PURE, PREDICTABLE AND WITH NO SULPHUR[1] AND VERY LOW AROMATIC AND UNSATURATES CONTENTS, SHELL'S GTL BASE FLUIDS HAVE HIGHER FLASH POINTS, LOWER DENSITIES AND TYPICALLY MORE EFFECTIVE THERMAL PROPERTIES THAN CONVENTIONAL MINERAL OILS.

This white paper was written solely by Shell and not with or on behalf of any consortium with which it is involved.

CONTENTS

1 Below the detection limits according to ISO 14596/ASTM D2622

HEYSHAM 2
TRANSFORMING TRANSFORMER RELIABILITY

Transformers are very expensive, business-critical assets for which reliability is paramount. Failures can be catastrophic, as the economic losses and non-delivery penalties that may be incurred during power interruptions can be severe. Shell recently introduced the first transformer oil to be based on GTL technology and it believes that this, coupled with scientific findings from a major research programme, could help to revolutionise the reliability and lifespan of transformers now and in the future.

THE TRANSFORMER CHALLENGE

EDF had observed oil degradation issues in its 132 kV station transformer. The operational temperatures of this transformer were trending higher, indicating loss of cooling performance and the potential for unwanted accelerated reduction of transformer and oil-life and performance, if not corrected.

The transformer had last been filled with an uninhibited oil two years previously and was already showing signs of accelerated ageing with potential for loss of performance. Poor surface tension and dielectric dissipation values, a high total acid number and rapid darkening were evident in the regular routine oil condition monitoring testing.

The customer contacted Shell for advice after hearing a conference presentation by Shell on the improved, high performance, longer-life Shell Diala S4 ZX-I transformer oil which is capable of meeting and exceeding IEC 60296 .

Following detailed technical discussions with Shell, the decision was made to replace the transformer's oil. The old oil was vacuum extracted and the system was hot flushed with the new oil and then refilled with Shell Diala S4 ZX-I during a maintenance period where the transformer radiators were replaced.

Shell Diala S4 ZX-I has now been in continual service in this transformer for more than 3 years and as well as the reduction in transformer operating temperature, the rate of oil ageing has also declined. "Conventional dissolved gas analysis and oil condition monitoring data has shown low total acid number, high surface tension and low dielectric dissipation factor values. The oil still appears clear and bright and water white, compared to the previous oil which aged and darkened more rapidly." Commented Douglas Barker, Electrical Engineer, Heysham 2.

Heysham 2 is an EDF Energy-operated nuclear power station on the north-western coast of the UK and is the UK's only site to have two operating nuclear power stations. The site was constructed in 1980 and the first power was generated in 1988, with an estimated end-of-generation to 2030. The power station now generates enough power to serve some two million homes. Heysham 2 is comprised of two advanced gas-cooled reactors, supplies 1,230 MW to the national grid and employs more than 750 full-time EDF Energy employees and contract partners.

2 Demonstrated by data from Shell, independent third party laboratories and universities, OEMs and utilities.

"The obvious improvements in reliability and performance Shell Diala S4 ZX-I has produced have prompted Heysham 2 to specify the high-performance oil for all future tap changer maintenance and in transformers above 23 kV."

— Douglas Barker, Electrical Engineer, Heysham 2

"Shell Diala S4 ZX-I being based on GTL technology, typically has a higher specific heat capacity and thermal conductivity, supporting good to improved cooling performance, when compared with conventional hydrocarbon transformer oils. Transformer performance, reliability and lifetime is proportional to various factors including design and operational parameters, as well as transformer oil performance properties and their resistance to degradation and thermal properties."

— Dr Peter Smith, Global Technology Manager, Shell

SHELL HAS DESIGNED A PORTFOLIO OF FLUIDS THAT ENABLES YOU TO CHOOSE A PRODUCT TO MATCH YOUR TECHNICAL AND OPERATIONAL NEEDS.

Heysham 2 has recently installed a state-of-the-art 3 – single phase 400 kV (800-MVA) Alstom generator transformer. It forms a critical link, a single-point of vulnerability, in the distribution of electricity from the power station. Any unplanned downtime for this transformer could trigger high penalty costs: typical industry standard charges can be more than $800,000 per day. Consequently, it has fully instrumented monitoring, including online partial-discharge and bushing monitoring, online dissolved gas analysis in every compartment and fibre-optic temperature monitoring.

