Understanding Oil Specifications

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Mineral oil plays a crucial role in the insulation system of vital transformers on the electric grid. Transformers facilitate energy transfer between electrical circuits without any moving parts, through inductively coupled conductors. The insulation, primarily composed of cellulose, is enhanced by a liquid dielectric. The chosen fluid must serve multiple functions, including preventing flashover, acting as a heat transfer medium, preserving the core and coil assembly, and reducing aging of the insulation by restricting oxygen and moisture ingress. Achieving the right mix of properties involves balancing considerations such as dielectric strength, viscosity, density, volatility, flash point, and chemical stability—all at a reasonable cost and without compromising environmental or safety concerns.

Specifications

There are several specifications available today that can be used to assure quality of mineral insulating transformer oils. Doble Transformer Purchase Specifications (TOPS) was one of the first specifications in North America, having been first published in 1961 and updated over the years to reflect the changing needs of the industry. Organizations such as IEC, IEEE, and ASTM have similar specifications.

Oxidation inhibitors, such as synthetic additives like DBPC/BHT and DBP, slow down this process by competing for available oxygen. Specifications typically separate oils into classification based on the amount of added antioxidant.

All of these specification standards essentially evaluate the same properties of the oils, differing somewhat in the particular tests included or the methods required; physical, electrical and chemical properties that relate to the functioning of the oil, its composition, purity, and stability. Additional properties, additives and behavior may also be included in these specification documents, for example stray gassing is a mandatory test in TOPS while it is not part of some other specifications. Figure 1 lists some of the properties typically included in oil specifications and the significance in practice of those characteristics.

Mineral oils are oxidatively unstable, which can lead to the formation of acidic by-products and eventually sludge deposition in transformer cooler areas. Oxidation inhibitors, such as synthetic additives like DBPC/BHT and DBP, slow down this process by competing for available oxygen. Specifications typically separate oils into classification based on the amount of added antioxidant, as shown in Table 1. In TOPS, oil with passivators which act as metal deactivators is evaluated as inhibited Type II.

Many commercially available oils have been evaluated against TOPS by Doble Engineering laboratories since the first such report was published in 1953. Reviewing the historical data shows the move away from uninhibited to inhibited oils, shown in Table 2, as refining processes developed and demand for the fully uninhibited oils receded. The oils tested as part of the survey are from refiners globally and include oils from the Americas, Europe and Asia.

Table 1:
Inhibitor Classifications

TOPS 3 Classes by Inhibitor Content	ASTM 2 Classes by Inhibitor Content	CAN/CSA C50 3 Classes by Application 4 Classes by Inhibitor Content			IEC 60296 2 Classes by Application	
		A(<25°C)	B(>25°C)	S(OCB)	Xfrms	Low T Switchgear
Uninhibited					Type U	Type U
Inhibited Type I **0.08% max**	Inhibited Type I **0.08% max**	Type I **0.08% max**	Type I **0.08% max**	Type I **0.08% max**	Type I **0.08% max**	Type I **0.08% max**
Inhibited Type II **0.3% max**	Inhibited Type II **0.3% max**	Type II **0.4% max**	Type II **0.4% max**			
		Type III **0.4% max** Extended performance	Type III **0.4% max** Extended performance			
		Type IV **0.4% max** Extended performance	Type IV **0.4% max** Extended performance			

Table 2:
Inhibited Oils Over the Years

Survey No	Year	Total Number of Oils Tested	Number of Uninhibited Oils	Uninhibited Oils, % of Survey Oils Tested
32	1969	13	13	100
41	1973	10	10	100
61	1983	18	7	38.9
100	2007	41	6	14.6
108	2015	37	1	2.7
110	2017	46	5	11
113	2020	43	3	7
115	2022	64	8	13

