating can occur in a closed-circuit hydrostatic drive, in which the oil returns to the reservoir gradually, and in the control valve of a knuckleboom loader due to the high pressure loss that occurs when the boom and stick boom are used simultaneously. Parallelogram booms create less heat locally than knucklebooms.



Machine Compatibility with Synthetic Esters

FERIC has not studied the use of synthetic esters, which are the most commonly used hydraulic bio-oils in European forestry machines. They are the only bio-oils accepted for use in harvesters and forwarders with hydrostatic transmissions in Germany, and most harvesters converted to use bio-oils in Nordic countries use synthetic esters. The maximum-temperature limits for synthetic esters are higher than for vegetable-based oils, and these products are generally adequate for use in current machinery, though the limits vary among brands. Low-temperature limits also vary, although synthetic esters generally perform better than vegetable oils in cold weather.

The presence of water at temperatures above 80°C will cause hydrolysis (one form of oxidation). To alleviate this problem, many operators in Germany have added a water-removing bypass filter or a kidney-loop filter to keep water content at a very low level. Some equipment manufacturers require the use of a bypass filter with synthetic esters to avoid negating the warranty of the machine. The water content in the test machines was lower than the permissible limit for use of synthetic esters. Nevertheless, since bypass filters can remove particles of 3 µm or even smaller, the system's oil would also remain cleaner than with a standard filter, and this would increase both oil and component life.

Each manufacturer has synthetic esters in several viscosity grades, and most machines can be converted relatively inexpensively to use synthetic esters. Certain synthetic esters would appear suitable for all Canadian forestry operations. Some brands of synthetic esters could even be used year-round in the Atlantic provinces. In the rest of eastern Canada, seasonal oils could be used.

Machine Compatibility with Fire-resistant Fluids

The extensive modifications, including the use of a large cooler and pressurizing the reservoir, required to use UCON Hydrolube (a water–glycol mix) are the main obstacles in converting machines to use this fluid (Makkonen 1996). Prospective users should thus consider ordering a new machine specifically designed to use this fluid. UCON Hydrolube should be suitable in all Canadian forestry operations and is a year-round fluid with good cold-start properties. Moreover, the fluid has already received the Canadian EcoLogo and would be acceptable where environmental certification is an issue.

Group II fluids include some vegetable oils and polyol esters. Based on expected ambient temperatures and FERIC's oil temperature data, the potential use of a vegetable-based oil in eastern Canada would likely be limited to the Atlantic provinces. Some polyol esters tested in Sweden had high viscosities at low temperatures, so prospective users in eastern Canada should verify each product's suitability for winter use. Because these fluids are esters, they are increasingly vulnerable to hydrolysis as temperatures and water contents rise. Some of these products are claimed to be miscible with mineral oil, but compared with the bio-oil itself, such a mixture would have increased toxicity, reduced fire resistance, and a reduced degree of biodegradation. As well, minor equipment modifications may be required before using these fluids.

Considerations When Using Bio-oils

Ester Oxidation is Harmful

Although rapid biodegradation is desirable, this property unfortunately seems to reduce the resistance of esters to oxidation caused by high temperatures, water (hydrolysis), catalytic contaminants, air in the oil, and high-pressure peaks. The products of oxidation are chemically aggressive and are believed to cause corrosion in pumps, formation of sticky coatings that result in valve malfunctions, and seal deterioration (Kempermann 1997).

Clean Oil Reduces Oil Oxidation and Component Wear

Since the 1980s, it has become practical to monitor oil cleanliness, and this parameter has become increasingly important because clean oil oxidizes more slowly and increases component life. The importance of cleanliness is reflected in the trend towards improved filtration systems in new machinery. Because vegetable oils keep contaminants in suspension, field staff have reported that the filters became blocked in some used machines as soon as they had been converted to use vegetable oil. Clean oil, proper conversion techniques, and appropriate filters thus become important aspects of bio-oil discussions.