The customer observed an average operating temperature reduction of 65 to 45°C, up to 30% lower than identical transformers in the rest of its fleet that are using conventional oils. The degradation rate of the solid insulation slows as the operating temperature reduces, with a rule of thumb indicating that a 6°C reduction can double the paper life.

Following the success of Shell Diala S4 ZX-I in its 132 kV station transformer, EDF Energy chose to fill all transformers and tap changers on site ranging from 23KV to 400KV with Shell Diala S4 ZX-I.

The obvious improvements in reliability and performance Shell Diala S4 ZX-I has produced have prompted Heysham 2 Power Station to specify the high-performance oil for all future tap changer maintenance and in transformers above 23 kV with a view to optimising the performance of the transformers and extending the lifetime of the oil across its entire operation.

A reduction in operating temperature supports the following operator benefits

- Energy usage reduction through less forced cooling
- Transformer lifetime increase
- Extended oil lifetime – protecting the solid insulation and helping extend its lifetime and that of the transformer.

STATION TRANSFORMER				
Oil	**Oil surface tension:** decreasing values indicate oil degradation	**Total acid number (oil acidity):** increasing values indicate oil degradation	**Dielectric dissipation factor:** increasing values indicate oil degradation	**Dissolved gas analysis**
Original uninhibited transformer oil performance change	Halved	6 times higher	20 times higher	Normal (low)
Shell Diala S4 ZX-I performance change	No change	No change	No change	Normal (low)

Table 1: A comparison of properties following inspection of the original uninhibited transformer oil after being in service for two years and Shell Diala S4 ZX-I after being in service for three years.

GTL TECHNOLOGY

MANUFACTURING A DESIGNER HYDROCARBON TRANSFORMER OIL WITH ENHANCED PERFORMANCE CHARACTERISTICS

Shell GTL base oil is a manufactured hydrocarbon (primarily isoparaffinic in structure) derived from natural gas rather than from crude oil. Natural gas is purified and then converted into a range of liquid products using proprietary technology.

First, the methane is reacted with oxygen to create synthesis gas, a mixture of hydrogen and carbon monoxide. This synthesis gas is then catalytically converted into liquid waxy hydrocarbons via a Fischer–Tropsch process.

$$(2n + 1)\ H_2 + nCO \longrightarrow C_nH(2n+2) + nH_2O$$

Finally, the liquid waxy hydrocarbons are upgraded (hydrocracked) using specially developed technology involving novel catalysts and then distilled into a wide range of products, including transport fuels, base oils and feedstocks for the chemical industry. Crucially, these products are essentially free from impurities and inorganic substances such as sulphur.

Because its starting materials are mostly carbon and hydrogen, the resultant fluid is almost entirely pure hydrocarbons. The GTL process ensures that those hydrocarbons are overwhelmingly saturated paraffins. The absence of sulphur[3] and very low levels of aromatic and unsaturated hydrocarbons, which can be present at significant levels in conventional crude-oil-derived mineral oil, give GTL products superior properties compared with conventional mineral oils that are particularly relevant to their application as base fluids for transformer oils.

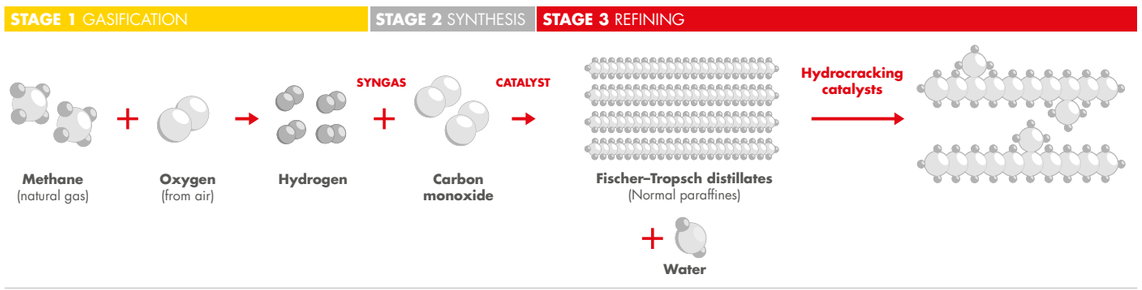
"Shell's GTL-based transformer oil is such an interesting proposition because it has essentially zero sulphur and very low aromatic and unsaturates contents. Consequently, it offers superior additive response, exceptional resistance to degradation and outstanding thermal properties, which can translate into increased transformer reliability and efficiency."

