# Global Experience with Environmentally Friendly, Fire-Resistant, HFDU/HEPG Hydraulic Fluids based on PAG's

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## Summary

The formulation of a lubricant starts with the choice of a base stock. The decision of what lubricant to use in the field is based on which lubricant will provide the highest performance, at the lowest "total cost", over the longest time period for the given application. With over 20 year's field experience, Poly Alkylene Glycols (PAG's) are proving that this class of base stock stands out as the clear leader amongst its commercially viable counterparts.

## Introduction

Industry today is confronted with a myriad of regulations and liabilities that did not exist 30 years ago. Greater emphasis today is placed on environmental impact and worker safety than ever before. This is changing the landscape and shaking the foundation of prior lubricant formulation chemistry. No longer is it acceptable to market a fluid based solely on its performance characteristics. If it represents a safety concern to workers or if it will persist in the environment indefinitely, then it is coming increased scrutiny. Increasingly, the choice of base stock is the determining factor as to the success of the formulated lubricant.

The base stock for the majority of lubricants comprises over 90% of the formulation. Therefore, most of the long-term performance of the lubricant is derived from this chemistry. Unfortunately, most of the decisions by formulators, as to this choice, are based on economic/supply advantages to the formulator, not to the end user. This decision – the choice of base stock – has the most far reaching effect on the long-term performance/success of the lubricant in the field. Figure 1 is a table of the most common, commercially available base stocks on the market today.

- Mineral Oil (Group I, II, III)
- PAO (Group IV)
- Vegetable Oil(s)
- Synthetic Esters
  - Phosphate Ester
  - Polyol Ester
- Poly Alkylene Glycol

Figure 1. Common lubricant base stocks

## PAG's the Right Choice

PAG's are unique in that they represent a class of lubricants that not only pass the stringent environmental tests; they also provide the end-user with unmatched long-term performance. For over 50 years PAG's have been solving problems that hydrocarbon lubricants cannot.

PAG's can be chemically designed to meet an extensive range of performance needs. No other base stock chemistry has such versatility. Generally speaking, a PAG (also known as a polyglycol, a polyol, and a polyether) is prepared by reacting an initiator with one or more alkylene oxides under alkaline conditions and elevated temperatures. Within this reaction, there are four variables: the initiator, the oxides, the way the oxides are reacted on to the initiator (i.e. random or block additions), and the molecular weight. This gives PAG chemistry its versatility, which makes it possible to create tailor-made products that meet desired requirements.

The *initiator* gives the PAG its 'chemical functionality', and influences the physical properties of the resulting product, for example imparting hydrophobicity to the polymer. Most initiators are alcohols such as butanol, mono-propylene glycol or glycerine. Oxides are then grafted on to their labile hydrogens to produce linear or branched structures depending on the functionality of the initiator. The choice of *oxides* will influence the hydrophilic/hydrophobic character of the resulting PAG. The most commonly used oxides include ethylene oxide, propylene oxide, and butylene oxide. A high content of ethylene oxide will normally result in fully water-soluble products, while a high content of butylene oxide will provide oil solubility. By combining the oxides, the solubility behavior of the products can be adjusted. *Molecular weight* of the PAG will affect the viscosity of the product. With PAG chemistry, almost the complete ISO VG viscosity range can be covered.

## Properties of Polyglycols

*Viscosity* With PAG chemistry, a broad range of the ISO VG viscosity classes can be covered. Typical standard grades range from ISO 10 to 1000. As indicated above, the viscosity of a polyglycol depends mainly on the molecular weight: the viscosity will in general, increase with increasing molecular weight.

*Viscosity Index* When compared with other base stocks, PAG's show, in general, very high viscosity indexes. Values up to 400 can be reached.

*Solubility* As mentioned above, it is possible to create polyglycols with solubility properties ranging from complete water solubility to complete oil solubility.

*Lubricity* Polyglycols show excellent lubrication properties due to the high affinity of the oxygen atoms in the polymer with the metal surface. This feature also provides mild extreme pressure properties.

*Thermal Stability* Polyglycols demonstrate a very good response to anti-oxidants, and can therefore be formulated for high-temperature applications (i.e. up to about 250C). Other base stocks, such as vegetable oils, some synthetic esters, mineral oils and PAO's, do not offer good enough thermal stability in this temperature range.

