Efficient Electrical Cooling with OptiCool Fluid

Operating Temperature Prediction
Increase in Transformer Loading Profile
Characteristics of OptiCool Fluid at Elevated Temperatures
Oxidation Resistance of OptiCool Fluid
Material Compatibility Studies

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Introduction

Many power utilities wish to increase the power rating of their transformers through the use of a OptiCool Fluid, a specialty insulating oil. This study was undertaken in order to assist these utilities in calculating the amount of increased load their systems may be able to withstand without an increase in operating temperature of their equipment.

Questions to answer in this study are:

1. What load rating can be gained by operating transformers at elevated temperatures? What would be the expected operating temperature of the transformers at different loads?
2. What would be the difference in oxidation (aging) rates between conventional transformer oil and OptiCool Fluid if used at elevated temperatures?
3. What will be the operating characteristics of OptiCool at elevated operating temperatures?
4. What will be the effect on transformer cooling if OptiCool Fluid is substituted for conventional mineral oil?
5. What changes (if any) need to be made to the transformer design in order to use OptiCool Fluid?

Transformer Loading:

Before the introduction of thermally upgraded cellulose insulation materials, the practice in North America was to design transformers to operate with a 55^{o}C. average winding temperature rise over ambient. Ambient temperature is estimated in design calculations to be 30^{o}C. Allowable hot spot temperatures are 10^{o}C. above the winding temperature. This means that the average transformer operating temperature for normal life expectancy was 95^{o}C. (30+10+55).

European standards permitted an average winding temperature over ambient of 65^{o}C. when the heat transfer in the windings was obtained by natural convection and 70^{o}C. when the winding heat transfer was by forced oil circulation. The IEC system is based on 20^{o}C. annual average ambient temperature with a maximum of 40^{o}C. ambient temperature.

In the 1960's, transformer manufacturers in North America introduced thermally upgraded cellulose. Chemical additives slowed the thermal degradation process, allowing a longer service life at the same temperature or the same service life at higher temperatures. A new average winding temperature rise limit of 65^{o}C. was adopted, with a 15^{o}C. incremental hot spot allowance. This resulted in a 12% increase in rated power (MVA) for the same physical sized transformer. Normal life expectancy was based on a continuous hot spot temperature of 110^{o}C. (65 + 15 + 30^{o}C. ambient temperature). This is the standard used today as ANSI/IEEE C57.12.00-93.

Most modern transformer designs operate with a low temperature differential between the average winding temperature and the oil temperature. A transformer's output can be increased if the allowable average winding temperature rise is increased. The table below shows the relationship between an increase in transformer output in MVA vs. the difference between average winding temperature and oil temperature.