For each machine, the requirements of the individual components and the machine's operating conditions will determine the required oil cleanliness level (Appendix 3). Several recommendations exist for bio-oil cleanliness levels. For example, one publication states that a bio-oil's cleanliness code should be one level better than with petroleum-based fluids (Faatz and Lang 1989). The Swedish recommendation (Myhrman 1995) proposes an ISO 15/11 cleanliness level for harvesters and forwarders using vegetable oils and synthetic esters. This recommendation appears to be slightly stricter than that of Faatz and Lang and the recommendations in Appendix 3.

Bio-oils Require More Effective Filtration than Mineral Oils

Higher cleanliness levels are generally required with bio-oils than with mineral oils, and the filtering system must be upgraded in many machines that were not specifically designed to use bio-oils. However, in FERIC's studies, even the test machines that used bio-oils lacked filtration systems that could meet the recommended ISO cleanliness level of 15/11. Sometimes all that would be required would be to add a more effective cartridge, but changing the cartridge alone may unacceptably increase the pressure loss across the cartridge. Before proceeding with such a modification, always verify with the manufacturer that this change is permissible. Sometimes a parallel filter can be added easily to compensate for the lost flow capacity of a finer filter. However, the parallel filter should not be equipped with a bypass valve, as this presents one more possibility for failure and leakage past the filter.

The next most cost-effective way to increase filtering capacity is to add a bypass filter instead of a parallel filter. However, care should be taken to ensure that the flow rate through the bypass filter and the filter's position in the system keep system pressure and flow losses at acceptable levels. Many bypass filters can also be equipped with water-absorbing filter elements to help reduce hydrolysis. Some of these filters have their own pumps, and an electric pump would permit oil filtering while the machine is parked. When a bypass filter is added, all other filters must be maintained to provide backup filtering capacity (e.g., if the bypass filter blocks or freezes or if a component fails).

Filters should be monitored to ensure that the maximum permissible pressure drop across the filter at a specified temperature and viscosity is not exceeded; following the filter change schedule may not itself guarantee that the filter works and that the oil remains clean.

Bio-oils are More Difficult to Filter than Mineral Oils

"Filterability" represents a fluid's ability to pass through a test filter material without blocking it. Bio-oils generally have poorer filterability than mineral oils. Filtration of esters can be affected by some of the additives used in mineral oils, so mixing of these two fluids should be avoided. For example, motor oil dispersants reduce boundary lubricity and cause gel formation that reduces filterability (Johansson, undated). Problems typically appear right after the conversion and again when the oil starts to deteriorate or contamination enters the system.

Oxidation products in used oils sometimes act as adhesives and stick to filter materials. Oxidation products can also be more polar than the oil and thus displace oil on all surfaces (Faatz and Lang 1989), resulting in corrosion (thus, reduced lubrication) in some cases.

Filters for water–glycol mixtures should be 27% larger than filters for mineral oils (Faatz and Lang 1989). This is because the presence of soapy residues and different settling characteristics for the contaminants decrease the filterability of these fluids. Traces of mineral oil in water–glycol mixes can reduce filtering efficiency greatly in 5- and 10-µm filters.

Bio-oils are More Likely to Cavitate

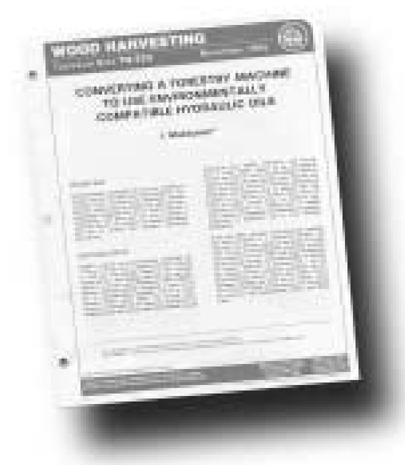
Long suction lines can lead to pump failure with bio-oils. Because most bio-oils have a higher specific gravity than the mineral oils they replace, accelerating the oil mass in the suction line requires higher pressure in the reservoir. Esters with increased low-temperature viscosity as a result of oxidation also increase the risk of cavitation.

