IMPROVED HEAT TRANSFER CAPABILITY USING ISO-PARAFFINS VERSUS NAPHTHENICS IN TRANSFORMERS

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ABSTRACT:

This paper will describe the results obtained from three separate tests run on transformers using both iso-paraffin fluid and naphthenic oil, focusing on the heat transfer capabilities of each.

INTRODUCTION

Why is heat transfer in a transformer important? As transformers operate, heat is generated in both the core and windings. This heat represents the "losses" of a transformer and these losses increase exponentially as the load through the transformer increases. Therefore it is critical that this heat is removed especially at higher load conditions. If this is not accomplished it will result in premature ageing of the transformer, specifically degradation of the paper insulation inside the transformer and ultimately the failure of the transformer itself. In today's electric energy industry, power transmission and distribution transformers represent a substantial and ever increasing investment for a utility. Furthermore, there is consistently less system reserve available in today's marketplace and transformers are routinely loaded to higher levels than what may have been practiced 10 years ago. For these reasons, performance of the transformer cooling system including the fluid is very important. Whatever fluid a transformer manufacturer or owner decides to use for heat transfer, there are some basic properties that need to be considered.

The physical properties of the fluid are determined by its composition. Such key properties include the viscosity profile, specific heat or heat capacity, relative density, and thermal conductivity. These properties determine how well the fluid will move to a point where heat can be "picked up" from the core and coils, absorb the excess heat, transport the excess heat from where it is not wanted to the shell of the transformer, and finally dissipate the excess heat to the atmosphere [1].

Naphthenic oils and iso-paraffin fluids are manufactured using distinctly different processes. Naphthenic oils are typically manufactured using solvent refining processes coupled with mild hydrotreating / hydrofinishing or hydrotreating alone. This leaves residual compounds in the oil, such as sulphur, nitrogen and aromatics [2].

Iso-paraffin fluids on the other hand, are highly refined using a newer technology, involving severe hydrocracking / hydroisomerization processes. This eliminates almost all of the contaminants from the fluid and leaves it virtually sulphur-free.

So, what benefit does this give an iso-paraffin fluid in terms of heat transfer? As stated above, heat transfer is dictated by the composition of the fluid and the physical properties that composition imparts. Two important heat transfer properties are: Heat Capacity and Thermal Conductivity.

Heat Capacity can be explained as "the smaller the temperature change in a body caused by the transfer of a given quantity of heat, the greater its capacity"[3]. Better heat capacity means that a transformer fluid can absorb more heat into itself without seeing a change in temperature.

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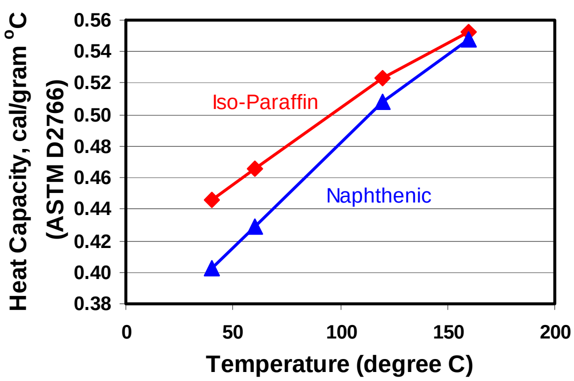
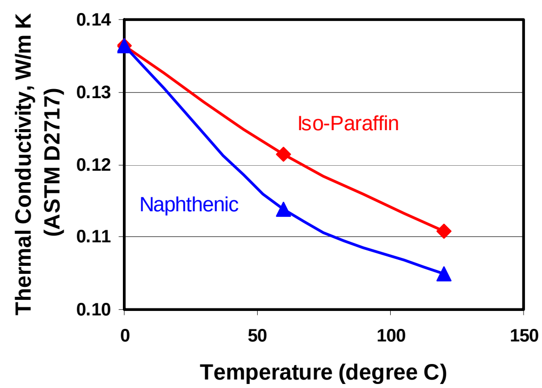
Thermal Conductivity is essentially "the measure of the ability of a material to conduct heat"[4] or to put it simply, it is the rate of heat transfer. The higher the thermal conductivity, the faster the transformer fluid will transfer the heat from the hot coils to the outside air.

