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Development and Application of Advanced Emulsion Hydraulic Fluids

K. J. Young
Shell Research Ltd

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ABSTRACT

The attendant hazards associated with the transmission of power in high fire risk environments necessitated the introduction of fire-resistant hydraulic fluids. Early water-based fluids, although fire-resistant, were generally of poor stability or lubricity, limiting the extent to which they could be applied. Advanced emulsion-based hydraulic fluids have now been developed which combine good fire resistance with good stability and lubrication performance.

This paper discusses the requirements for emulsion-based fire-resistant hydraulic fluids, the development of advanced fluids, and the field performance of such fluids.

INTRODUCTION

Fire-resistant hydraulic fluids are often specified for the transmission of power in hazardous operating environments where there is a risk that fire could endanger life or damage valuable equipment. These fluids are used extensively in underground mining [1,2] where the risk is not only that of the fire itself but of toxic by-products of hydraulic fluid combustion which could spread along the airways. They are also used in steel plants and rolling mills [3] where there is a risk that hydraulic fluid leaking, or being sprayed, on to hot surfaces could cause a fire.

ISO 6743/4 [4] establishes the detailed classification of lubricants, industrial oils and related products for hydraulic systems. Eight types of fire-resistant hydraulic fluids are included in the specification in four classes:

- HFA Oil-in-water emulsions, or chemical solutions, with typically more than 80% water
- HFB Water-in-oil emulsions
- HFC Water-polymer solutions, with typically less than 80% water
- HFD Synthetic fluids, free of water

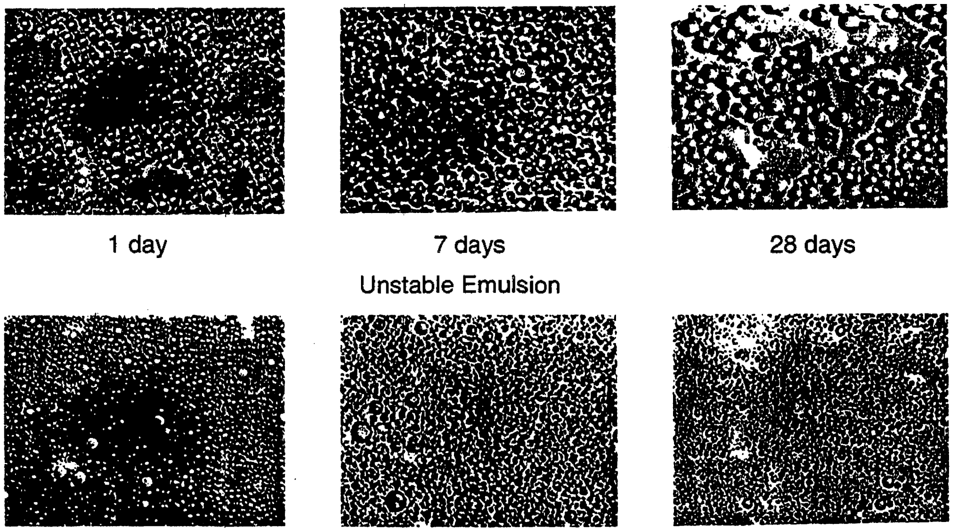
Although fire-resistant, the use of some types of HFD fluids, particularly those consisting of, or containing, chlorinated hydrocarbons, has had to be restricted, due to associated environmental or health hazards. This paper will focus on the development and field application of water-based, specifically emulsion-based, fire-resistant hydraulic fluids.

DEVELOPMENT AND APPLICATION

The fire resistance of a fluid refers to its ability to resist ignition, to resist flame propagation, and to self extinguish if ignited. Water is non-combustible and would therefore appear to be an attractive medium with which to transmit power in hazardous applications. Despite its advantages, however, there are some severe disadvantages to its use, such as its limited temperature range and high vapour pressure, low viscosity, corrosivity and poor lubrication performance. Mineral oil and/or additives are therefore normally combined with water to overcome, or at least reduce, the effects of these disadvantages.