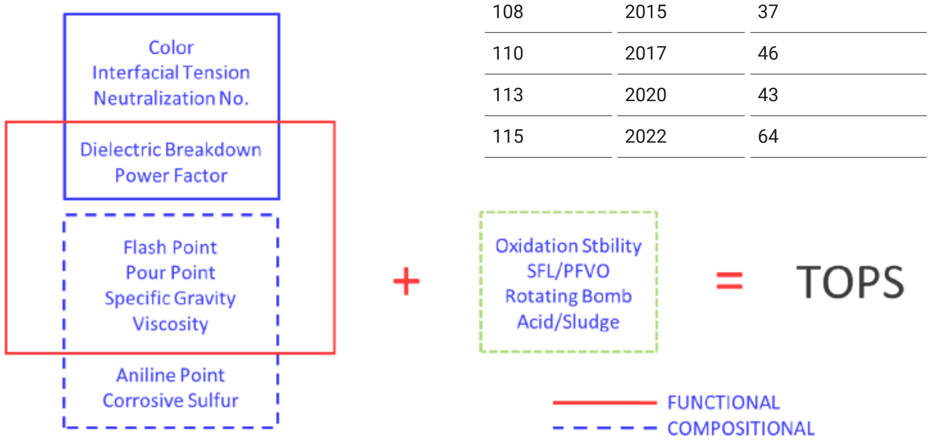

Figure 1:
Relevance of Common Specification Tests

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Mineral insulating oils are thermally stable and can withstand temperatures as high as 700°C in low oxygen environments. They are, however, oxidatively unstable, especially at high temperatures. All oxidation stability testing is essentially the same – the oil is aged in an accelerated manner using heat, oxygen, and a copper catalyst. Natural and added inhibitors will slow the aging process and therefore less stringent limits are allowed for uninhibited and less inhibited oils. Maximum concentrations of inhibitors are specified to avoid poor performance of the base oil being masked by the presence of excessive retardants. A typical aging test, ASTM D2440, calls for the heating of the oil at 110°C in the presence of sanded copper wire, which acts as a catalyst, while oxygen is fed to the oil through a thin tube throughout the 64 and 120hour aging periods. At the end of each period, the acidic byproducts and any sludge formed are quantified,

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Figure 2:
Accelerated Aging Testing ASTM D2440

Electrical Properties

To ensure the oil can satisfy the demands of an effective dielectric, several electrical tests are included in TOPS. The dielectric breakdown volage, measured using ASTM D1816, involves a voltage being applied across spherically shaped electrodes with a defined gap of 1mm or 2mm, until a flashover between the electrodes occurs (Figure 3). The limits given in TOPS apply to a fluid that has been filtered and dried, which is generally done with new oil prior to filling in an electrical asset. Typical data for new oil is shown in Table 3.

Power factor, also referred to as dissipation factor, is a test used to measure the dielectric losses of the fluid at room temperature and at 100°C. Testing at both temperatures helps qualify the type of material causing the losses. A high reading at room temperature not reflected in the higher temperature measurement is an indication of moisture or conducting particles that are driven off in the heating process. A high reading at 100°C suggests the cause is contamination of the new fluid with polar compounds.

The impulse breakdown test is carried out using the cell shown in Figure 4, which is a negative needle to sphere configuration. It is an indicator of the oil's ability to resist lightning voltage stresses and is influenced by the concentration of polycyclic aromatics. The TOPS limit for this test is 145kV minimum.

Table 3:
ASTM D1816

Product From Refiner	Dielectric Breakdown Voltage D1816 1mm Electrode Gap kV	Dielectric Breakdown Voltage D1816 2mm electrode gap kV
Oil 1-As received	12	18
Oil 1-After Filtering and Drying	39	73
Oil 2-As received	41	70
Oil 3-As received	23	48
Oil 4-As received	17	30
Oil 4-After Filtering and Drying	35	64

Figure 3:
Dielectric Breakdown ASTM D1816

The gassing tendency (ASTM D2300) is a measure of the ability of an oil to absorb or evolve gas over a set period after the oil has been saturated with hydrogen and has had voltage applied to the oil/gas interface. The resultant ionic bombardment of the oil molecules results in some hydrogen gas being released from saturated hydrocarbon molecules in the oil and some gas absorbed by unsaturated aromatics. The resultant net absorption or evolution under these conditions will determine whether the oil is deemed positive or negative, and the latter can be important under certain high-stress applications.

Physical Properties

Properties such as color and interfacial tension are an indicator of oil purity, with new oils typically having a clear appearance with little color noticeable. Exposure to light can cause darkening due to photodegradation reactions, and contamination or contact with incompatible materials will similarly cause new oils to exceed the 0.5 maximum color allowed.