Figures 1 and 2 show a comparison of iso-paraffin fluid versus naphthenic oil for these two key heat transfer properties:



Heat Capacity Comparison
FIGURE 1



Thermal Conductivity Comparison
FIGURE 2

In both the above Figures, the iso-paraffin fluid has better properties than the naphthenic oil. What this translates to in terms of heat transfer is that if each transformer fluid saw the same heat generated at the windings and coils, the iso-paraffin fluid would be noticeably cooler in temperature than the naphthenic oil. This information was presented to Cinergy Substation Services and accepted in theory. To validate the data presented, a test was commissioned by Cinergy on newly built transformers to determine the practical results of the heat transfer capability of iso-paraffin fluid.

TEST ONE: HEAT RUN TESTING AT MANUFACTURER'S SITE

In November 2003, "Heat Run" tests were performed on a matched pair of transformers. They were brand new, having been manufactured in 2003 by Ferranti-Packard. Each transformer had a high side winding voltage of 67 kV and a low side winding voltage of 13.09 kV. They were both rated for 10.5 MVA and had ONAF (Oil Natural Air Forced) cooling.

One transformer was filled with iso-paraffin transformer fluid and the other filled with conventional naphthenic transformer oil. The tests were performed at the manufacturer's site and the data collected was recorded by their personnel. A report internal to Petro-Canada and Cinergy Substation Services[5] was written and the results summarized below.

First, it is assumed the two transformers were designed and manufactured sufficiently similar so that, all other things being equal, they have the same electrical efficiency, and the "dry" transformers exhibit the same heat generating capabilities prior to being filled with oil.

Second, at a given power setting, P, in a transformer where no heat exchange occurs within the surroundings, the following equation can be used:

$E_{oil} = \int P\, dt$

where

E_{oil} is the amount of energy inputted to the oil during the heat run test.

If P is expressed in Watts (or Joules per second), then after one hour, E_{oil} = 3600s x P.

In a simplified model developed by Cinergy Substation Services, we define Heat Flow, Q, such that:

$Q = h \times A \times \Delta T$

Assuming that $Q = E_{oil}$, and that A (the area across the winding wire) is the same for both transformers, then A becomes irrelevant and the equation becomes:

$Q / \Delta T = h$

Where h, the Heat Transfer Coefficient, is defined as the Heat Flow from the windings to the air across a fixed area.

Using the above equations, Tables 1 and 2 were developed and show the variations in h for both the naphthenic oil and iso-paraffin fluid. The original test results were converted to SI units and unfortunately, some of these numbers are quite large.

TABLE 1: Oil Air (OA) Cooled – Heat RUN Comparison

	HV Winding			**LV Winding**		
	Naphthenic Oil	**Iso-Paraffin Fluid**		**Naphthenic Oil**	**Iso-Paraffin Fluid**	
Power (BTU/hr)	188733	190781		188733	190781	
Power (Watts)	55300	55900		55300	55900	
Heat Flow (J/hr)	199080000	201240000		199080000	201240000	
Ambient Temp (°C)	26.30	26.20		26.30	26.20	
Winding Temp Rise (°C)	57.60	54.71	**5.28%**	60.40	57.06	**5.85%**
Winding Temp Abs (°C)	83.90	80.91		86.70	83.26	
Heat Transfer Coeff (J/hr-°C)	3456250	3678304	**6.42%**	3296027	3526814	**7.00%**

TABLE 2: Forced Air (FA) Cooled – Heat Run Comparison

	HV Winding			**LV Winding**		
	Naphthenic Oil	**Iso-Paraffin Fluid**		**Naphthenic Oil**	**Iso-Paraffin Fluid**	
Power (BTU/hr)	276445	278834		276445	278834	
Power (Watts)	81000	81700		81000	81700	
Heat Flow (J/hr)	291600000	294120000		291600000	294120000	
Ambient Temp (°C)	24.90	27.50		24.90	27.50	
Winding Temp Rise (°C)	48.88	45.72	**6.91%**	53.42	49.63	**7.64%**
Winding Temp Abs (°C)	73.78	73.22		78.32	77.13	
Heat Transfer Coeff (J/hr-°C)	5965630	6433071	**7.84%**	5458630	5926254	**8.57%**

The shaded numbers for both Tables 1 and 2 reflect the percentage difference in the winding temperature rise and the calculated heat transfer coefficients for each run. In all cases, the iso-paraffin performed better than the naphthenic oil.