Water–glycol mixtures have much higher specific gravity than the other hydraulic fluids described in this report and consequently require considerably higher pressure in the reservoir to accelerate the fluid. Pressurizing the reservoir and decreasing the pump's rate of rotation can eliminate cavitation. Reducing valve shifting speeds also helps, but may reduce the machine’s responsiveness.

Other Factors to Watch

- When an oil change is incomplete, the residual used oil can accelerate oxidation of the new oil, regardless of the oil type in the machine (Blok 1995). In general, oil changes should be as complete as possible (i.e., flushing the system is recommended).
- Trials of bio-oils are generally monitored carefully, and equipment failures are avoided thereby. However, operators forced to use bio-oils outside these trials may neglect this monitoring under the pressure of their work schedule, and failures can occur in the absence of close supervision. This problem has been experienced in Finland (Törmänen 1995). Consequently, regular oil sampling is recommended for machines that use bio-oils, and the sampling should be more frequent than when using mineral oils (Galiano-Roth et al. 1994). Shell Canada (Anon. 1998) recommends sampling every 300 hours until a more appropriate sampling interval can be defined. Sampling should focus on viscosity at 40°C, TAN, cleanliness level, and water content.

- The compatibility of a machine's various hydraulic components must also be verified. Certain metal coatings (e.g., zinc) cannot be used, and seals must be selected carefully. The proposed German standard VMDA 24569 recommends the use of polyester urethane rubber, acryl nitrile rubber, sulfur-netted acryl nitrile rubber, and Viton® seal materials with esters at oil temperatures under 80°C, but states that only Viton® seals should be used at oil temperatures above 80°C (Johansson, undated). This is consistent with observations that low operating temperatures generally improve seal life. When the system operates at low oil temperatures, it is also easier to find a suitable year-round oil that would permit a single, annual oil change.
- Each machine must be evaluated separately to determine its suitability for use with bio-oils. In general, avoid converting old machines or be prepared to carry out extensive cleaning of the system and, subsequently, extensive repairs of leaks; for example, old seals impregnated with mineral oil seem to lose their hardness and start to leak when exposed to an ester-based fluid. Makkonen (1995) provides more information on the conversion process to prepare a machine for use with bio-oils. Oil and machine suppliers can also provide conversion instructions; these should be followed carefully to maintain warranty protection.



Conclusions

New machine models generally prove more suitable than old models for use with bio-oils. New European-built harvesters and forwarders are approved for use with certain synthetic esters, but are rarely approved for use with vegetable oils. John Deere guarantees some of its machines only when the company's Bio-HyGard oil is used. The observed lack of oil sampling and failure to obtain the cleanliness levels possible with the specified filters suggest that hydraulic system monitoring and maintenance must be improved. Many machines in FERIC's survey revealed high oil operating temperatures and high levels of oil contamination; these conditions would exclude the use of most bio-oils, and particularly those based on vegetable oils.

Synthetic esters and fire-resistant polyol esters have a greater operating temperature range than vegetable oils. High fluid temperatures should be avoided because they promote hydrolysis unless the fluid can be kept free of water. Based on the observed range of oil temperatures, most modern machinery could use synthetic esters, but although synthetic esters have the least restrictive machinery requirements, they are the most expensive bio-oils. With some machines, it may be preferable to modify the system so it can use a less expensive type of bio-oil. These modification costs can often be recovered in one or two years, making it economically feasible to use less-expensive fluids.

Vegetable-based oils should only be used in machines that have a light duty cycle, that have a well-designed hydraulic system, that operate in areas where it is not colder than –30°C, and whose oil operating temperatures do not generally exceed 70°C; moreover, hydraulic systems with high pressure drops across the control valves should be avoided. Vegetable oils can be suitable for year-round use under these conditions.