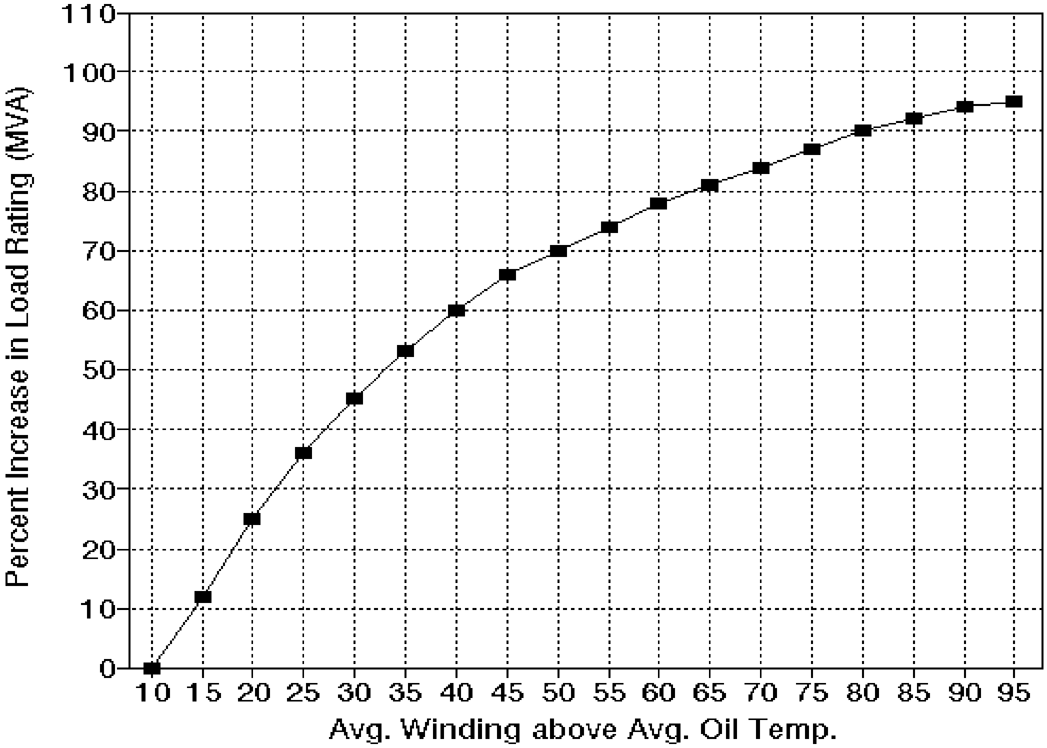

Figure 1
Relationship between Load Rating and Winding Temperatures

This table was developed through DSI's computer analysis of transformer data in the U.S. for 25 MVA units and the use of European data.

This graph shows that increasing the operating load by 50% (in this case to 37.5 MVA) increased the average operating temperature by approximately 25°C. Above 35% additional load factor, the rate of change in temperature (the slope of the plotted line) decreases, so that a 60% additional load results in 40°C. additional operating temperature.

Factors Influencing Operating Temperatures in Retrofilled Units

Transformer operating temperatures will be the result of four factors in a retrofilled unit:

- The ambient temperature
- The effect of using a different cooling fluid
- The effect of raising the power load on the transformer

Other factors also influence the operating temperature, such as cooling duct size, amount of heat transfer area (radiators), the operation of cooling fans, and oil pumps. These factors are usually not changed during a retrofill operation, however.

We will examine each of these factors individually, and then together.

1. <u>The ambient temperature.</u> In most designs, ambient temperature is expected to be 30^{o}C. Transformers are designed to operate at 55 or 65^{o}C. rise over the ambient temperature.

2. <u>The effect of using a less viscous fluid</u> (OptiCool Fluid) to cool the transformer, Instead of conventional transformer oil. Because of lower viscosity OptiCool Fluid more efficiently transfers heat than conventional transformer oil. Even with the power rating and the size of the transformer remaining equal, the transformer will run slightly cooler than it did with conventional transformer oil as the insulating fluid.

Because the two fluids do not have the same heat transfer characteristics, changing from conventional transformer oil to OptiCool will have an effect on the operating temperatures of the transformer. The transformer will operate at lower temperatures because of the lower viscosity of the OptiCool Fluid. To predict the difference in operating temperatures due to viscosity effects alone, we have used a sophisticated computer model to estimate oil temperature.

This computer model was developed by DSI in 1992 and has been used successfully many times to predict operating temperatures in transformers that are under consideration for retrofill. The model has been presented to IEEE and IEC in technical meetings. It calculates fluid heat transfer parameters and uses information about the specific transformer to estimate the difference between winding temperature and insulating fluid temperature.

The calculations are shown on the in the graph below (Figure 1). The data shows the difference in winding temperature (W) over oil temperature (O) for transformer oil and OptiCool fluid. One can see that the difference between the two fluids decreases as the operating temperature of the unit is increased.

As cooling efficiency is a function of transformer cooling duct size and shape, the temperature rise relationship between the two fluids is only approximate, and will be different with other engineering designs. The basic relationship and trends, however, will be similar.

The graph below shows an example of the difference in operating temperatures for a typical power transformer (10 MVA, convection cooling, 4 mm internal cooling ducts) when the fluid is changed from transformer oil to OptiCool Fluid. Notice that the cooling enhancement of OptiCool Fluid is itself a function the transformer operating temperature.