Figure 4:
Impulse Breakdown Voltage

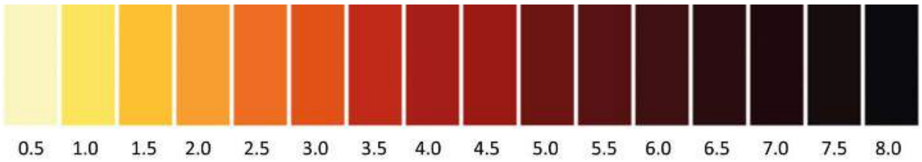

Figure 5:
Color

The number refers to a standard color scale that increases in increments of 0.5 as shown in Figure 5.

The interfacial tension (IFT) of an oil is the amount of force needed to break the oil water interface with a fine platinum ring (Figure 6) and is a measure of the polar compounds left in an oil. Clean new oil should easily meet the minimum of 40 mN/m specified by TOPS. Figure 7 plots the data from 2019 survey report and all easily satisfy the requirements. Given the consistently high recent values in IFT which are likely a reflection of more modern refining, an increase in the IFT minimum is under consideration for the next revision of TOPS.

Pour point, relative density and viscosity are indicators of flow characteristics and the oil's suitability as a heat dissipation medium.

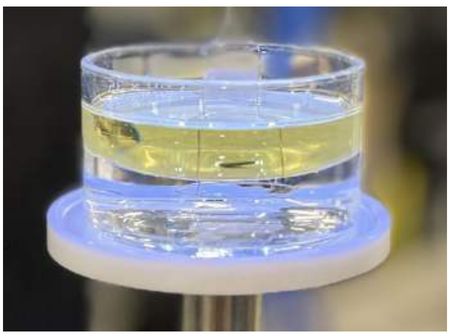

Figure 6:
Interfacial tension

Viscosity is measured at 0°C, 40°C and 100°C to ensure it can perform adequately over the range of temperatures likely to be encountered in service. The pour point is a measure of the oil's ability to flow at very low temperatures and can be of importance for cold start up conditions. These properties should not change over the service life of the oil and any significant change would indicate contamination or very advanced aging where sludge has precipitated from the oil.

Corrosive Sulfur and Additives

Corrosive sulfur compounds, if present in an oil, will attack copper and silver leaving deposits of metal sulfides on the metal and paper surfaces inside a transformer in service, and can contribute to failure. This has been an ongoing issue in service since the early 2000s and in response, oil specifications, including TOPS, updated the requirements to include more rigorous testing to aid in detecting problematic oils. Corrosive sulfur testing by ASTM D1275 and Doble Covered Copper Deposition (CCD) must both be passed for an oil to be deemed non-corrosive by TOPS. Testing for dibenzyl disulfide and elemental or free sulfur were added as mandatory tests to help reduce the incidence of corrosive sulfur in service. Figure 8 shows copper sulfide deposits on conductor paper insulation from a transformer winding and on the conductor in an in-service bushing.

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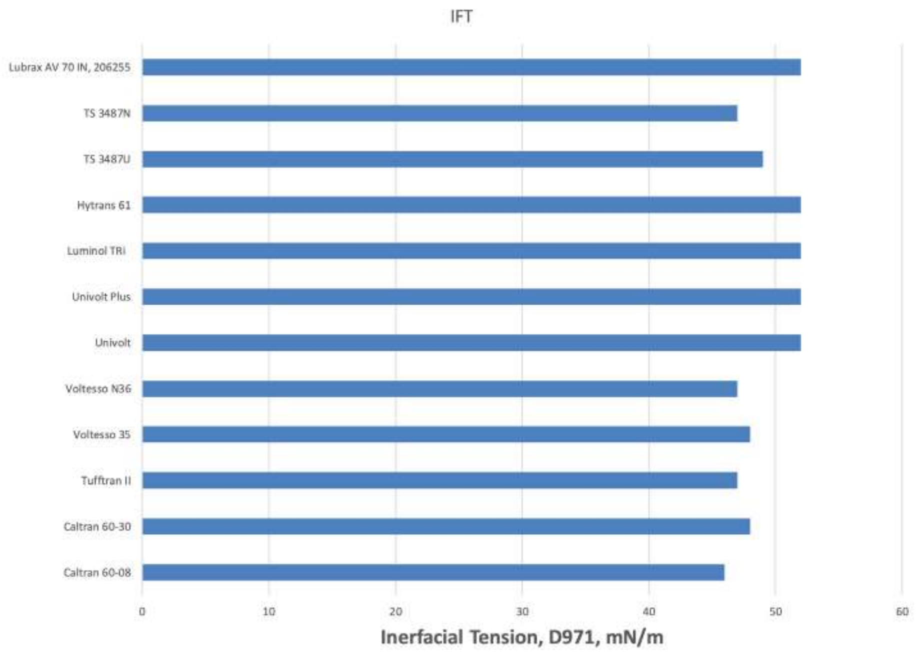