The winding temperature rise is the value most often used to determine how effective a fluid is at heat transfer during these tests. As shown above, the iso-paraffin temperature was noticeably lower than the naphthenic oil, however, note that the power imparted to the iso-paraffin was slightly higher in each case. This translates into the theory that if the power levels were the same, the iso-paraffin fluid would perform slightly better than shown.

To try and capture this thought, the calculation of the heat transfer coefficient, h, was performed. h is important in that it allows the comparison of the results without bias due to variation in power or ambient temperature. The numbers in Tables 1 and 2 show that, with all other things being equal, the iso-paraffin fluid has a 6.5 to 8.5 % advantage over the naphthenic oil based on the results of this heat run test.

How does this relate to the basics of heat transfer discussed earlier? Remember that it is the properties of a fluid that dictate the heat transfer capability of that fluid. The iso-paraffin was able to absorb the same amount of power as the naphthenic oil but had a lower winding temperature rise (better heat capacity and thermal conductivity). As well, the heat transfer co-efficient indicates that for the same area, the iso-paraffin can dissipate more heat than the naphthenic.

Cinergy Substation Services felt that these results were compelling enough to try a test run of their own.

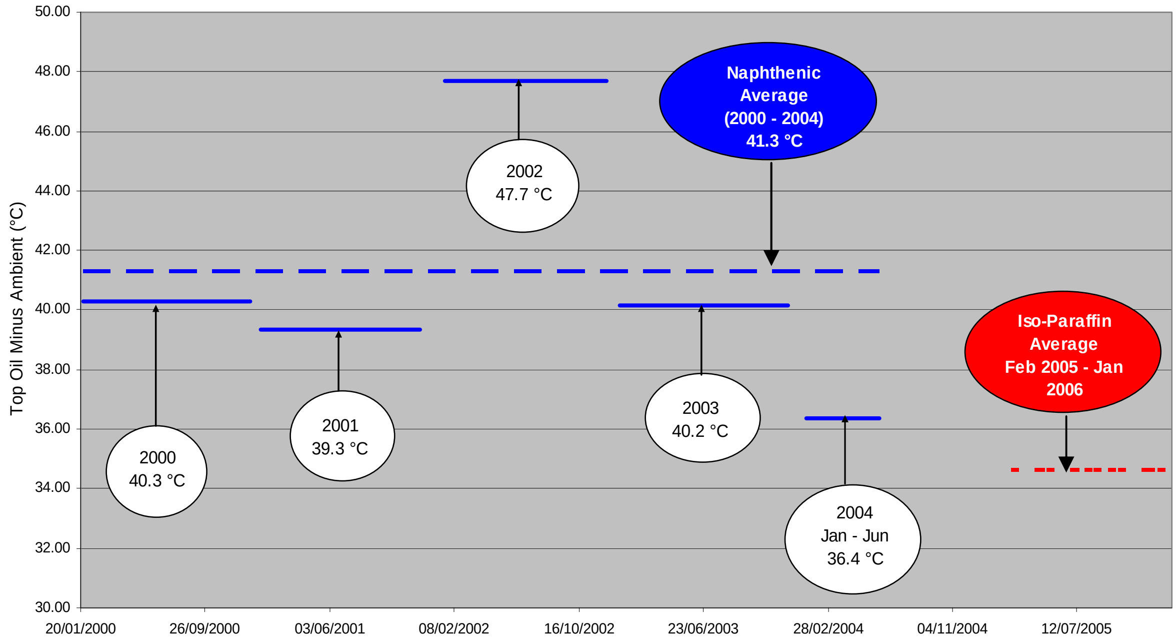
TEST TWO: IN-SERVICE COMPARISON

Based on the encouraging results of the Heat Run tests, Cinergy Substation Services decided to try a field test of their own at their New Palestine substation. A 1971 vintage General Electric transformer was selected that had five years of data using naphthenic oil. This transformer was drained and refilled with iso-paraffin fluid. The transformer is rated at 10.5 MVA and is Forced Air cooled with two fans, both of which are on constantly. It has a high side winding voltage of 70.60 kV and a low side winding voltage of 13.09 kV.