*Low Residue* Polyglycols show superior deposit control characteristics over all other base stock classes. Oxidation of polyglycols results in a partial breakdown of the product into volatile components and polar compounds soluble in the base fluid, resulting in low formation of residue. In the case of most other base stocks, oxidation normally leads to polymerization, which produces high molecular weight polar by-products that are insoluble in the parent base oil leading to significant residues, which can be an important disadvantage in certain applications. Figure 2 lists the varnish formation mechanisms for the various base stocks shown in Figure 1. Figures 3-5 are photos of these residues from the field and laboratory.

| | |
|---|---|
| **Mineral Oil:** | Agglomeration/Density |
| **Polyol Esters:** (natural & synthetic) | Polymerization |
| **Phosphate Esters:** | Hydrolysis |
| **Polyglycol:** | NONE - degradation results in low molecular weight by-products, soluble in the PAG base stock |

Figure 2. Varnish Formation Mechanisms

Figure 3. Phosphate ester gels in an EHC reservoir.


Figure 4. Polyol ester gels from an aluminum plant.

Figure 5. Varnish formed during TOST testing.

*Low Pour Points* Pour points as low as -45C can be obtained with polyglycol chemistry. This makes polyglycols suitable for low temperature applications. Low pour points combined with their high viscosity indexes, make polyglycol lubricants an excellent choice for applications requiring one product for all-seasons. Figure 6 is a graph showing how the viscosity for several fluids will change with changes in temperature. This data is extremely valuable to know how a lubricant will perform during a cold start-up and when the system reaches its normal operating temperature.

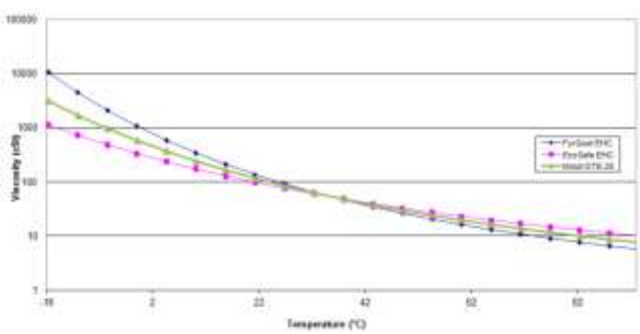


Figure 6. Viscosity vs. Temperature

*Thermal Conductivity* In general, PAG's offer better thermal conductivity than mineral oils. This means that better cooling characteristics can be achieved with PAG's, and as a result, a smaller heat exchanger can be used.

*Hydrolytic Stability* Polyglycols do not hydrolyze, which can be seen as a major advantage over natural esters (vegetable oils) and synthetic esters. With esters, hydrolysis leads to acid formation, which will increase the lubricants corrosion potential and accelerate further fluid degradation. In many applications, contamination with water cannot be completely avoided. This is especially true for equipment operating outside, exposed to the elements where rain and humidity ingress into the lubricant system and the hydrolysis process starts. For polyglycols, however, this is not a problem. A further unique feature is their ability to absorb water that contaminates the lubricant through ingress. When this occurs in the equipment, the PAG can act as a polymeric sponge that renders to water inert.

*Elastomer/Metal Compatibility* Care should be taken in the choice of elastomers with all base stocks. A broad range of commercially available elastomers, such as NBR (acrylonitrile/butadiene rubber) and FKM (flouro-rubber), can be used with polyglycols. The same is true for ferrous and non-ferrous metals.

Figure 7 lists the fluid properties for two commercially available, water insoluble PAG hydraulic fluids.

| Properties | ISO VG 46 | ISO VG 68 |
|---|---|---|
| Viscosity @ 40°C, cSt | 50 | 68 |
| Viscosity @ 100°C, cSt | 9.6 | 12.6 |
| Viscosity Index | 180 | 185 |
| Density @ 15°C | 0.985 | 0.986 |
| Pour Point, °C | -48 | -45 |
| Copper Strip Corrosion | 1a, shiny | 1a, shiny |
| Rust Test, synthetic sea water | Pass | Pass |
| TOST (with water), 2,000 hours | Pass | Pass |
| Foam Test (Sequences I, II, III) | Pass | Pass |
| Air Release, Min. | | 8.1 |
| Four Ball Wear, scar, mm | 0.35 | 0.35 |
| FZG, stages passed | 12 | 12 |
| Vane Pump Test | Pass | Pass |
| Brugger Value | >40 N/mm² | >40 N/mm² |
| Readily Biodegradable | Yes | Yes |
| FM Approved (fire-resistant) | Yes | Yes |