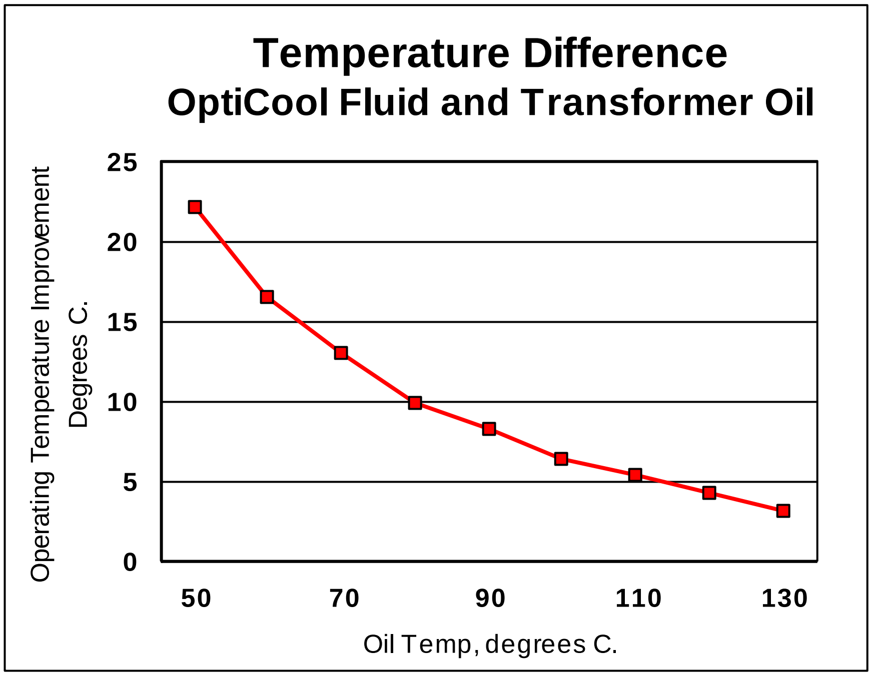

Figure 1
Cooling Benefit of OptiCool Fluid

As the transformer operating temperature increases, the difference between the cooling performance of OptiCool and transformer oil is decreased. In this particular transformer, when the oil temperature is 90 degrees C., the benefit of retrofilling to OptiCool Fluid is approximately 8 degrees C. That is, the transformer top oil temperature will be approximately 8 degrees lower after the retrofill with OptiCool. Other transformer designs may show different results.

Analyzing the data in this graph, we can develop the relationship of the temperature rise of the transformer because of changing to OptiCool Fluid:

Equation 1: $T_{OptiCool} = -31.27-.241(T_{Oil})$

Where: $T_{OptiCool}$ = the decrease in temperature due to changing to OptiCool Fluid
T_{Oil} = the transformer oil temperature before changing to OptiCool Fluid

At an operating temperature of 120°C., this difference is 3- 4°C. This figure differs with the geometry of different transformers, the heat flux input by the coils, and the cooling duct size in the core/coil assembly.

3. The effect of raising the power load on the transformer Transformers will run warmer due to increased power load. The chart shown as Figure 1 indicates that the temperature rise resulting from an increase in power rating of 50% would be approximately 35°C.

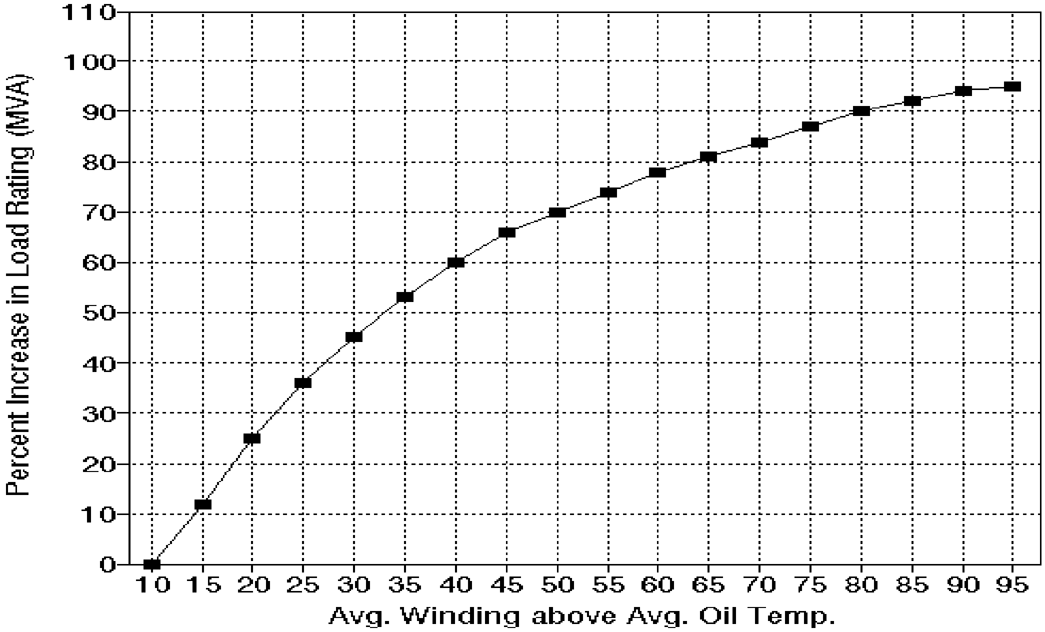

Figure 1
Relationship between Load Rating and Winding Temperatures

Using the Y axis (percent increase in load rating) as the independent variable, and applying statistical analysis to the data in the above chart yields the following relationship between the increase in power rating and the increase in temperature (winding temperature over oil temperature):