The key performance requirements for advanced water-based fire-resistant hydraulic fluids are stability to changes in temperature, pressure and the effects of shearing forces experienced in pumps valves and filters, and the ability to provide protection against wear and corrosion.

Appropriate test methods, with which to evaluate these aspects of performance, can be found in several national and international specifications, examples of which are the former British Coal Corporation's (BCC)



1 day 7 days 28 days

Unstable Emulsion

1 day 7 days 28 days

Stable Emulsion

FIG. 1 - Comparison of water-in-oil emulsion stability by disperse-phase droplet size

Specification No. 570 "Fire Resistant Fluids for Use in Machinery and Hydraulic Equipment" [5], and the Commission of the European Communities (CEC) Safety and Health Commission for the Mining and Other Extractive Industries reports (so called "Luxembourg Reports"). The Luxembourg Reports, the seventh version of which, "Requirements and Tests Applicable to Fire-Resistant Hydraulic Fluids Used for Power Transmission and Control", has just been published [6], are widely regarded as a Standard for fire-resistant hydraulic fluids in many industries and countries. An ISO Standard, which draws on many of the tests in the 7th Luxembourg Report, is currently being drafted.

The advanced water-in-oil and oil-in-water emulsion-based hydraulic fluids which are the subject of this report have been developed using BCC and Luxembourg 6th Report test methods, together with in-house methods. All BCC 570 test methods are included in the Luxembourg 6th Report.

ADVANCED WATER-IN-OIL (HFB) EMULSIONS - With water-based hydraulic fluids there is a balance to be struck between fire resistance and lubrication performance. Generally, the higher the water content, the better the fire resistance, but the poorer the lubrication performance. Water-in-oil emulsions, with a water content of around 40%, represent a good compromise for many applications, particularly in underground mining [1,2], where they are employed in hydraulic systems in mobile equipment.

Water-in-oil emulsions, sometimes referred to as invert emulsions, are dispersions of water droplets, usually less than 2 μm in diameter, in an oil phase. Formulations are usually complex, consisting of mineral base oils and water, with emulsifiers, and additives providing or contributing to antiwear, ep, antirust, antifreeze, antipitting and antibacterial performance. During development critical attention must be paid to the emulsifier chemistry, which has to be carefully selected to ensure long term stability, and manufacturing technique. Figure 1 illustrates the difference in droplet size with time for well formulated and poorly formulated emulsions. Unstable emulsions will have poor performance, with particularly poor fire resistance and poor lubricity.

BCC 570 Specification and Luxembourg Report tests and the performance which can be achieved in these, and in in-house tests, with a water-in-oil emulsion are illustrated in Tables 1 and 2. As indicated in the tables, some of the test methods specified in the BCC and Luxembourg specifications, and used in-house, are standard ASTM or IP methods. The specifications require that fluids should meet ISO 3448 viscosity range requirements, and common grades are ISO 68 and 100. Results tabulated are for an ISO 68 grade. Similar results were obtained for an ISO 100 version.

In service, it is important that if the fluid comes into contact with a source of ignition, the water in the fluid evaporates forming a steam blanket which displaces oxygen from the immediate area. In the event of a fluid being sprayed onto a hot surface, or if it cascades onto