— Dr Peter Smith, Technology Manager, Shell

REDUCING THE RISK OF COPPER CORROSION

Corrosive sulphur species in conventional transformer oils have caused transformer failures, but Shell Diala GTL transformer oils are manufactured from pure GTL base oil, which is essentially sulphur free. Consequently, the risk of oil-related-sulphur copper corrosion in the transformer is removed and, thus, higher reliability is possible.

Shell's GTL base fluids are made from synthesis gas, a mixture of hydrogen and carbon monoxide, rather than from crude oil. **[Shell Lubricants "The Perfect Partner" GTL Technical Paper, May 2014 P6]**



3 Below detection limits, according to ISO 14596/ASTM D2622

BECAUSE SHELL DIALA S4 ZX-I IS ESSENTIALLY FREE FROM SULPHUR, THE RISK OF OIL-RELATED CORROSIVE SULPHUR DEVELOPING AND CAUSING COPPER CORROSION IS MINIMISED.

RESISTANCE TO DEGRADATION

With modern transformers getting smaller and operating at higher voltages, the stresses placed on the oil are higher than ever before. Shell Diala GTL oils have an excellent response to antioxidant additives, which means that they have outstanding resistance to degradation in even the most demanding applications.

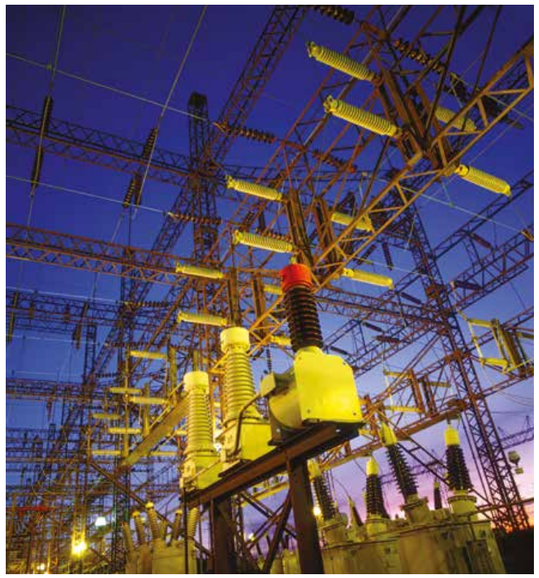
In addition, they show lower acidity and sludge formation on ageing, and have an oxidative stability performance level more than five times better than the highest standard requirements[4]. Consequently, they can help to enhance the lifespan of the paper insulation.

MODELLING PREDICTS GOOD-TO-SUPERIOR COOLING IN SERVICE

Effective cooling in a transformer is determined chiefly by two oil parameters: its thermal properties (specific heat capacity and thermal conductivity) and its fluidity or viscosity. An oil's thermal properties are proportional to its density. Calculations and measurements show that specific heat capacity and thermal capacity values are typically higher for Shell Diala S4 ZX-I than for conventional transformer oils, which indicates better thermal properties. This may provide cooling benefits for transformers in operation, and enable either higher loading or a reduced requirement for forced cooling, or some other design optimisation such as a reduction in transformer size.

Another important parameter that influences the ability of an oil to provide cooling in a transformer is its fluidity or viscosity across the usual transformer operating temperature range. The usual temperature ranges are defined in various specifications; see, for example IEC 60076 Part 1, which defines the normal ambient lower temperature limit for power transformers as –25°C.

At higher temperatures, most of the oils have a good low and comparable viscosity, which facilitates good cooling. At lower temperatures, most oils will thicken significantly, which reduces their flow rate and cooling ability. The inhibited GTL oil thickens significantly less at lower temperatures than the conventional oils tested. This means it will maintain its good fluidity and flow properties better, even under extreme conditions.



4 IEC 60296:Ed 4 2012 (Chapter 7.1)

ALLEVIATING COMPATIBILITY AND MISCIBILITY CONCERNS

Compatibility and miscibility are not the same. Two fluids are miscible if they form a clear fluid when they are mixed. Compatibility goes much further than this. Obviously, compatible fluids have to be miscible, but to be compatible they must have no negative effects on each other. One fluid's performance must not be diminished by the other's.