The data for the naphthenic oil had been collected once per month during substation inspections by operations personnel. The peak load for that month was recorded as well as the corresponding peak top oil temperature, ambient temperature and the date. The naphthenic oil was a blend taken from a main central storage tank used for all their transformers. Cinergy typically purchased from only one or two manufacturers.

For the iso-paraffin fluid, an electronic temperature monitor (ETM) was installed which provided temperature information to a data historian system for permanent archival. To try and determine an accurate comparison between the iso-paraffin and naphthenic oil, the peak load for the month was retrieved and the subsequent top oil and ambient temperatures were used.

Figure 3 shows the comparison of the difference between top oil temperature and ambient temperature for both the naphthenic oil and iso-paraffin fluid:



Comparison of Delta Temperatures (Top Oil – Ambient) For Iso-Paraffin Fluid and Naphthenic Oil
FIGURE 3

The solid blue lines are averages for each year using naphthenic oil. The dotted blue line is the overall average for the naphthenic oil from 2000 through 2004. The dotted right line to the far right is the data for the iso-paraffin fluid from Feb 2005 to Jan 2006 for comparison. Note that the data for the naphthenic oil from 2004 run is only for six months. It is expected that the average delta for 2004 would be higher with a full year's worth of data, as the summer months typically put more load on the transformer.

Comparing the data shown above and using the industry "Rule of Thumb" that a 12% increase in load will result in approximately a 10 °C rise in oil temperature, we generated Table 3:

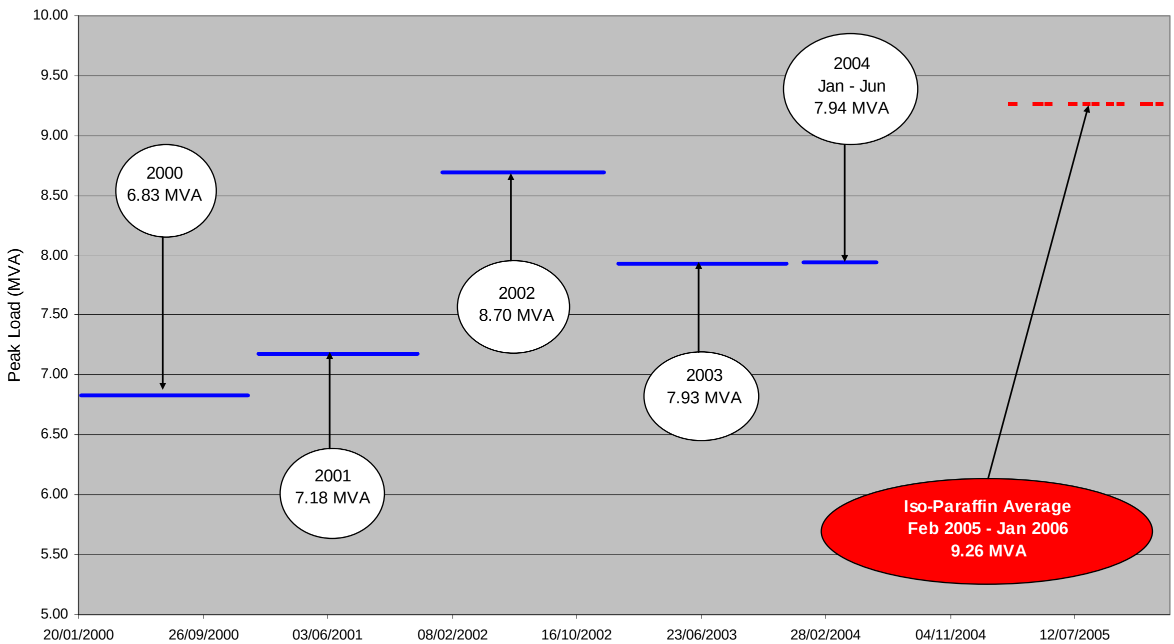
TABLE 3
Potential Load Increase Available by Using Iso-Paraffin Versus Naphthenic