Equation 2: (W-O) = 9.14 + (.6867 x R) - (.01198 x R^2) + (.00014875 x R^3)

Where: (W-O) = the average winding temperature differential over oil temperature

R = the increase in load rating, expressed as a percentage of the design rating

This equation will assist the user in calculating the increased operating temperature when a the desired load rating is known. For example, when increasing the operating load from 100% to 125% (R=25), the calculated increased operating temperature is 21^{o}C. <u>The user should keep in mind, however, that these equations are derived from field transformer data, and will contain flaws and uncertainties that are inherent in measuring temperatures in transformers</u>.

Summary of Temperature Effects

As stated before, we are concerned with the following components of the operating temperature of a retrofilled transformer: the ambient temperature, the heat transfer characteristics of the cooling oil, and the load on the transformer. We will calculate the effect of changing the cooling fluid last, as it is a function of the temperature of the transformer.

Calculations for increasing the power load by from 100% to 125% and, at the same time, retrofilling the transformer with OptiCool Fluid

- Design Operating Temperature: We will use **55^{o}C**. rise over ambient temperatures
- Ambient temperature: We will use a constant **30^{o}C.** in our calculations.
- Effect of increasing the load factor on the transformer:

1. To calculate the temperature increase due to increased load, we use Equation 2. In this case, R = 25 (25% rise in load)

W-O = 9.14 + (.6857 x R) - (.01198 x R^2) + (.00014875 x R^3)

= 9.14 + (.6857 x 25) - (.01198 x 625) + (.00014875 x 3125)

= 9.14 + 17.14 - 7.49 + 2.32

= **+ 21.12^{o}C.**

- Effects of changing from transformer oil to OptiCool fluid:

The transformer is now operating at (55 + 21 =) 76 ^{o}C. rise over 30^{o}C. ambient = 106 ^{o}C. top oil temperature. Changing the fluid from transformer oil to OptiCool will have the following effect: (Using Equation 1)

$$T_{OptiCool} = 31.27-.241(T_{Oil})$$

$$T_{OptiCool} = 31.27-.241\ (106)$$

$$T_{OptiCool} = 31.27 – 25.5 = 5.77$$

Retrofilling the transformer with OptiCool under these circumstances will lower the top oil temperature by about 5.8 degrees C.

The resulting operating temperature of the transformer will be approximately (106—5.7 = 100.2 C.)

Methods of Minimizing Operating Temperatures:

1 In new transformers, use larger cooling ducts inside the transformer core and coils. Using ducts that are 6.35 mm to 6.52 mm in size will lower the operating temperatures by 3 - 6^{o}C.

2 Use thermostat-controlled fans to cool the transformer radiators when operating temperatures rise above a certain point, for example 125^{o}C. These fans have been proven to be very effective in maintaining lower temperatures in the transformer.

3 Use pumps to increase the heat transfer efficiency of the cooling oil. These pumps can be operated continuously, or they can be controlled by thermostats.

4 Minimize the changes in cooling surface area and power rating that are happening at the same time.

Cautions:

The equations and tables that were developed in this study use data from actual operating transformers. Measurements taken during experimentation and during field studies are only as accurate as the equipment and instruments used. Some transformer designs may react to the concepts presented here in different ways from other designs. In many instances, temperatures of actual transformers will differ by a few degrees from the temperatures shown here because of design differences. We have developed this study in order to assist power utilities in their evaluation of transformer operating temperatures. We sincerely believe that the data and equations developed are accurate, but cannot be responsible for changes in design that do not match the predicted transformer operating temperatures stated in this paper.

Other Considerations:

Oil Oxidation at Elevated Temperatures

Hydrocarbon oils oxidize when exposed to heat and oxygen. The first phase of the oxidation process breaks down the hydrocarbons to form acids. These acids will then polymerize to form sludge. Accumulations of the acids and sludge can shorten the life of a transformer, as the acids will attack the cellulose insulation, weakening it. Sludge build-ups can block cooling ducts in the transformer's core and coil, hindering the flow of cooling fluid. Hydrocarbon fluids oxidize more rapidly when they are heated. A rule in chemistry called the Arrhenius Rate Equation states that the rate of a chemical reaction, such as oxidation, will double with every 10 ^{o}C. rise in temperature. Thus, raising the operating temperature of a transformer from 80 to 120^{o}C. will oxidize the oil 16 (2^4) times as fast as operating it at 80^{o}C.