Table 1

Properties and Performance of Advanced Emulsion Hydraulic Fluids

Property	Method	Performance	
		HFB (ISO 68)	HFA (ISO 10)
Appearance		White opaque fluid	White opaque fluid
Kinematic Viscosity, $mm^2 s^{-1}$	ASTM D445	-10 0 20 40 50°C 1140 563 167 70 49	20 40 50°C 18 10 8
Pour Point, °C	ASTM D97	-30	0
Water Content, % volume	ASTM D95	38	84
Density at 20°C, kg/m^3	ASTM D1298	930	-
pH	CEC Report*	8	10
Fire Resistance			
Spray Flammability, Persistance of Flame, s	CEC Report	5	0
Wick Test, Persistance of Flame, s	CEC Report	12	0
Emulsion Stability			
168 hours at 70°C	CEC Report		Pass
48 hours at 70°C	CEC Report	Pass	
1,000 hours at ambient temp.	IP 290	Pass	
336 hours at -10°C, followed by 168 hours at ambient temp.	CEC Report	Pass	
Rust Prevention	ASTM D665 (no added water)	Pass	Pass
Multimetal Corrosion, Wt loss, mg	CEC Report		
steel, copper, zinc		0, -2.0, +0.3	0, -8, 12
aluminium, cadmium, brass		-0.4, -0.9, -0.7	0, 13, 0
Combinations		Pass	Pass

* Commission of the European Communities 6th Report on "Specifications and Testing Conditions Relating to Fire Resistant Fluids used for Power Transmissions". Ref. [6]

a hot surface and runs off, it is important that the fluid will not support its own combustion. Fire resistance is affected by the distribution and size of the water droplets, and the ability of the fluid to maintain its structure over long periods of time, which, in turn, is dependent on the additives used; particularly the emulsifiers. Widely different fire resistance results can be observed with different formulations, even though they may have the same water concentration.

Fire resistance is evaluated using both spray and wick tests. In the spray test, fluid is sprayed through a nozzle and attempts made to ignite the fluid using an oxy-acetylene flame. The flame is repeatedly applied and the maximum duration of burning after withdrawal of the igniting flame noted. The flame should not persist for longer than 30 seconds after removal of the igniting flame. In the wick test, a length of tape is soaked in the test fluid and placed in a reservoir of fluid with one edge exposed forming a wick. A small igniting flame is applied to the wick and the persistence of flame on the wick after removing the igniting flame is recorded. The test is carried out at 5 different exposure times and 6 observations of the persistence of flame at each exposure time noted. The largest average for each exposure time is reported as the "Mean Persistence of Flame". The mean persistence of flame should be less than 60 seconds. As shown in Table 1, significantly better performance than the requirement can be achieved.

Emulsion stability is a key property and the requirements are that the fluid be stable under 3 sets of test conditions covering a temperature range from -10°C to 70°C and up to 1000 hours duration. These test requirements also have to be met after a two year storage period, requiring careful formulation to ensure that water droplets remain small and homogeneously dispersed in the bulk oil.

Table 2

Lubrication Performance of Advanced Emulsion Hydraulic Fluids

Property	Method	Performance		
		HFB (ISO 68)	HFA (ISO 10)	Early HFA (95:5)
Rolling Bearing Fatigue	IP 305			
L10 Life, hours		19	15	
L50 Life, hours		49	22	
Vane Pump Test	IP 281			
Ring Wear, mg		200		
Vanes Wear, mg		16		
Piston Pump Test (1)	In-house*			
Total Piston Wear, mg		691	217	
Slipper Lift Increase, mg		0	0	
Piston Pump Test (2)				
Piston Wear Rate, mg/h			0.4	30
Gear Pump Test	In-house*			
Driven Gear Wear, mg		124	240	445
Thrust Plates Wear, mg		196	292	7,429

* Piston Pump Test (1): 1,000 hours at 14 MPa and 50°C, 100 l/min
* Piston Pump Test (2): 250 hours at 21 MPa and 50°C, 12 l/min
* Gear Pump Test: 1,000 hours at 14 MPa and 50°C, 60 l/min

Emulsions should protect against corrosion of a variety of metals found in hydraulic systems. The performance which can be achieved is illustrated in Table 1.

The lubricating performance of water-in-oil emulsions can be inferior to that of mineral oil, particularly in rolling contact. Widely different performance can be obtained from different emulsions. Test methods are left to the discretion of the supplier but should include rolling and sliding contact.