When testing for compatibility, pairs of fluids are mixed and observed under different conditions to see if they are miscible. Then, using performance tests, they are assessed to see whether any pair behaves differently. Incompatibility can show itself through the formation of deposits, the worsening of oxidation stability or differences in any of the electrical properties of the fluid pairs.

Shell has commissioned a series of tests on miscibility, compatibility and solvency issues, and has concluded that GTL-based transformer oils can be used alongside traditional hydrocarbon oils.

Moreover, it is also possible to see positive effects, as appears to be the case when GTL-based fluids are added to aged oils. Some improvement is expected when adding a fresh fluid to an aged one. However, with the GTL-based fluids a bigger improvement is realised than would seem likely from the proportion of fluid added.

For a copy of the complete paper on this issue, please contact Shell.

"Laborelec has tested and evaluated Shell Diala S4 ZX-I and can confirm that it meets and exceeds the inhibited transformer oil specification IEC 60296:2012 Edition 4, including the requirements for Section 7.1 in terms of highest oxidative stability and low sulphur. These characteristics can have a positive effect on the lifespan and reliability of the transformer."

— Steve Eeckhoudt, Senior Expert LABORELEC ENGIE lab & Key Expert ENGIE

GTL FLUIDS: ENHANCED MISCIBILITY AND COMPATIBILITY CHARACTERISTICS

To evaluate the effect of mixing transformer oil types in service, the properties of several mixed inhibition and unmixed inhibition test oils, both aged and unaged, and in different ratios and combinations, were tested. Table 2 shows the results for 15% aged uninhibited naphthenic oil mixed with 85% GTL inhibited oil. The mixture of 85% GTL fluid with 15% aged naphthenic oil still shows the highest oxidation stability. The GTL-based product compensates for the decreased performance of the aged oil: more than if the test had been conducted using a conventional inhibited oil.

			100% aged naphthenic oil	15% naphthenic; 85% GTL	100% GTL
Oxidation stability	IEC 62535	164-hour test			
Total acidity	mg KOH/g		0.81	<0.01	
Sludge	% mass		0.27	0.01	
Dielectric dissipation factor		90°C	0.070	0.002	
Oxidation stability	IEC 62535	500-hour test			
Total acidity	mg KOH/g			0.02	0.02
Sludge	% mass			<0.01	<0.01
Dielectric dissipation factor		90°C		0.013	0.001

Table 2: Adding Shell Diala S4 ZX-I oil can boost other conventional mineral transformer oils' performance.

SHELL DIALA S4 ZX-I CAN BE ADOPTED EASILY BECAUSE IT IS MISCIBLE AND COMPATIBLE WITH TRADITIONAL HYDROCARBON OILS. ADDING IT TO SOME MINERAL OIL GRADES CAN EVEN HELP TO IMPROVE THEIR PERFORMANCE.

INHIBITED VERSUS UNINHIBITED

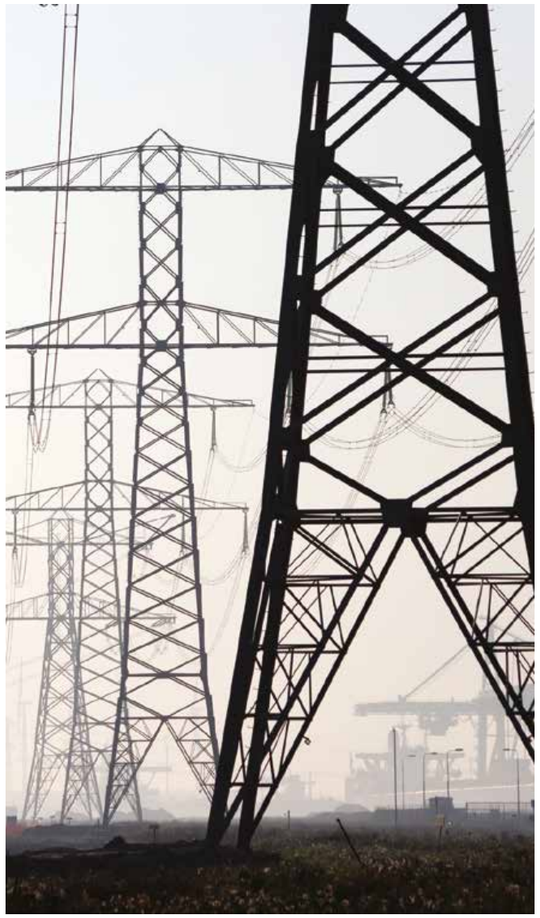
In chemical terms, an inhibitor is a synthetic antioxidant added to a transformer oil to slow down the process of oxidative degradation. If allowed to proceed unchecked, this process would shorten the fluid's life and decrease its performance.