The use of water–glycol mixes such as Ucon Hydrolube can reduce the risk of oil fires, but can require extensive modifications to the machine. A better solution might be to order a compatible machine directly from the manufacturer. The manufacturer of the hydraulic fluid can provide advice on the requirements for a conversion, but this does not guarantee that the machine manufacturer will approve the use of the oils. Water–glycol mixtures can be used year-round.

Unless a machine is specifically designed to use bio-oils, the filtering system should generally be upgraded. Bio-oils need a greater filtering surface than mineral oils because of the generally poorer filterability of bio-oils; this is a particular problem immediately after the conversion. Purchasers must request hydraulic system performance guarantees from machine suppliers to confirm the machine's suitability for use with bio-oils, the maximum oil operating temperatures, and the filtration performance. These guarantees will help buyers to choose a machine whose system will last longer with bio-oils, as well as with mineral oils.

The costs of using bio-oils are higher than those of using mineral oils because of higher oil prices, increased monitoring and fluid sampling requirements, potentially higher usage of filters, and higher prices for machines that have been modified to ensure compatibility with bio-oils. Because bio-oils are more expensive than mineral oils, efforts to prolong oil life and reduce leaks should somewhat reduce the cost penalty incurred by using bio-oils.

Disclaimer

References

Anon. 1962. Operation and care of hydraulic machinery. Texaco Canada Ltd., Montreal, Que. 95 p.

Anon. 1998. Shell Naturelle HF product literature. Shell Canada. http://www.shellcan.com/clubes/3-76-02.htm. 2 p.

Blok, P. 1995. The management of oil contamination in hydraulic equipment. Koppen & Lethem Aandrijf techniek B.V., Waddinxveen, The Netherlands. 320 p.

Faatz, H.; Lang, R. Ed. 1989. Planning and design of hydraulic power systems. Mannesmann Rexroth GmbH, Lohr am Main, Germany. Training Manual RE 00 281/04.89. 360 p.

Galiano-Roth, A.; Cheng, V.; Marougy, T.; Berezinski, J. 1994. Vegetable-based hydraulic oil in piston pumps. p. 43-57 *in* Proceedings of the 46th National conference on Fluid Power. March 23-24, 1994. National Fluid Power Association, Milwaukee, Wisc.

Johansson, L. (no date). Maskinprovningarnas Miljöoljeproject—Passar miljöanpassad olja utan teknikanpassing? Staatens Maskinprovningar, Umeå, Sweden. Dnr 30:28-90. 54 p. [In Swedish.]

Kempermann, C. 1997. Neuer Feldversuch mit Bio-Oel im Harvester. Forst & Technik 12/1997:10-12. [In German.]

Makkonen, I. 1995. Converting a forestry machine to use environmentally compatible hydraulic oils. For. Eng. Res. Inst. Can. (FERIC), Pointe-Claire, Que. Tech. Note TN-234. 12 p.

Makkonen, I. 1996. Ucon Hydrolube fire-resistant hydraulic fluid. For. Eng. Res. Inst. Can. (FERIC), Pointe-Claire, Que. Field Note General-48. 2 p.

Makkonen, I. 1997a. A trial of Bio-HyGard environmentally compatible hydraulic fluid in a feller-buncher. For. Eng. Res. Inst. Can. (FERIC), Pointe-Claire, Que. Field Note General-54. 2 p.

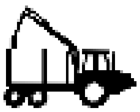
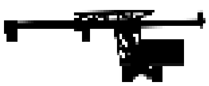
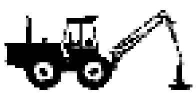
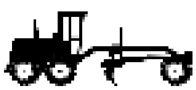
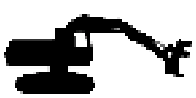
Makkonen, I. 1997b. Performance of Raisio BioSafe 32NE hydraulic oil in a Silvana Selective cleaning machine. For. Eng. Res. Inst. Can. (FERIC), Pointe-Claire, Que. Field Note General-60. 2 p.