Data Set	Oil Temp - Ambient (°C)	Temperature Delta (°C) (Naphthenic – Iso-Paraffin)	Potential Increase in Available Load (%)
Naphthenic (2000)	40.3	5.7	6.8
Naphthenic (2001)	39.3	4.7	5.7
Naphthenic (2002)	47.7	13.1	15.7
Naphthenic (2003)	40.2	5.6	6.7
Naphthenic (2004) (6 month data)	36.4	1.8	2.1
Naphthenic (2000-2004)	41.3	6.7	8.0
Syn. Iso-Paraffin (05-06)	34.6		

As we saw in Test One, there is a definite advantage in the top oil temperature of the iso-paraffin versus the naphthenic oil.

The potential increase in available load indicates that due to the cooler oil temperatures observed with iso-paraffin fluid, the transformer could be loaded that much more and still maintain required limits for top oil temperature (and presumably winding temperatures). To continue on this train of thought, one could also conclude that by using an iso-paraffin fluid, the maximum load of a transformer (based on our industry Rule of Thumb - a 10 °C temperature rise results in 12% more MVA load) could be greater than if a naphthenic oil was used.

Now, if iso-paraffin fluids do exhibit better heat transfer capability than naphthenic oils, is there any way we can see this from the results we have? The simple answer is yes. If we take our basic definition for Heat Capacity again (that better heat capacity means a lower oil temperature for the same amount of power or load), then we should see the loading on the transformer for iso-paraffin fluid be the same or higher than the naphthenic oil. Figure 4 shows the average loadings for each year:



Comparison of Peak Loads For Iso-Paraffin Fluid and Naphthenic Oil
FIGURE 4

Again, it is shown that the iso-paraffin fluid demonstrated better heat transfer than the naphthenic oil. Cinergy Substation Services felt that the results were very compelling and wanted to perform another test to try and show an "apples to apples" comparison.

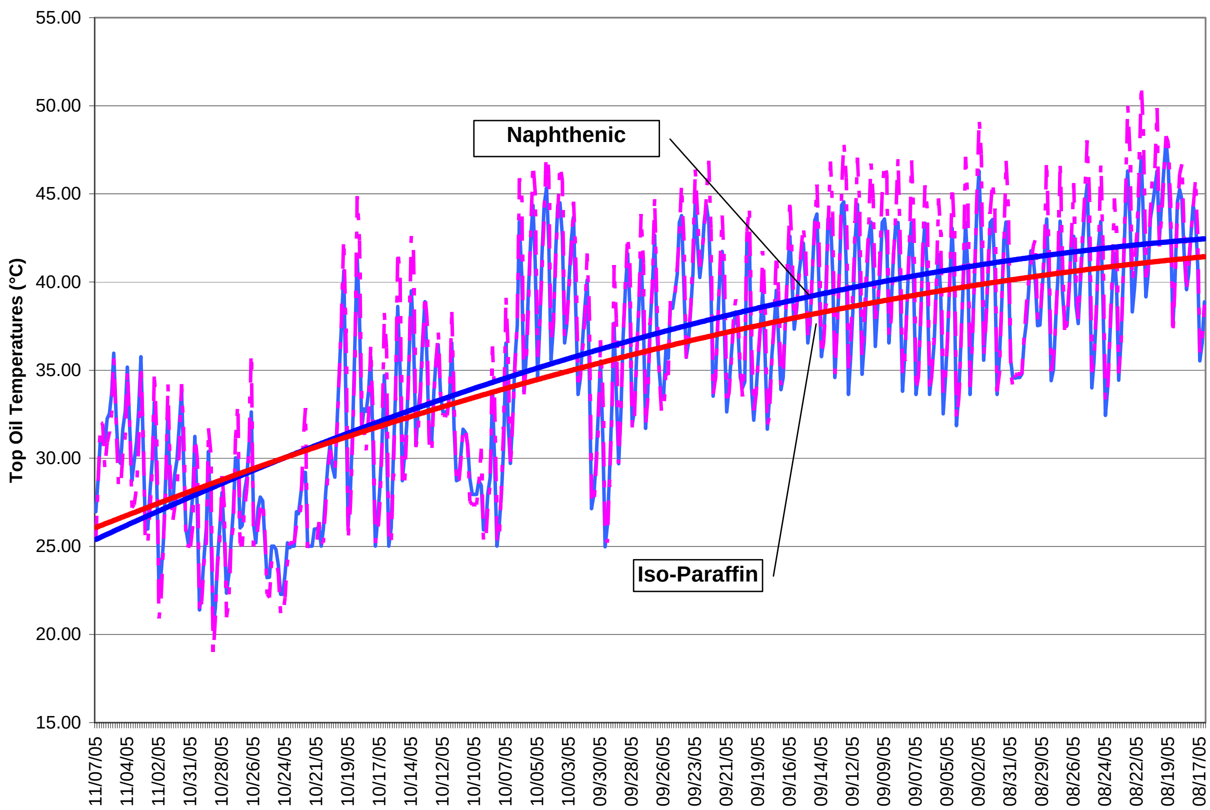
TEST THREE: SIDE-BY-SIDE IN-SERVICE COMPARISON