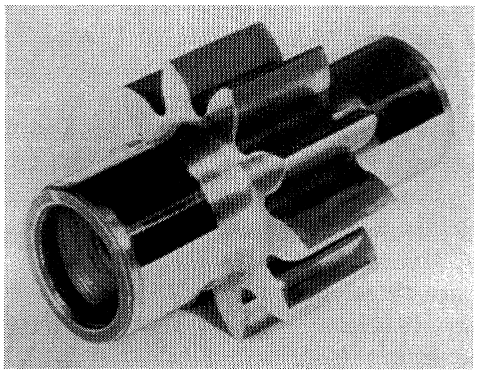
Rolling contact fatigue is the most difficult aspect of emulsion lubricating performance to control. The lower fatigue life of emulsion based hydraulic fluids relative to mineral oil fluids is related to the lower EHD film thickness and chemical effects which promote crack growth. It is important to note that water-in-oil emulsions are non-Newtonian in nature, and that when water is added, viscosity, as measured by ASTM D445, is increased relative to that of the base oil used. For example, the base oil blend used for the ISO 68 formulation shown in Table 1 had a viscosity of 15 mm^2s^{-1} at 40°C. In service, the viscosity of the fluid in lubrication contacts will be significantly less than the ISO grade would suggest and may even be as low as the base oil viscosity [7]. The effect of shear on viscosity is illustrated in Table 3. The mechanism by which crack growth is promoted by water is not clearly understood [8], three possible mechanisms being involved to a greater or lesser extent. These are hydrogen embrittlement, stress corrosion cracking and corrosion fatigue. It is necessary to include additives to control this chemically induced promotion of fatigue crack formation and growth. Judicious selection of these additives can significantly improve this aspect of

Table 3

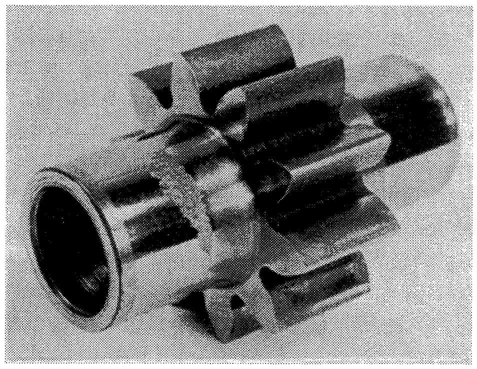
The Effect of Shear on Water-In-Oil Emulsion Viscosity

Shear Rate, s^{-1}	Viscosity, mPa s
503	48
1,007	43
5,033	35
10,066	32
16,608	31

Tests run using a Ferranti Shirley Viscometer (Standard cone of 35mm radius and 21'24" cone angle. Nominally at 50°C)



Bearing journal condition after a 1000 hour test with a good quality water-in-oil emulsion



Bearing journal condition after 300 hours with a poor quality water-in-oil emulsion

FIG. 2 - Gear pump tests on water-in-oil emulsions

performance as shown in Figure 2, where performance approaching that of mineral oil has been achieved.

To control wear with water-in-oil emulsion-based lubricants it is necessary to control EHD film thickness, the occurrence of fatigue, the propensity for removal or prevention of chemical films due to dissolution by water or the lower contacting surface temperatures which occur with emulsion based lubricants, and the increased risk of corrosion. There is some evidence to suggest that with very small dispersed water droplets, the EHD film thickness is higher than that of the base oil alone [9]. The propensity of water to remove chemical films and for the lower surface temperature to prevent the action of standard antiwear/ep and corrosion inhibition additives, requires different additive chemistry to that which would be used with mineral oil based hydraulic fluids. Properly formulated, good antiwear performance can be achieved, as shown in Table 2.

