Differentiating Performance in Water Glycol Fluids

HFC fluids, otherwise known as water glycol hydraulic fluids, are the most widely used type of fire-resistant hydraulic fluid in heavy industry. Their price-performance profile and fire-resistant properties make them a suitable choice for a wide range of applications. However, when selecting an HFC fluid, specifiers should be aware that not all HFC fluids are created equally. This article will discuss factors that impact HFC price-performance characteristics based on field and laboratory analysis.

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Introduction

Hydraulic fluids are at the core of many of the heavy industrial processes that enable modern life. From steelmaking, continuous casting, hot rolling to welding, modern-day hydraulic fluids are the life blood of power transmission. Hydraulic fluids are plentiful with considerable diversity in formulation, purpose and performance. Conventional hydraulic oils are formulated from petroleum base stocks (mineral oils) and provide excellent performance in the field. However, a major disadvantage of petroleum hydraulic fluids is that they burn quite well. There are many tragic stories in which accidental ignition of petroleum hydraulic fluid has led to catastrophic damage and loss of life. Fire-resistant hydraulic fluids (FRHF) are a special class of fluids engineered to provide enhanced safety and asset protection in applications where the risk of ignition is present. The International Organization for Standardization (ISO) designates four categories of FRHF, each with their own accolades and advantages: HFA (water dilutable concentrates), HFB (water-in-oil emulsions), HFC (water glycol) and HFD (water-free). HFC fluids by far have the largest market adoption due to their price vs. performance profile. Approximately 80% of a typical HFC formulation is water and glycol — typically ethylene or diethylene glycol — so it may come as no surprise that HFC fluids are sometimes viewed as a commodity. Specifiers will find that there are many HFC fluids commercially available, each with their own claims about quality, performance and price. For noncritical, low-pressure and/or leaky hydraulic systems, any decently inhibited water glycol fluid may work. However, there are critical applications where corners ought not be cut, and careful selection of a high-performance HFC fluid can pay dividends when viewed from a "total cost of ownership" perspective. This article provides an overview of water glycol FRHF and some of the factors that impact their price-performance profiles.

HFC Development

Water glycol hydraulic fluids were originally developed in the late 1940s after the U.S. Navy experienced several disastrous fires on ships due to ruptured high-pressure lines containing conventional petroleum hydraulic fluid. The first iterations of this "new" technology were simple formulations of water, glycol and maybe some corrosion inhibitor. It would be several more years before these fluids began to see general industrial adoption. Alongside the advancement of lubricant additive technology, modern-day HFC fluids can be complex formulations of many components designed to balance lubricity, corrosion inhibition and long-term solution stability, etc. Hydraulic equipment has also evolved thanks to advancements in metallurgy, polymeric materials, machining capabilities, hydraulic pump and circuit design, etc. Modern hydraulic systems run under demanding conditions that require a high-performance hydraulic fluid to get the job done. The fluid must be capable of meeting operating temperatures and pressures while providing robust wear protection, corrosion inhibition and long-term stability.

Fire-Resistant Hydraulic Fluids

Hydraulic systems operate at high pressures, and a ruptured hose or leaking pipe can quickly become catastrophic should it spray directly on an ignition source. Unlike conventional petroleum oils, fire-resistant hydraulic fluids are engineered to resist ignition and flame propagation, which provides enhanced safety and peace of mind. It should be noted that there exists no globally applicable standard for determination of fire resistance, though regional approvals are in place. In North America, the governing body for FRHF is Factory Mutual Global (FM), an insurance underwriter with standardized processes for evaluating all sources of asset risk. For fire resistance, FM developed class 6930 — Less Flammable Industrial Fluids — to evaluate, test and approve hydraulic fluids as less flammable, or fire-resistant. The context of this article is specific to HFC fluids explicitly designated as a category of fire-resistant hydraulic fluid per ISO. Not all water glycol solutions are HFC fluids. It is strongly recommended that specifiers confirm FM approval status (or equivalent) for any FRHF under consideration for use in a high-risk environment. Water glycol FRHFs achieve fire resistance by virtue of their water content, but they cannot be considered fireproof. Formulations contain organic components with measurable flash points. It is the responsibility of the fluid supplier to demonstrate fire resistance of their product(s).

Formulation Chemistry

HFC fluids typically contain 35–45% water by mass. This range is quite important — a “sweet spot” that optimizes lubrication performance, cooling capacity and fire resistance. Too much water leads to a significant drop-off in pump efficiency and wear protection. Too little water, and the fire resistance becomes compromised. Within these parameters, the water portion of the formula imparts fire resistance, but plays no role in the price-performance profile.