The final test by Cinergy Substation Services was to run a side-by-side in-service comparison of iso-paraffin fluid versus naphthenic oil in a matched pair of transformers at their Columbus substation. This would be the most poignant test so far, as the transformers would be run in parallel and have identical ambient conditions and loading.

Each unit was a 1953 vintage, Westinghouse 50 MVA transformer. They had high side winding voltage of 242.00 kV and each had secondary winding voltages of 114.90 kV and 72.50 kV. There were three identical units lined up north to south, with iso-paraffin fluid being used in unit #1 and naphthenic oil being used in units #2 and #3. The data for the naphthenic oil came from unit #3. As with test #2, the naphthenic oil would likely have been a blend of oil from two different refiners.

The prevailing wind direction was from the west and the distance between units was such that identical ambient conditions could be assumed. The cooling for these transformers was by Forced Oil and Forced Air (ie. pumps and fans). Cinergy's practice of cooling was to operate everything full out so all pumps and fans were on constantly. Every indication was that both transformers were being cooled the same.

Figures 5 through 8 show the results of the test. Figure 5 plots the top oil temperatures for each oil versus time. A second-order polynomial was used to fit the data to a curve. There is a distinct temperature advantage for the iso-paraffin fluid during the hotter months of the test, when more power would be demanded of the transformers.



Top Oil Temperatures versus Time
FIGURE 5

Figures 6 through 8 took the top oil temperatures and subtracted the naphthenic from the iso-paraffin to come up with a series of data points (six per day) called the "iso-paraffin advantage". These were then plotted against ambient temperature, naphthenic oil temperature, and load to create scatter plots. These plots were then fitted using a second-order polynomial to provide the trend curves.

As any of the three parameters increased, there was a distinct advantage to the iso-paraffin fluid over the naphthenic oil.