Figure 7. Finished fluid properties – PAG hydraulic fluids

AUTHORS NOTE: A fallacy perpetuated by lubricant marketers is that these test results automatically extrapolate to long-term performance in the field. When in actuality, these are the best results most fluid chemistries will ever produce again. These are controlled tests, run under extremely precise conditions, on 'virgin fluid', in a laboratory environment. Any problem during the test and it is terminated, the equipment cleaned and recalibrated, and the test re-run. The question that is never answered is; what are the results after the fluid has been in service for one year, two years, etc. What happens when 1,000 ppm of water ingresses into the reservoir? What if the system runs hotter than anticipated? Does the fluid chemistry change? Does the fluid have to be dumped, or can the chemistry handle this scenario and continue to provide performance? Moral of the story – "Test results from product literature may be no indication of the long-term performance of the lubricant. The lubricant must perform in the application it is expected to be used in, not, the environment modified to meet the lubricants drawbacks"!

# Field Experience with Water-insoluble PAG Lubricants

## Mobile Equipment – 22 year History

Mobile equipment is unquestionably the most demanding application for a hydraulic/hydrostatic lubricant. Reservoirs are under-sized, flow rates are high (multiples of reservoir volume), operating temperatures can reach 100°C and they have to operate outside in the elements. Combine this with cold temperature start-ups and ingression of water from the condensation formed in the reservoir as the fluid is heated and cooled, and one can begin to understand the strain that this will place on the lubricant. Long-term performance of the lubricant in the equipment is critical, as the cost to bring the machine back from the field for repairs or fluid change-outs is expensive.

Mobile equipment was the first application for EcoSafe® FR dating back 22 years. Over this time period, pump life has been extended six-fold over other synthetic, fire-resistant hydraulic fluids. Over this same time frame, studies have shown that drain intervals can be increased to match the diesel core rebuild cycle (approximately 11,000 hours). The versatility of this PAG chemistry has also allowed OEM's to use one fluid across several applications on one piece of equipment. Figure 8 is the photo of a track loader where EcoSafe® FR-46 is being used in the implement hydraulics, hydrostatic drives and the splitter gear box. The success of this chemistry, across these three lubrication disciplines, now exceeds 17 years.

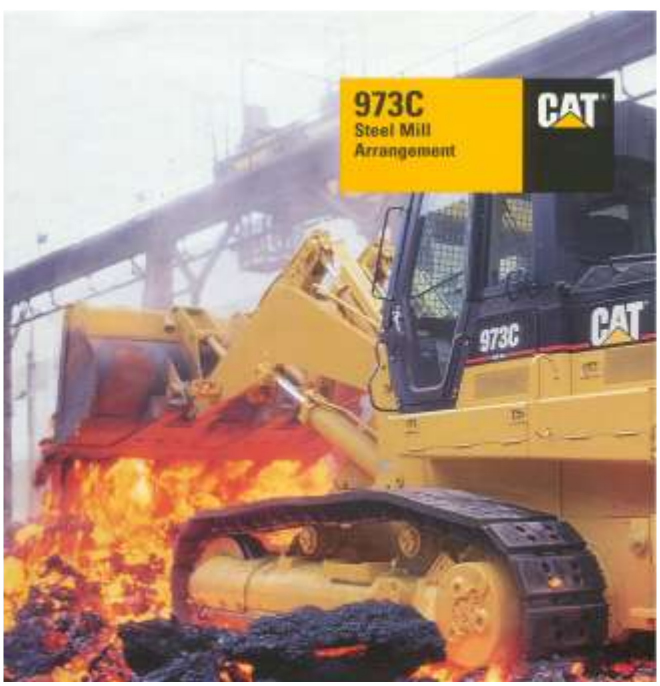



Figure 8. Track Loader – slag operation.
Photo courtesy of Caterpillar, Inc.

## Steel Industry – 17 year History

The first steel mill application for a fire-resistant, PAG fluid was in 1996. The success within the steel industry was equally as apparent as that with mobile equipment and came without any changes/modifications to the system. The most notable being achieving over 85,000 hours on axial-piston pumps operating at 345 bar (5,000 psi). The most hours attained on synthetic ester chemistry over the initial 10 years of operation, was 4,000 hours.

Figure 9 is a historical graph of the acid number versus water content for this system. Of note is the gentle increase in acid number over time even though water ingression has exceeded 6% (60,000 ppm). This demonstrates the flexibility of this PAG chemistry. The water ingression has been dealt with, on-line, real-time, via vacuum dehydration without shutting down the system.