Myhrman, D., Ed. 1995. Miljöanpassade hydrauloljor. SkogForsk, Uppsala, Sweden. 16 p. [In Swedish.]

Törmänen, M. 1995. Bioöljyt sopivat luontoon, entä koneyrittäjille? Koneyrittäjä 1/1995:47-48. [In Finnish.]

van Slingerlandt, P. 1996. Neues zum Thema Bio-Öle. Forst und Technik 1/1996:12-15. [In German.]

Appendix 1
Machines Tested by FERIC

	Machine type	Operating area	Study date
	Six-wheeled forwarder	Nova Scotia	June 1996
	Eight-wheeled forwarder	Nova Scotia	Oct. 1996
	Six-wheeled harvester	Nova Scotia	June 1996
	Excavator-based harvester	Nova Scotia	Oct. 1996
	Tracked forestry carrier used as a harvester	Newfoundland	July 1997
	Six-wheeled harvester	Newfoundland	July 1997
	Excavator-based delimber	Northern Ontario	July 1995
	Excavator-based delimber	Northern Ontario	July 1995
	Cleaning machine, main hydraulic system	Northeastern Quebec	Sept. 1997
	Cleaning machine, auxiliary hydraulic system	Northeastern Quebec	Sept. 1997
	Grader	Northern Ontario	June 1995
	Grader	Northern Ontario	June 1995
	Purpose-built feller-buncher	Nova Scotia	Oct. 1996
	Purpose-built feller-buncher	New Brunswick	Aug. 1996
	Purpose-built feller-buncher	New Brunswick	Aug. 1996

Appendix 2
Bio-oils Available in Canada

The selection of bio-oils in Canada is limited and their availability is poor due to their limited use. Many more fluids are available in Europe, and these could be marketed in North America if demand increased.

	Fluid name	Fluid type[a]	Viscosity (mm^2/s at 40°C)	Fire resistance
Manufacturer				
Caterpillar	Bio Hydro[b]	HETG	37	–
Esso	Univis Bio 40	HETG	38	–
	Univis Bio SHP	HEE	46	–
Fuchs/Century	Plantohyd 40 N	HETG	40	–
Greenland Corp.	Greenplus ES	HETG	42	–
Houghton International Inc.	Cosmolubric B-230	HETG	68	Group II
	Hydro-Drive B-245	HETG	37	–
John Deere	Bio-HyGard	HETG	48	–
Mobil Oil	EAL 224 H	HETG	34	–
	EAL Envirosyn 32 H	HEE	32	–
	EAL Envirosyn 46 H	HEE	46	–
	EAL Envirosyn 68 H	HEE	68	–
	EAL Envirosyn 100 H	HEE	100	–
Power Up Inc.	Marinus AW 32	HETG	35	–
	Marinus AW 46	HETG	43	–
	Marinus AW 68	HETG	64	–
Quaker Chemical Corp.	Quintolubric 822-220[c]	HEE	48	Group II
	Quintolubric 822-300	HEE	65	Group II
	Quintolubric 822-450	HEE	97	Group II
Raisio Chemicals	BioSafe 32 NE	HETG	33	–
	BioSafe 46 SE	HEE	49	–
	BioSafe 68 SE	HEE	63	–
Shell	Naturelle HF	HETG	35	–
Union Carbide Corp.	UCON Hydrolube HP-5046	HFC	46	Group I

[a] HETG = vegetable-based oil, HEE = synthetic ester, HFC = water–glycol
[b] Caterpillar markets Bio Hydro HEES, a synthetic ester, in Europe.
[c] Quintolubric fluids are rapidly biodegradable; however, no data have been provided to FERIC concerning their toxicity.