The glycol accounts for 25–40% by mass and plays a significant role in the cost of the finished HFC fluid. Glycols are organic compounds belonging to the “alcohols” family, and they are fully miscible with water. The primary function of the glycol is to improve the low temperature properties by depressing the freezing point. This improves start-up pumpability and extends the practical operating range of the fluid. This is akin to “antifreeze” in automotive coolant circuits, which happen to use ethylene glycol. The most common glycol used in HFC fluids is diethylene glycol (DEG), but ethylene glycol (EG), propylene glycol (PG) and glycerin can also be used. Table 2 highlights some pros and cons of each. In the late 1980s, EG became a Superfund Amendments and Reauthorization Act (SARA) Title III reportable chemical due to toxicity, environmental impact and public safety concerns. This encouraged the general standardization to DEG as the preferred glycol, which has a favorable hazard profile vs. EG, and still offers decent freezing point depression characteristics at a good price point. Accounting for a large portion of the formula, the glycol has a significant impact on the price of the finished HFC fluid, and some impact on the performance.

A thickener is used to give body and viscosity to the fluid, properties that impact pumpability and efficiency of power transmission. The most common thickeners used are polyalkylene glycols (PAG). These are available in a wide range of molecular weights with varying degrees of thickening efficiency and shear stability. The thickener and the glycol together comprise the primary cost drivers of the finished HFC fluid.

The balance of the formula are the additives — and this is where the line in the sand is drawn. The overall performance of the HFC is a function of the additive package. This is where formulation savvy becomes the differentiator from the dime-a-dozen HFCs to top-shelf, original equipment manufacturer (OEM)-recommended products. Table 3 breaks down a typical HFC formulation.

Table 1

Typical Chemical Contents of Toledo HBI

ISO category	Composition	Detail
HFA	High-water-content fluids	Oil-in-water emulsions (HFAE) Full synthetic solutions (HFAS)
HFB	Invert emulsion fluids	Water in oil emulsions
HFC	Water glycol fluids	35–45% water
HFD	Anhydrous fluids	Natural esters, Polyol esters, polyalkylene glycols, phosphate esters

Table 2

Pros and Cons of Common Glycols Used in HFC Formulations

Factor	Ethylene glycol (EG)	Diethylene glycol (DEG)	Propylene glycol (PG) and glycerin
Pros	• Good price point • Excellent pour point depressant	• Effective pour point depressant • Not SARA III reportable	• Food-grade options • Best hazard/toxicity profile
Cons	• Known toxicity and regulatory issues (SARA III reportable chemical) • Most volatile	• Not as effective at depressing freeze point vs. EG • Marginal hazard profile	• Most expensive options • Poor wear performance (glycerin)

Table 3

Typical HFC Formulation

Component	Concentration (wt. %)	Purpose
Water	35–45	Fire protection
Glycol (EG, DEG, glycerin, etc.)	25–40	Freeze point reduction
PAG thickener	10–20	Viscosity modifier
Additives	5–10	—
Corrosion inhibitor(s)	2–5	Liquid and vapor phase corrosion protection
Lube additive	2–5	Mixed-film and boundary lubrication
Copper passivator	0.5	Yellow metal deactivator
Dye	0.1	Leak detection

Performance Drivers

The performance profile of HFCs may be a somewhat subjective topic. Every application is unique, with variations in operating conditions, duty cycles, environment, etc. Low-grade HFC and high-performance HFC both have their place. Therefore, in selection of the most appropriate HFC for the job, consideration should be given to the following factors that impact the price-performance profiles.

Lubricity and Wear Protection

One of the primary functions of hydraulic fluids is to provide adequate lubricity to the hydraulic pump(s) to minimize internal wear. For conventional petroleum-based lubricating oils, there are plenty of options for anti-wear and extreme pressure agents available to the formulator. HFC fluids are water-based — they play by different rules with a limited selection of lubricity additives. Organic soaps derived from carboxylic acids and amines are well documented and widely adopted as the primary lubrication solution. The soap chemistry lends to flexibility in tailoring characteristics. Fatty acids may be linear or branched, and amines may be primary, secondary or tertiary. Subsequently, there exist many possible soap combinations, with varying molecular weight and chemical structures. The goal is to maximize the lubricity of the soap, while keeping it stable in solution across its operating range. The lubricity additive is the workhorse anti-wear agent, so it is critical that it is well-formulated. Cutting corners on the quality of the lubricity additive to save a few cents will lead to higher wear rates in hydraulic pumps and is detrimental to reliability. High-performance HFCs are formulated from premium-quality acids and amines designed to optimize anti-wear properties and long-term solution stability.