Figure 7:
IFT of North American Oils from Survey Report 2019

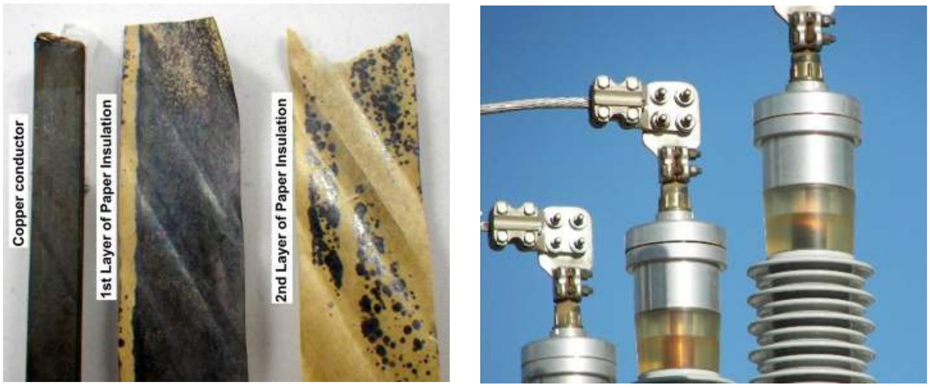

Figure 8:
Copper Sulfide Deposits In Service

Testing by ASTM D1275 involves heating the oil with a small copper strip for 48hours at 150°C and comparing the tarnish level to a standard corrosion chart, as shown in Figure 9. The oil is considered to have failed if the tarnish level is 4a or darker.

The Doble CCD evaluates both the copper strip and a layer of paper aged with it, in both a low and high oxygen environment, to mimic both sealed and free-breathing conservator conditions in the field. Again, the copper is compared to the corrosion chart, and the paper is examined for deposition of copper sulfide, a characteristically shiny deposit on the copper-facing side of the paper wrap (Figure 10). If any one of the paper or metal strips fails, the oil is deemed corrosive.

Passivators

Passivators, also known as metal deactivators, are sometimes added to an oil to improve oxidation stability and can also mitigate corrosive sulfur by reducing the rate of metal sulfide reactions. These passivators attach to the metal surfaces thereby reducing the number of reaction sites available for the corrosive sulfur compounds from the oil, as depicted in Figure 11. TOPS specifies there should be no detectable passivator unless agreed otherwise by the buyer.