Note: Quintolubric Greensave 46 (HE, VG 46) is sold in Europe as a non-toxic and biodegradable product. Quintolubric fluids are sold in Canada by H.L. Blachford Ltd., Missisauga, Ont. Greenland Corporation and Power Up Inc. have their head offices in Calgary, Alta. Shell offers Naturelle HF-M (VG 32), which is a mix of vegetable oil and synthetic esters, and Naturelle HF-E (VG 15, 32, 46, and 68), a fully synthetic ester, in Europe. Fuchs Lubricants Ltd. (Century Lubricants Division, Langley, B.C.), does not market their Plantohyd S and Plantohyd Super S synthetic esters in Canada, but the products are available in Europe.

Appendix 3
Filter Ratings and Recommendations

Definition of a Filter's ß-rating

A filter's $ß_x$ rating represents the number of contaminant particles equal to or larger than a specified size x (in µm) counted upstream of the filter element divided by the number of these particles counted downstream of the filter; the result defines the efficiency of contaminant separation from the oil.

$ß_x = n_{(x)upstream} / n_{(x)downstream}$ (e.g., $ß_{10}$ = 100 000 / 1000 = 100)

The $ß_x$ values can also be expressed as filter efficiency (in %):

$ß_x$ = 2 = 50% filter efficiency
$ß_x$ = 20 = 95% filter efficiency
$ß_x$ = 75 = 98.6% filter efficiency
$ß_x$ = 100 = 99% filter efficiency

Each filter has a different ß-rating for each particle size; the bigger the particle size, the larger the ß-rating. The ISO standard specifies a single $ß_x$-rating based on the particle size at which $ß_x$=75 to make comparisons easier. However, the $ß_x$ rating 75 is often inadequate, and filter manufacturers have started to provide ratings at 100 or 200.

Definition of the ISO 4406 Cleanliness Code

The ISO cleanliness code consists of two numbers separated by slash (e.g., 18/15). The first number indicates the number of particles equal to or larger than 5 µm and the second number indicates the number of particles larger than 15 µm. Table A1 shows the cleanliness codes for different particle counts in 100 mL of oil.

Table A1. ISO codes for particle quantities in 100 mL of fluid

	Number of particles in 100 mL of oil[a]				
ISO code	more than	up to	ISO code	more than	up to
8	130	250	17	64 k	130 k
9	250	500	18	130 k	250 k
10	500	1 k	19	250 k	500 k
11	1 k	2 k	20	500 k	1 M
12	2 k	4 k	21	1 M	2 M
13	4 k	8 k	22	2 M	4 M
14	8 k	16 k	23	4 M	8 M
15	16 k	32 k	24	8 M	16 M
16	32 k	64 k	25	16 M	32 M

[a] k = thousand, M = million.

A proposed improvement of the ISO code adds a third code number in front of the two current code numbers to indicate the number of particles equal to or larger than 2 µm. This proposal has not been formally accepted, but is nonetheless widely used. The third code number would be very useful in analyzing oil cleanliness for systems that use servo valves, which are sensitive to silt (contaminants smaller than 5 µm).

Filter ß-rating vs. Oil Cleanliness

Filter ß-ratings have been established under laboratory conditions, where the flow is steady and pressure changes are slow. Filters thus perform differently in a machine's hydraulic systems. Oversized filters seems to have better performance in machines because pressure variations become smaller. Table A2 will help designers to determine the ß-rating requirements for a filter, but the actual filtration results observed will vary among machines.

Table A2. Recommended hydraulic system cleanliness limits

	Recommended cleanliness limits								
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
Component or type of system									
Servo valves									
Regulator valves									
Proportional valves									
Pumps, p>16.0 MPa									
Pumps, p<16.0 MPa									
Low-pressure hydraulics									
Filter's required degree of separation[a]									
$ß_x = 75$	–	–	3	5	10	20	25	25–40	–
$ß_x = 100$	3	3	–	–	–	–	–	–	–

[a] "x" is the required particle size (µm) above which a 75- or 100-times reduction in particle count is required as the oil passes through the filter.