Differentiating wear performance of HFCs has proven challenging. Some studies show that four-ball wear testing, commonly employed as a lubricity screening test for anhydrous lubricants, shows little differentiation for water glycol fluids, with similar wear scars reported for low-grade and high-grade HFC fluids. The practical anti-wear characteristics of HFC fluids is generally benchmarked according to hydraulic pump testing as there is no direct correlation between lubrication bench testing and real-world pump wear. In North America, the most popular test method is ASTM D7043 – "Indicating Wear Characteristics of Non-Petroleum and Petroleum

Hydraulic Fluids in a Constant Volume Vane Pump." The typical conditions for the standard test are: 5 gallons of hydraulic fluid recirculated for 100 hours at 2,000 psig, with a pump speed of 1,200 rpm and a fluid temperature of 150°F (65°C). The ring and vanes are weighed before and after the test, and any difference in weight is considered lost as wear. The lower the total weight loss, the better the anti-wear protection provided by the fluid. This test is far from perfect, and in the past, it has been subject to scrutiny due to issues surrounding reproducibility of results, particularly for HFC wear analysis. For consistent results and accurate performance comparisons, care should be taken to thoroughly clean, dry and inspect all pump components prior to assembly, replacing any reusable parts showing signs of wear or failure.

Cusatis et al.[1] evaluated eight commercially available HFC fluids, categorized as "standard water glycol fluids" with >40% water content, and "high-performance" water glycols with <38% water content. In the context of their paper, standard water glycols "may further be defined as fluids typically used in piston pumps at hydraulic pressures no greater than 3,500 psi, whereas high-performance water glycol hydraulic fluids may be used satisfactorily in some piston pumps with operating pressures of 5,000 psi." The eight fluids chosen were all PAG-thickened, with similar ethylene oxide to propylene oxide ratio, but had varying molecular weights and viscosity index. A summary of their results is shown in Table 4. Some key takeaways from their work: (1) The bench tests did not always reflect the claims of the product literature; (2) Reserve alkalinity appears to have no correlation to standard bench test performance; (3) Small differences in water content appears to have no correlation to standard bench test performance parameters; (4) At least one of the fluids marketed as high-performance performed worse in pump testing vs. some of the standard HFC tested; (5) Bench tests can be modified (higher temperatures, higher pressures etc.) to further differentiate performance; (6) Performance is not one dimensional — multiple factors may impact anti-wear properties and corrosion protection.

Additionally, Quaker Houghton contracted Clark Testing (Jefferson Hills, Pa., USA) to perform hydraulic pump testing according to ASTM D7043 on four HFC fluids all commercially available from leading manufacturers. HFC #1 and HFC #3 are explicitly marketed as high-performance fluids. Fig. 1 and Table 5 highlight the results of the testing.

HFC #1 is marketed as a high-performance water glycol and demonstrated the lowest wear rate vs. all others under identical test conditions. HFC #3 is also marketed as a high-performance HFC, but it generated twice the wear rate vs. HFC #1. It should be noted that wear targets have changed over the last few decades. In the 1990s, total wear <100 mg was considered acceptable. Today, many OEMs have a requirement of <50 mg total wear. In this data set, only HFC #1 would meet the strictest OEM requirements for high-performance hydraulic applications.

Table 4

Summary of HFC analysis from Cusatis et al., "Property and Performance Evaluation of Water Glycol Hydraulic Fluids," ASTM International, STP 1573, April 2014.

Fluid name	Water content (%)	Reserve alkalinity (mL)	Ferrous corrosion ASTM DD665-B 24 hours @ 60°C	ASTM D7043 100 hours, 2,000 psi, 1,200 rpm, 150°F	Total pump efficiency (%)
1-ST	40.5	18.1	Fail, 20% rust	12.2	93.2
2-HP	36.6	17.3	Borderline pass	27.7	87.7
3-LRA	44.7	13.2	Pass	27.9	88.1
4-LRA	41.9	13.4	Pass	1,022.5	80.2
5-HP	35.5	19.8	Pass	180	87.4
6-ST	43.5	19.9	Borderline pass	31.7	89.3
7-LMW	42.5	17.6	Pass	18.0	87.4
8-AT	41.5	22.6	Pass	68.5	83.7

Figure 1

Graphical results of ASTM D7043 testing of four commercially available HFC fluids.