The development programme produced water-in-oil emulsions having a combination of good fire resistance, emulsion stability and mechanical performance. These emulsions are now used extensively, mainly in underground mining equipment, where good stability and lubrication performance, particularly with rolling element bearings, is important. Typically, they are used in machines designed for developing access tunnels or roadways and in production machines associated with cutting and loading of the mineral being mined. The application of hydraulic systems is diverse, some examples being the raising and lowering of cutter drums and rotation of loading cowls around these drums, and the use of hydraulic drives for tracks, loading and conveying systems and roof bolting systems. Variable volume axial piston pumps, gear pumps, pressure compensated load sensing controls, and both solenoid and electro servo valves are used, with hydraulic fluid pressures in the region of 20 MPa, and flows of up to 1200 l/min, being experienced.

All fluids in service are susceptible to degradation; emulsion-based fluids perhaps more so than mineral-oil-based fluids. The lubrication performance of an emulsion is also more sensitive to contamination. Field experience has shown that it is important, therefore, to monitor fluid condition regularly during service.

To maintain fire resistance it is necessary to maintain the water concentration close to initial values. Water content can be monitored by measuring changes in density, and water loss due to evaporation replenished by very slowly adding distilled water to the vortex in the hydraulic fluid reservoir, usually close to the pump inlet line. The water will be re-emulsified by the shearing action in the pump. Experience has shown that the optimum system temperature for water-in-oil emulsion hydraulic fluids is 40°C, and that, to avoid excessive water evaporation, temperatures should not exceed 65°C. It has been found that, due to the higher thermal conductivity, systems tend to run at a lower temperature (approximately 10°C) with water-in-oil emulsions, compared with mineral oil.

Emulsion stability has not been found to be a particular problem, but can readily be assessed by measuring viscosity, as separation of water from the emulsion leads to a decrease in viscosity. If necessary, stability can be assessed further by heating the emulsion to 70°C and measuring the degree of oil and water separation.

Analysis of failure modes reveals that the most common cause of hydraulic system failure underground is through excessive particulate contamination. If possible fluid analysis should include particle counting to provide an ISO cleanliness level, however it is recognised that careful sampling is required to avoid contamination at the point of sampling and subsequent misinterpretation of calculated cleanliness levels. As a minimum, operators need to be aware of the ingress routes for this contamination, and steps taken to avoid or minimise it wherever possible.

Bacteria and fungi continually enter hydraulic fluid systems through air breathers. Wide spectrum biocides are included in the formulation, however as the fluid reaches the end of its useful life, the biocides can become depleted. If this occurs, bacteria and fungi can become established, and, if allowed to multiply unchecked, can eventually lead to filter blocking, causing the filter to switch to "by-pass" mode. If particulate contamination is high, this will, in turn, result in excessive wear of pumps and valves. The presence of bacteria and fungi can be assessed using dip slides, and, either the biocide can be replenished, or the fluid in the system changed before a filterability problem occurs.

Field trials have shown that these advanced water-in-oil emulsions offer improved service as a result of improved stability, improved pump life, resulting from lower levels of bearing fatigue and wear, and improved hose compatibility. The improved performance of the advanced fluids resulted in less fluid leakage and less machinery downtime, giving operating cost savings.

ADVANCED OIL-IN-WATER (HFA) EMULSION - For some applications, for example in the production of iron and steel, better fire resistance than that offered by HFB type (and HFC type) fluids is required [3]. HFA fluids, which contain the highest water content, typically more than 80 percent, provide the best fire resistance, but as their lubrication performance is usually relatively poor compared with that of mineral oil, their application normally requires specialised hydraulic components specifically designed for use with water. An advanced HFA oil-in-water emulsion fire-resistant hydraulic fluid has been developed using a comprehensive programme derived from the test methods contained in the Luxembourg Reports, together with in-house pump tests using pumps designed and intended for use with mineral oil hydraulic fluids.