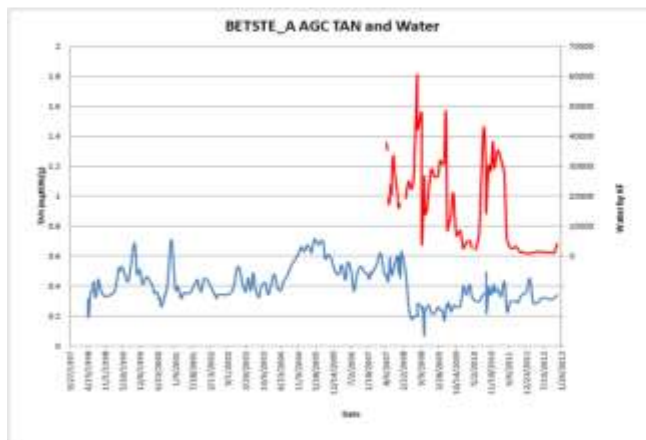



Figure 9. Steel Mill HAGC – acid no. vs. water content

## PAG's in the Power Generation Industry

The last ten years has seen PAG chemistry make great strides into the power generation industry. From electro-hydraulic control (EHC) fluids that regulate the speed of the turbine, to the actual turbine bearing lubricant and most recently as a varnish control agent for in-use turbine oils.

As with mobile equipment and steel mills, long-term performance is critical, no matter what the operating parameters. PAG's success is derived from its key chemistry attributes: low residue, inert to water, excellent lubricant, worker/environment safety and in certain viscosities, fire-resistance. These systems operate 24/7 and are either servo controlled or have close tolerance bearing clearances which makes fluid chemistry stability and cleanliness (low residue) of paramount importance.

The most effective way to measure to life of a PAG fluid is by monitoring the acid number. As can be seen in Figure 10 and 11, these fluids are showing almost no change in fluid life even after 5-8 years in-service.

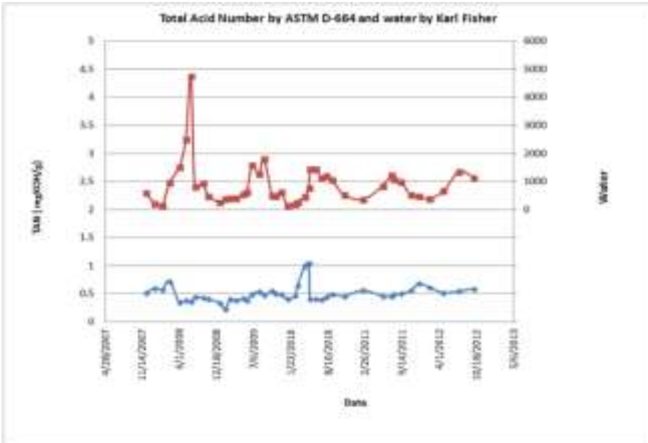



Figure 10. PAG EHC Fluid – acid no. vs. water content

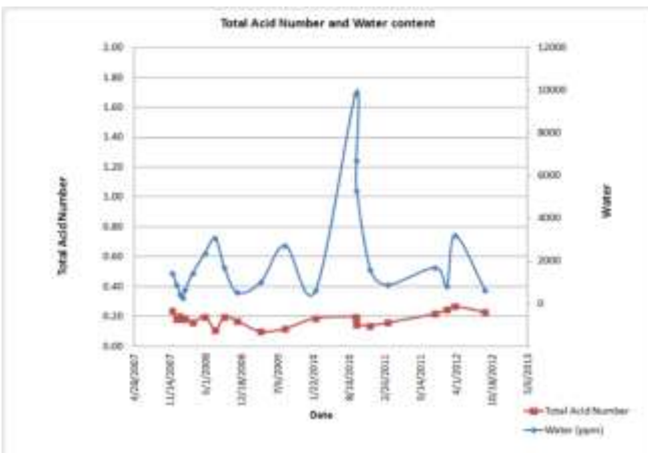
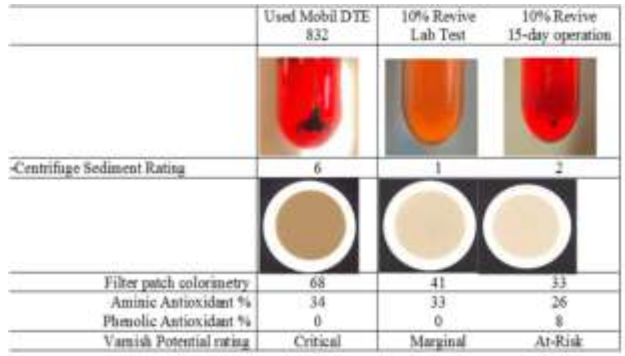