Figure 9:
ASTM D1275 Corrosive Sulfur Testing

Figure 10:
Covered Copper Deposition Testing

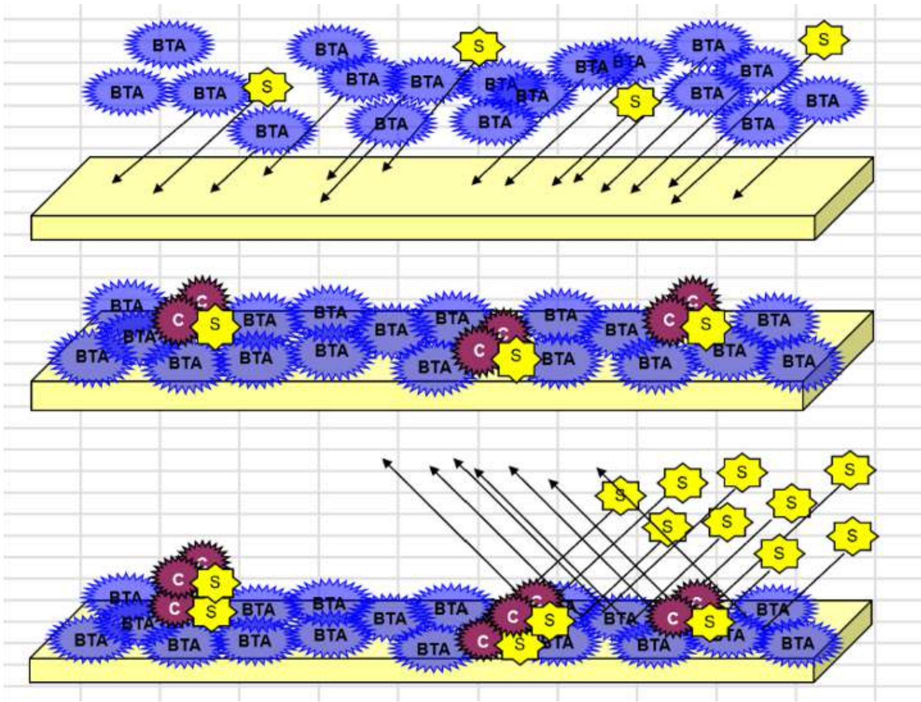

Figure 11:
Passivator Action

Stray Gassing

Dissolved Gas Analysis (DGA) is a crucial test for monitoring electrical asset performance during service. Gases generated from oil and insulation breakdown offer insights into asset management and grid reliability. Stray gassing, caused by the fluid or additives like passivators, should be considered to avoid misinterpreting in-service data. Table 4 presents norms based on survey data, helping identify oils prone to stray gassing through tests in high oxygen and high nitrogen environments simulating different service conditions.

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Oils with passivator added can show a greater tendency to produce higher than normal concentrations of some gases, typically hydrogen and carbon monoxide, which are formed at lower temperatures. Concentrations of Hydrogen from survey oils tested is shown in Figures 12, with the concentration of passivator shown for any oil that had detectable concentrations of BTA or Irgamet 39.

Table 4:
Stray Gassing Norms TOPS

Typical Stray Gassing Values 95% Norms Determined by Doble over 3 years (with outliers removed)		
	Concentration, ppm (ul/l)	
GAS	**Air Sparged**	**Nitrogen Sparged**
Hydrogen	590	250
Methane	120	80
Carbon Monoxide	450	115
Ethane	120	36
Carbon Dioxide	1580	385
Ethylene	8	6
Acetylene	0	0

Note:
Analysis performed by ASTM D3612C after aging

Composition

Mineral transformer oils can be sourced from naphthenic, paraffinic, or natural gas, each with distinct properties due to the hydrocarbon composition. Naphthenic oils have fewer waxy compounds and are refined using solvent extraction and hydrotreating, which produces a base oil that is receptive to oxidation inhibitor additives. The refining process needs to allow some aromatics,

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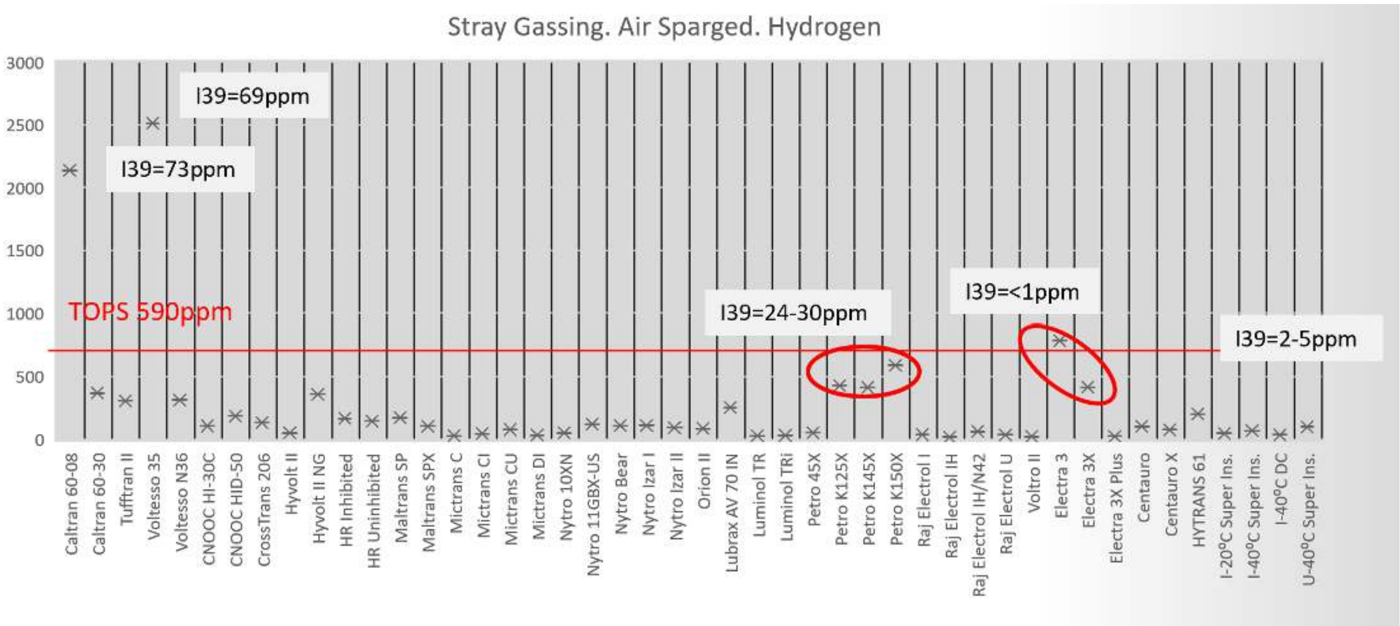