HFA fluids typically consist of 5 percent of oil phase dispersed as small droplets in 95 percent of water. As with HFB fluids, emulsion stability and small, sub-micron, droplet size is the key to good performance, however as the continuous phase is comprised of water, different emulsifier chemistry is required. The boundary lubrication properties of oil-in-water emulsions can be greatly influenced by the emulsifier used [10] and wear protection requires control of the base oil and emulsifier chemistry, with careful selection of antiwear additives and antipitting additives which can control bearing fatigue.

During the development of the advanced HFA fluid it was possible to meet all of the performance requirements with a 95:5 emulsion having a viscosity of 1 mm^2s^{-1} at 40°C, except for high pump volumetric efficiency. It was found that a 'thickener' additive was required to raise the viscosity to achieve high volumetric efficiency. Thickeners which were very efficient in raising viscosity (high viscosity for low treat rate), were found to be unstable to shear; the high molecular weight polymers either shearing in pump tests and/or suffering a high temporary loss in viscosity at high shear rates. This illustrates the limited value of, and caution which should be exercised, when selecting an emulsion as a lubricant on the basis of its ISO viscosity grade. Owing to the non-Newtonian characteristics of thickened emulsion fluids, the viscosity at high shear rate, rather than that measured in a capillary glass viscometer at low shear rate, is a more reliable measure.

The selection of the preferred viscosity grade for the 'thickened' HFA emulsion was made on the basis of volumetric efficiency tests using an axial piston pump rather than on the basis of ISO viscosity grade. In pump tests it was found that as pressure increased, delivery decreased, and pump body leakage increased, especially for the 95:5 fluid which gave a volumetric efficiency of only 80 percent at 21 MPa. There was however practically no difference in volumetric efficiency for ISO 10 and ISO 22 fluids, both giving 98 percent volumetric efficiency; equivalent to mineral oil. The ISO 10 fluid had the best balance of fire resistance (highest water content) and volumetric efficiency.

The results of Luxembourg Report tests, including fire resistance tests (normally only carried out on HFB, HFC and HFD fluids), and in-house tests, are shown in Tables 1 and 2. A comparison with the results of wear performance for an early 95:5 emulsion, which is still used in powered roof support systems in the mining industry, are also shown in Table 2, to illustrate the improved performance of the latest thickened emulsion. The in-house piston and gear pump tests, which use standard production hydraulic pumps, show a dramatic improvement of the latest fluid over the earlier technology fluid.

The development programme produced a new ISO 10 oil-in-water emulsion with significantly improved lubrication performance relative to an early 95:5 emulsion, while still retaining its superior fire resistance. Many industries having hazardous processes have either changed or are changing from mineral oil to fire resistant hydraulic fluids. For some established industries it is desirable that the changeover should be made at minimum capital cost, with a minimum of downtime and effort. The availability, therefore, of an HFA fluid of improved lubricity, should mean that the changeover can be made at low cost using standard hydraulic components, without down rating conditions.

Trials have been undertaken in hydraulic systems on a continuous casting steel plant, formerly operated using mineral oil hydraulic fluid, using the new ISO 10 oil-in-water emulsion, to establish that a direct replacement of mineral oil is indeed possible in a practical environment. The fluid has been used to provide power in 11 different hydraulic systems, comprising Servo Adjustable Mould Units, Ducking Rolls, Weighbridge/Pusher, and Cold Scarfer, during normal operation of the plant using standard hydraulic components. Results quoted in this paper were obtained in the Ducking Roll systems. The Ducking Roll hydraulics are used when steel slabs are being cut to size, to sequentially "duck" one of the rolls under the advancing steel slab, across which an oxyacetylene cutter is passing, to avoid damage to the roll.

As with water-in-oil emulsion based fluids, it is important to monitor fluid quality regularly during service. The properties of the fluid in one of the systems after approximately 12 months service are shown in Table 4. The fluid was stable over the time period, with no separation of free oil or water from the emulsion. There was no change in viscosity, indicating that the fluid is stable to the shearing forces experienced in pumps, valves and filters. Bacterial resistance was achieved through the high pH, although if necessary, biocides could have been added to control this aspect of performance. The fluid was easier to seal in the hydraulic system than would have been the case with a 95:5 emulsion of lower viscosity. An added advantage of its use, relative to mineral oil, was that leakage of an opaque white fluid from the system was easier to identify, and, being water-based, easier to clean up.