Figure 11. PAG Turbine Fluid – acid no. vs. water content

The newest member to the power generation family of fluids is EcoSafe® Revive (patent pending). This chemistry draws upon PAG's polar nature. This polarity allows a shift in the solubility of mineral oils that now helps to dissolve and/or inhibit the future formation of varnish. This is of critical importance in the lubrication of gas turbines because varnish causes a gas valve (servo controlled) to stick which causes the turbine to 'trip'. As one can imagine, system trips are quite expensive. Furthermore, after so many, operators are required to take the turbine down for inspection. This is incentive for the power plants to minimize downtime because the power companies are now responsible to purchase their contracted megawatts on the open market. Figure 12 shows beta test data within the first two weeks of operation in a GE 7FA gas turbine.



| | Used Mobil DTE 832 | 10% Revive Lab Test | 10% Revive 15-day operation |
|---|---|---|---|
| Centrifuge Sediment Rating | 6 | 1 | 2 |
| Filter patch colorimetry | 68 | 41 | 33 |
| Aminic Antioxidant % | 34 | 33 | 26 |
| Phenolic Antioxidant % | 0 | 0 | 8 |
| Varnish Potential rating | Critical | Marginal | At-Risk |

Figure 12. Beta test site results in a GE 7FA gas turbine.

## Conclusion

Figure 13 is the authors attempt at providing a numerical score to rate the various base stocks against a list of necessary attributes. It also allows the reader to give weight to attributes they feel are more important to a given application. These scores need to then be followed up with field experience to corroborate the expected, long-term performance of the lubricant. In many instances, standard laboratory testing needs to be modified based on the application, to see what effect it will have on the lubricant. To draw a conclusion on a 'dry TOST' test, when in reality the fluid will be constantly running with 1,000 ppm water, is misleading. Generally speaking, if it fails in the modified test, it will fail in the field. To date, no fluid chemistry has matched the long-term performance ability of PAG's!

**Rating of Fluid Base Stocks**
Ratings: 1 (poor) to 5 (excellent)

| Property | MO | PAO | VO | PE | POE | PAG |
|---|---|---|---|---|---|---|
| Readily biodegradable | 2 | 2 | 5 | 3 | 5 | 5 |
| Renewable content | 1 | 1 | 5 | 1 | 1 | 1 |
| Aquatic toxicity | 5 | 5 | 5 | 2 | 5 | 4 |
| EPA "Static Sheen" | 1 | 1 | 1 | 5 | 1 | 5 |
| Worker friendly | 5 | 5 | 5 | 2 | 5 | 5 |
| Hydrolytic stability | 3 | 3 | 2 | 1 | 3 | 5 |
| Chemical Stability | 3 | 4 | 2 | 4 | 3 | 5 |
| Oxidative stability | 3 | 4 | 2 | 4 | 3 | 5 |
| Seal compatibility | 5 | 5 | 5 | 2 | 4 | 5 |
| Metals compatibility | 5 | 5 | 4 | 4 | 3 | 5 |
| High-pressure performance | 5 | 5 | 3 | 5 | 5 | 5 |
| All-season performance | 3 | 4 | 2 | 1 | 4 | 5 |
| Varnishes and residues | 3 | 4 | 2 | 4 | 3 | 5 |
| Fire-resistance | 1 | 1 | 4 | 5 | 4 | 4 |
| Heat release on burning | 1 | 1 | 4 | 4 | 3 | 5 |
| Combustion by-product toxicity | 4 | 4 | 5 | 1 | 5 | 5 |
| Total Score | 50 | 54 | 56 | 48 | 57 | 74 |

Figure 13. Numerical rating of commercial base stocks.

## List of References

**Polyglycols as Base Fluids for Environmentally-Friendly Lubricants**

R. van Voorst *Dow Benelux NV, Terneuzen, The Netherlands* and F. Alam *Dow Europe SA, Horgen, Switzerland* (Paper originally presented at the 11th International Tribology Colloquium ‘Industrial and Automotive Lubrication’, Technische Akademie Esslingen.)