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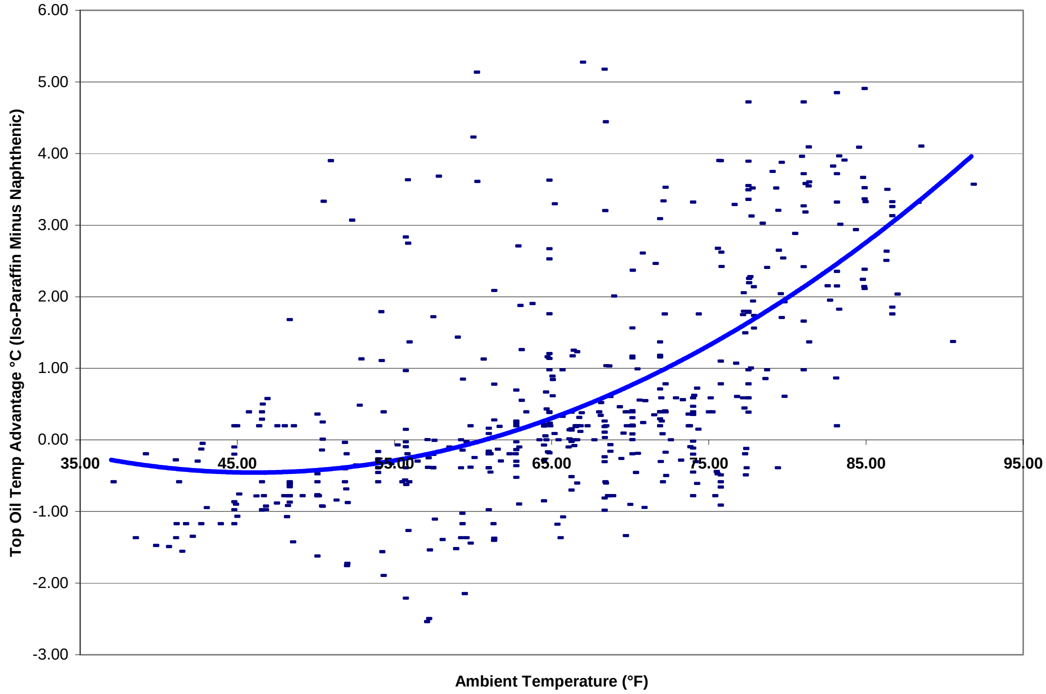
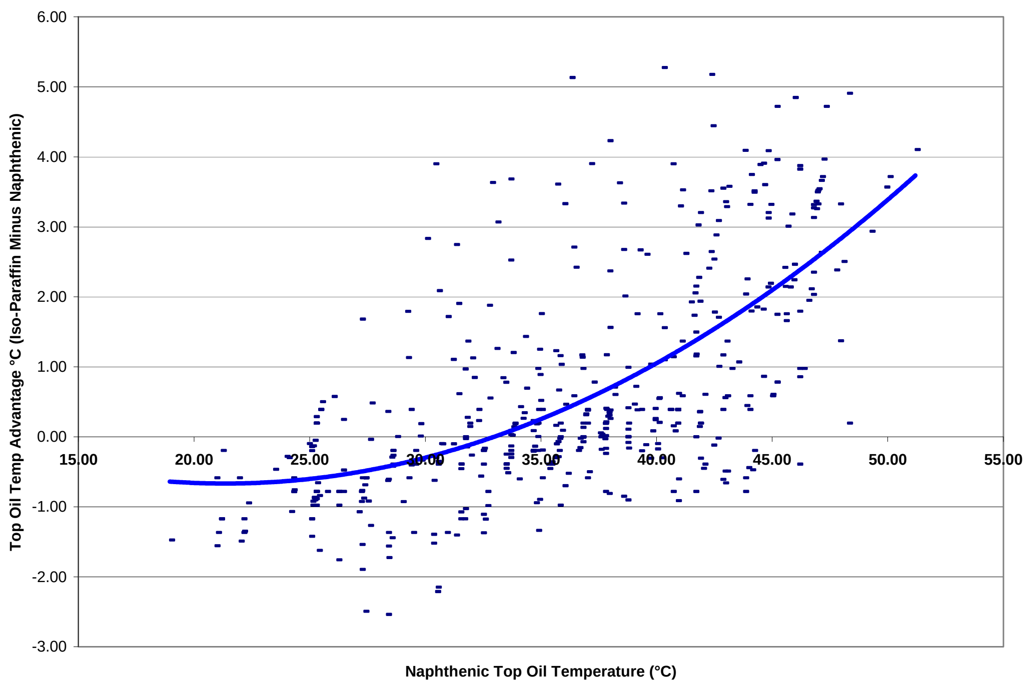
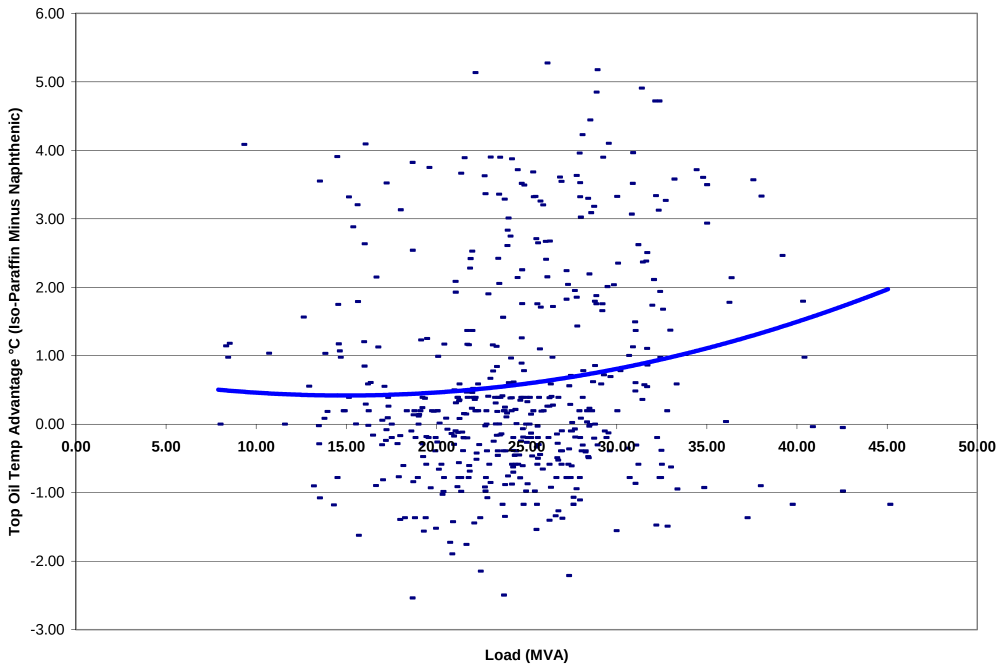