During system operation, the duty pump was run at constant speed and pressure, and maximum flow. When the system was not operating, the pump was stationary. The results of body leakage, over a duty period of approximately 12 months, for a standard, variable displacement, axial piston, swashplate design pump, formerly operated using mineral oil hydraulic fluid, are shown in Table 4. Temperature and pressure changes influence the leakage rate; however, taking this into account, the results show no problems with lubrication over the duty period.

In the Ducking Roll systems, the action of each of the seven cylinders used to "duck" the rolls, over which the slab being cut is passing, was controlled by an associated spool control valve. The results of leakage across a set of 7 spool valves (and any leakage through the cylinder seals), for one of the systems, at a particular temperature and pressure, over the same duty period are also shown in Table 4. The spool valves were standard, stainless-steel spool/cast-iron body valves, normally used with mineral oil. Leakage was used to assess the ability of the valves to operate with this fluid, as any erosion and cavitation damage will increase the size of the gap between spool and body, resulting in an increase in flow across the valves. Normally, such spool valves cannot be used with HFA fluids, because their low viscosity usually leads to flow erosion, cavitation damage, and early valve failure. The results for the ISO 10 fluid, however, show no problems with valve operation over the duty period.

The mild-steel reservoir tanks and lines used with the former mineral oil hydraulic fluid were not replaced for operation with the ISO 10 fluid. No corrosion problems were experienced where the components were flooded with fluid; slight corrosion of the tank roof caused by water evaporation from the fluid was observed but not considered to be a problem. No changes were made to the cylinders used to actuate the rolls. Service from the cylinders was equivalent to that with mineral oil, with no seal leakage problems or deterioration of the rod surfaces.

SUMMARY AND CONCLUSIONS

Advanced water-in-oil emulsion fire-resistant hydraulic fluids have been developed, which have been shown to offer improved service, as a result of improved stability, improved pump life, resulting from lower levels of bearing fatigue and wear, and improved hose compatibility. The improved performance of the advanced fluid resulted in less fluid leakage and less machinery downtime, giving operating cost savings.

An advanced oil-in-water emulsion fire-resistant hydraulic fluid has been developed which overcomes the problems of poor lubricity, poor pump volumetric efficiency and inability to operate standard spool control valves, normally associated with HFA hydraulic fluids. It has been shown that the fluid is able to replace mineral oil in continuous casting steel plant hydraulic systems, without the need for the more expensive water hydraulic components normally required with this type of fluid, and without the need to down rate system operating parameters. The hydraulic systems on the continuous casting plant, using this fluid, have operated well, with no downtime associated with failure of the fluid, or lack of its ability to lubricate the equipment under test. The pressures employed were the same as those employed with mineral oil. The use of this advanced oil-in-water emulsion has eliminated the high risk of fire that was associated with the previous mineral oil hydraulic fluid.

Table 4

Field performance of an advanced oil-in-water-emulsion hydraulic fluid

Cummulative Service, hours	0	3075
Appearance		
Colour	White	White
Oil Separation	Nil	Nil
Water Separation	Nil	Nil
Creaming	Nil	Nil
Thinning	Nil	Nil
Water Content	83.5	84.2
pH	9.5	9.6
Bacteria	Nil	Nil
Viscosity at 40^{o}C, mm^{2}s^{-1}	10.8	10.6

Cummulative Service, hours	Pressure, MPa	Temperature, ^{o}C	Pump Body Leakage, l/min	Valve Leakage, l/min
0	10	16	2.3	0.6
421	20	24	3.8	1.4
2330	20	36	3.0	2.3
3075	20	28	3.2	2.1

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