Depending on the level of refining, the mineral oils produced from crude oils contain sulphur-based chemical species that can act as mild inhibitors for oxidation. These are exploited in so-called "uninhibited" oils. Strictly speaking, they are not uninhibited oils but they do not have any added synthetic inhibitor.

Very highly refined mineral oils and synthetic oils contain no natural inhibitor, so are prone to oxidation if chemical inhibitor is not added. This may appear to be a disadvantage but it is actually a benefit: the complete system is more consistent and behaves in a more predictable and measurable way when ageing occurs than do uninhibited (naturally inhibited) mineral oils. Furthermore, inhibited transformer oils, with their greater purity and predictability, are made to be far more oxidation resistant than uninhibited oils. This is becoming essential, as the combination of longer oil life expectancy and transformer design and operation (for example, smaller transformers and higher voltages and loads) dramatically increases the stress on the fluid.

"Our laboratory and field testing of transformer oils show that inhibited oils offer enhanced performance compared with uninhibited oils."

— Ivanka Hoehlein, Manager, Material Testing Laboratory, Siemens



PERFORMANCE ADVANTAGES OF SHELL GTL-BASED TRANSFORMER OILS CHARACTERISTICS

TRANSFORMER OILS BASED ON GTL TECHNOLOGY OFFER SOME CLEAR IMPROVEMENTS OVER TRADITIONAL MINERAL-BASED PRODUCTS.

These include:

- **Increased reliability.** Because GTL-based transformer oils are free from sulphur, the risk of oil-related corrosive sulphur causing copper corrosion is minimised. In addition, modelling predicts good to superior cooling in service.
- **Longer life.** They have exceptional resistance to ageing and degradation and perform more than five times better than the highest industry standard oxidation test requirements. They have an excellent ability to withstand severe voltage transients.
- **Simple implementation.** They are miscible and compatible with traditional hydrocarbon transformer oils. In fact, adding them to some mineral oil grades can help to improve their performance.
- **Consistency.** They have a consistent, narrow molecular structure range that provides predictable performance, and they are globally available. They contain only GTL base oil and antioxidant. They do not require and so are free from other additives such as copper passivators and dibenzyl disulphide.

Nowadays, inhibited oils typically have greater purity and predictability than uninhibited oils. This is becoming essential, as the combination of longer oil life expectancy and transformer design and operation (for example, smaller transformers and higher voltages and loads) dramatically increases the stress on the fluid.

Consequently, Shell's GTL-based transformer oil, Shell Diala S4 ZX-I, is gaining traction worldwide. The number of original equipment manufacturer approvals is growing and utilities around the world are selecting the oil for their transformers.

SHELL DIALA S4 ZX-I IS GAINING TRACTION WORLDWIDE. THE NUMBER OF ORIGINAL EQUIPMENT MANUFACTURER APPROVALS IS GROWING, AND UTILITIES AROUND THE WORLD ARE SELECTING THE OIL FOR THEIR TRANSFORMERS

"During the design and implementation of our transformer change strategy we have been extremely pleased with Shell, their approach and the technical support received"

— Douglas Barker, Electrical Engineer, Heysham 2 Power Station

"GTL technology is the product of some 40 years of research and technology driven by Shell. The company holds more than 3,500 patents for it. In 2013, Shell introduced the first transformer oil to be based on Shell GTL technology – Shell Diala S4 ZX-I. It is extremely exciting because this technology offers so much value for our customers and the new oil is gaining traction worldwide. It continues to gain equipment manufacturers' approvals and reference projects. Numerous tests are demonstrating that it offers major advantages compared with conventional oils."

— Andrew Hepher, Shell Vice President for Lubricant Technology

APPROVALS

Shell Diala S4 ZX-I meets the requirements of most major European original equipment manufacturers and utility companies. It has been validated and approved by, among others:

- Siemens n ABB
- Alstom
- CG Power Systems
- Hyundai Heavy Industries (Bulgaria)
- Maschinenfabrik Reinhausen (MR)
- Starkstrom-Gerätebau (SGB).

Find out more by visiting

www.shell.com/diala

or by contacting your local representative