Iso-Paraffin Advantage versus Ambient Temperature
FIGURE 6



Iso-Paraffin Advantage versus Naphthenic Top Oil Temperature
FIGURE 7



Iso-Paraffin Advantage versus Load
FIGURE 8

The results of this test are very encouraging. As we have stated throughout the paper, for the same load (or power input) to the oil, the iso-paraffin will tend to have a lower oil temperature than the naphthenic oil. By using the difference between top oil temperatures as a reference and the fact that both transformers had the same loading (by being run in parallel), this clearly indicates that the iso-paraffin fluid displays better heat transfer capability than the naphthenic oil.

What is the overall benefit to a transformer owner / operator? There are two. With a lower top oil temperature the paper will age less quickly in an iso-paraffin fluid when compared to a naphthenic oil. As well, and perhaps more importantly, by using an iso-paraffin fluid, one could get more capacity from a transformer before hitting the rated temperature limit (either 55 °C or 65 °C temperature rise) – given it does not exceed any other limits of the transformers.

SUMMARY

The processes used to manufacture iso-paraffin fluid leaves it virtually sulphur-free and imparts the physical properties that make it a better heat transfer fluid than a naphthenic oil.

Heat transfer capability is a combination of the effects that these physical properties impart on the fluid. Heat Capacity and Thermal Conductivity are two significant properties of heat transfer that iso-paraffins have shown to have advantage over naphthenics.

Three tests were performed using iso-paraffin fluid versus naphthenic oil in transformers. In a Heat Run test performed at a manufacture's facility, iso-paraffins showed a lower winding temperature rise and a better heat transfer coefficient under these test conditions, both of which are indicators of superior heat transfer capability.

The second and third tests were performed by Cinergy Substation Services. One was on a transformer drained of naphthenic oil and refilled with iso-paraffin fluid. The next was a side-by-side comparison using two identically manufactured transformers in parallel so each saw the same loading and ambient conditions. In both cases, the iso-paraffin top oil temperature was lower than the naphthenic top oil temperature when compared to the loading during each test.

The benefits of using iso-paraffin fluids versus naphthenic oils in transformers means less ageing effect on the paper insulation due to lower oil temperatures as well as the potential for more capacity before hitting the upper rated temperature limit for the unit. Overall, the advantage in heat transfer using iso-paraffins is clear.

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AUTHORS

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