Figure 12:
Stray Gassing Hydrogen Air Sparged

which are natural inhibitors, to be retained in those oils that will not have synthetic inhibitors added (Uninhibited products). Highly refined paraffinic oils produced using hydroprocessing, which removes waxy components and undesirable compounds such as sulfur and nitrogen, have very low aromatic contents and typically have lower specific gravity and viscosity than naphthenic oil. This lower viscosity can be most evident at lower temperatures.

Gas-to-liquid (GTL) oils, derived from methane, are almost entirely isoparaffinic and without added aromatics have very high gassing tendency values. Flash point is influenced by the volatile compounds in an oil and iso-paraffins tend to be well in excess of the 145°C minimum specified by TOPS. This limit may be reviewed in the next revision of TOPS. Extended rotating pressure vessel times are also a typical feature of iso-paraffin oils.

Properties of oils from various sources are detailed in Table 5.

Summary

In summary, there are many oils in the market from different crude sources and specifications should be employed to help you evaluate them. Advances in refining processes result in changes over time and specifications need to keep up with these changes so that they remain relevant. Oils from these various sources are generally fully miscible and compatible with one another, with the caveat that when replacing an oil in service with one that has a significantly different aromatic content, may lead to gasket issues, impacting seal effectiveness.

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Table 5:
Properties of oils from different sources

Doble 2022 Survey Report No. 115	Aniline Point	Flash Point	Interfacial Tension	Neutralization Number	Pour Point	Power Factor at 100°C	Power Factor at 25oC	Relative Density 60/60	Viscosity at 0C	Viscosity at 100C	Viscosity at 40°C	Viscosity at 40°C	Oxidation Inhibitor Content	Sludge-Free Life	Oxidation Stability D2440 72		Oxidation Stability D2440 164		Rotary Bomb	Gassing Tendency at 80°C	Impulse Breakdown Voltage	Carbon Type Composition, C_A	Carbon Type Composition, C_N	Carbon Type Composition, C_P
Units	°C	°C	mN/m	mg KOH/g	°C	%	%		KIN cSt	KIN cSt	KIN cSt	SUS	% wt.	Hrs	% wt.	mg KOH/g	% wt.	mg KOH/g	Min.	microL/min	kV	%	%	%
Product	D611	D92	D971	D974	D97	D924	D924	D4052	D445	D445	D445	D2161	D2668	Doble (b)	None	D974	None	D974	D2112	D2300	D3300	D2140	D2140	D2140
Naphthenic NA	80.7	154	51	<0.01	-66	0.057	0.002	0.879	62.77	2.44	9.71	57.8	0.27	>88	<0.01	<0.01	<0.01	<0.01	315	32.8	>300	4.0	47.0	49.0
Isoparaffin-NA	103.3	181	49	<0.01	-57	0.070	0.005	0.824	50.14	2.55	9.20	56.1	0.23	>88	<0.01	<0.01	<0.01	<0.01	604	19.8	>300	1.1	26.6	72.3
Isoparaffin-Asia	105.1	188	51	<0.01	-51	0.016	0.002	0.835	59.34	2.89	11.41	63.8	0.35	>88	<0.01	<0.01	<0.01	<0.01	640	35.7	>300	0.0	27.5	72.5
GTL	112.1	194	55	<0.01	-48	0.010	0.001	0.808	54.80	2.70	9.29	58.40	0.26	>88	<0.01	<0.01	<0.01	<0.01	678	52.6	>300	No value registered		