Petroleum oils oxidize at different rates from one another because of naturally occurring chemicals that accelerate the rate of aging. These chemicals, usually sulfur or copper compounds, are found in the crude oil from which the transformer oil is refined. The refining process does not remove these chemicals; they are therefore present in the finished insulating oil.

Synthetic oils, such as OptiCool fluid do not contain any chemical contaminants. They contain none of these naturally occurring oxidizing materials. This is the reason for their exceptional stability. OptiCool fluid oxidizes (ages) much more slowly than conventional transformer oil or any other petroleum based oil. Table One, below, shows the amounts of acids and sludge formed when OptiCool Fluid and transformer oil are tested in a standard ASTM Oxidation Stability test. <u>This test shows that transformer oil oxidizes 40 times more quickly than OptiCool Fluid, which indicates that the OptiCool Fluid will last approximately 40 times as long in service as the mineral oil.</u>

Characteristics of OptiCool at Elevated Temperatures:

The physical, chemical, and electrical characteristics of OptiCool fluid at different temperatures are shown in Table 2. There is very little change in the electrical characteristics of OptiCool with respect to temperature.

Table 1
Oxidation Results for OptiCool Fluid
ASTM D2440 oxidation test (bubbling O_2, 110 °C., Cu wire catalyst)

Standard Value for	OptiCool Fluid	Transformer Oil
72 Hours		
Sludge, wt %	<0.10	0.10
Acid Value Mg KOH/g	<0.10	0.30
164 Hours		
Sludge, wt %	0.010	0.020
Acid Value Mg KOH/g	0.010	0.40

Table 2
OptiCool Fluid Characteristics at Elevated Temperatures

Parameter	**80°C.**	**120°C.**
Density, g/cc:	0.7746	0.7434
Kinematic Viscosity, cSt:	2.17	1.52
Coefficient of Expansion:	0.00073/°C.	0.00071/°C.
Dielectric Strength, ASTM D1816, kV:	53 kV	54 kV
Dielectric Constant	2.12	2.05
Dissipation Factor, ASTM D924, %:	0.001	0.0012
Impulse Breakdown, kV:	> 300	>300
Specific Resistivity, ohm-cm:	1.1×10^{14}	4.0×10^{13}
Specific Heat. J/g/K	2.35	2.50
Thermal Conductivity, W/mK:	0.132	0.130

Compatibility with Equipment Construction Materials:

OptiCool Fluid is compatible with all equipment construction materials that are used with conventional mineral oil. OptiCool Fluid is less aggressive to paints, varnishes, rubbers, and other materials than is conventional oil.   OptiCool Fluid is compatible with all gasket materials that are commonly used with conventional mineral transformer oil. Some of these materials are:

Nitrile Rubber
Buna-n Rubber
Cork
Silicone Rubber
Viton
Fluorocarbon Rubber

OptiCool Fluid is compatible with a wide variety of transformer components, including several types of plastic and paper insulation. OptiCool Fluid has been used with many types of phenolic, epoxy and formaldehyde resins. Both conventional and high-temperature application papers (Nomex) have been used in equipment filled with OptiCool Fluid. As most retrofilled transformers have been used for several years with conventional transformer oil, we expect that there will not be any problems with material compatibility in OptiCool Fluid.

Conclusion:

This study has examined the retrofill of distribution and power transformers with OptiCool Fluid in order to operate them with higher loads at higher temperatures.

Calculations show that power utilities can operate the transformers at 25-50% higher load. The use of OptiCool Fluid will minimize the temperature rise associated with the higher load profile.

OptiCool Fluid will oxidize much more slowly than conventional transformer oil at the elevated operating temperatures. Tests indicate that OptiCool will create only 2.5% (1/40) as much acids and sludge as mineral oil.

The physical, electrical, and chemical characteristics of OptiCool Fluid do not degrade at the higher temperatures expected.

The materials used in distribution and power transformers are be compatible with OptiCool Fluid. This is based on the fact that they have proven compatible with conventional mineral oil.

References:

ANSI/IEEE Standard C57.12"Standard Guide for Loading Mineral Oil Insulated Transformers"

IEEE Project P1276 "IEEE Guide for the Application of High Temperature Insulation Materials in Liquid Immersed Power Transformers"

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