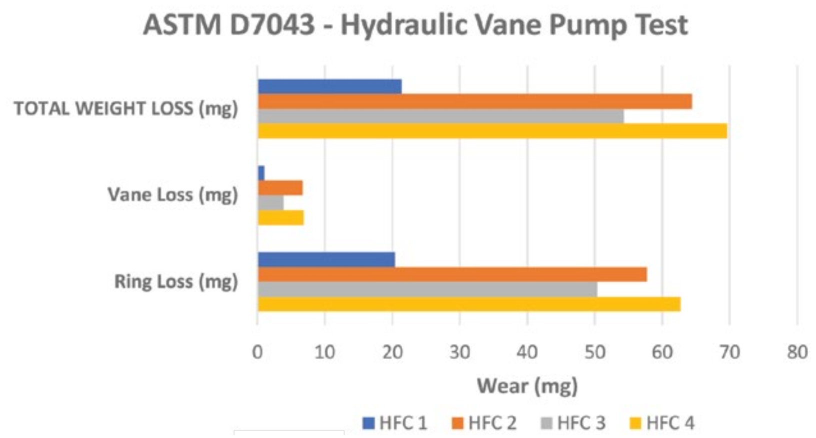

Table 5

Tabulated Results of ASTM D7043 Testing of Four Commercially Available HFC Fluids

Fluid name	Ring loss (mg)	Vane loss (mg)	Total wear loss (mg)
HFC #1	20.4	1.0	21.4
HFC #2	57.7	6.7	64.4
HFC #3	50.4	3.9	54.3
HFC #4	62.7	6.9	69.6

As can be seen in these examples, it is possible to differentiate HFC fluids based on their wear prevention characteristics in the D7043 test. Although this test does not claim to mimic real-world performance, simple conclusions can be drawn in that better anti-wear performance in the lab should translate to better anti-wear performance (and reliability) in the field.

Corrosion Protection

The corrosion inhibitor package of a water glycol fluid is another area that differentiates performance. HFC fluids are formulated to provide corrosion protection in both the liquid and vapor phase. Common corrosion inhibitors such as phosphates, borates and nitrites are typically avoided due to stability and reactivity issues with other formulation components, therefore organic amines are the preferred choice. Liquid phase corrosion inhibitors are dissolved in solution and form protective films on metal surfaces in direct contact with the fluid. Vapor phase corrosion inhibitors are typically volatile amines, designed to vaporize out of solution under normal operation, forming a protective film on exposed metal surfaces in the reservoir head space.

Optimal corrosion protection is highly dependent solution pH which is driven by the amine chemistry and concentration, and more is not necessarily better. As with all lubricant additives, there is, of course, a point of diminishing returns. A poorly formulated corrosion inhibitor package may not provide long-term solution stability or the necessary surface protection. Additionally, the volatility of the vapor phase corrosion inhibitor (VPCI) should not be overlooked. If it is too volatile, it will be depleted more rapidly, dropping pH and reserve alkalinity, necessitating the need for makeup additive to restore properties. If the VPCI is not volatile enough, it may not provide the necessary protection to exposed surfaces in the head space.

There are pros and cons to the various amines readily available to the formulator. Some amines are more effective at neutralizing acidic components, which helps prevent acid-induced corrosion. Others may be better "film formers" on the metal surfaces, and others may have better compatibility or hazard profiles. Of course, they all have different price points as well. High-grade HFC fluids are formulated with premium amine packages that optimize performance. These products not only pass all typical corrosion tests, but they also tend to have more stable pH and reserve alkalinity over time, minimizing or eliminating altogether the need to make alkalinity adjustments on the in-service fluid.

Maintenance Requirements

As part of a total evaluation of the performance profile of HFC fluids, total cost of ownership should be considered. Although they are less expensive up front, low-grade HFC fluids have been associated with a higher rate of pump failure, and higher demands on maintenance crews to maintain depleted additive levels. While it is normal for fluid properties to deviate over time, the best HFC fluids resist those changes much more effectively than standard-grade fluids. This leads to longer drain intervals, better wear and corrosion protection and better reliability of the entire system. Unfortunately, it can be difficult to quantify these advantages up front when pricing is being evaluated, and many times the best price wins, but the end user does not. For example, a typical steel mill consumes tens of thousands of gallons of hydraulic fluid annually. When critical hydraulic processes go down, it can cost a mill hundreds of thousands of dollars per hour in downtime. A single unplanned event can far exceed any savings realized in specifying a lower-tier product, which would be especially embarrassing if the failure was directly related to poor hydraulic fluid performance.

Conclusion

There are many factors that contribute to the price point and performance level of HFC fluids, but they all revolve around the quality of the formulation. High-performance HFCs are component formulated, utilizing carefully selected raw materials to optimize key parameters. Such parameters include wear protection, corrosion protection and maintenance requirements. High-performance HFCs carry OEM approvals and demonstrate improved reliability in the field. These fluids provide superior wear protection, stable pH, stable alkalinity, longer drain intervals and more reliable hydraulic systems compared to standard HFC.

This article is available online at AIST.org for 30 days following publication.

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AISTech This paper was presented at AISTech 2025 — The Iron & Steel Technology Conference and Exposition, Nashville, Tenn., USA, and published in the AISTech 2025 Conference Proceedings.